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ENERGY, ENVIRONMENT, AGRICULTURE, AND INDUSTRY

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MASTER

NOTICE

Preface

The oral papers and poster papers presented at the First Biomass Conference of the Americas in Burlington, Vermont, August 30–September 2, 1993, and available when publication of this book began, are reproduced herein. It should be emphasized that almost all of these papers were published as received, whether they were in camera-ready form or not. The technical content of each paper and the opinions expressed are attributed entirely to the authors. In a few cases, grammatical changes were made, and abstract pages were retyped to improve readability.

The First Biomass Conference of the Americas was designed to provide a national and international forum to support the development of a viable biomass industry. Although papers on research activities and technologies under development that address industry problems comprised part of this conference, an effort was made to focus on scale-up and demonstration projects, technology transfer to end users, and commercial applications of biomass and wastes. The conference was divided into these major subject areas:

- Resource Base
- Power Production
- Transportation Fuels
- Chemicals and Products
- Environmental Issues
- Commercializing Biomass Projects
- Biomass Energy System Studies
- Biomass in Latin America — Overview

The papers in this book are grouped in the same subject areas.

We believe this conference is the first of its kind and that it fills a real need to document and disseminate information on important developments in biomass. It is our intent to continue this program biannually in coordination with the biannual conference presented by the Commission of the European Communities on biomass developments in Europe, and to expand the program by including an exposition of vendors who market biomass equipment and services to the industry. The Second Biomass Conference of the Americas has been scheduled for 1995.

We would like to express our sincere appreciation to all the authors, who made an extra effort to produce quality papers under a rather stringent time schedule, to the Session Chairs who also doubled as members of the Program Committee and assisted in the selection of papers, to the Executive Committee who kept us headed in the proper direction, and to the sponsors of the conference—the U.S. Departments of Agriculture and Energy; the U.S. Environmental Protection Agency; Energy, Mines and Resources Canada; and the National Renewable Energy Laboratory, under whose auspices the conference was presented. The cooperation of these organizations was a key ingredient essential to the planning, organization, and presentation of this conference.

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BIOMASS: AN OVERVIEW IN THE UNITED STATES OF AMERICA

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Abstract

Concerns about the heavy reliance on foreign sources of fossil fuels, environmental impacts of burning fossil fuels, environmental impacts of agricultural activities, the need to find sustainable renewable sources of energy, and the need for a sustainable agricultural resource base have been driving forces for the development of biomass as a source of energy. The development of biomass conversion technologies, of high-yielding herbaceous and short-rotation woody biomass crops, of high-yielding food, feed, and fiber crops, and of livestock with higher levels of feed conversion efficiencies has made the transition from total reliance on fossil fuels to utilization of renewable sources of energy from biomass a reality. A variety of biomass conversion technologies have been developed and tested. Public utilities, private power companies, and the paper industry are interested in applying this technology. Direct burning of biomass and/or cofiring in existing facilities will reduce emissions of greenhouse and other undesirable gases. Legislation has been passed to promote biomass production and utilization for liquid fuels and electricity. Land is available. The production of short-rotation woody crops and perennial grasses provides alternatives to commodity crops to stabilize income in the agricultural sector. The production of biomass crops can also reduce soil erosion, sediment loadings to surface water, and agricultural chemical loadings to ground and surface water; provide wildlife habitat; increase income and employment opportunities in rural areas; and provide a more sustainable agricultural resource base.

Background

This paper is divided into two major sections. The first will highlight the current situation with respect to the production and use of biomass to produce energy. The second will give a brief overview of the past, present, and future role of the agricultural sector as a supplier of biomass as a renewable source of energy.

What Is Biomass?

For this paper, the term biomass (plant and animal matter) includes a broad range of materials that are biological in nature and can be used to produce various forms of energy. This includes agricultural and forestry products, agricultural and forestry waste products, and animal wastes such as manure. These products may be used for direct combustion, gasified, and/or processed into biofuels such as ethanol, methanol, ethyl or methyl esters, methane, and biocrude. This paper will emphasize the use of biomass as a renewable source of energy for electric power generation and the potential land base available to produce biomass.

Why Biomass?

The developing of a public consciousness of the environmental effects of burning fossil fuels has probably done more than anything else to identify biomass as a desirable renewable source of energy. There have been many concerned persons over the years. About two centuries ago, the English economist Thomas Malthus predicted that the world's resource base was limited and that population growth would eventually outstrip the ability of the world's resource base to provide food for the growing population. At that time, population was growing faster than agricultural production technology. Since Malthus, the wonders of technology have increased the rate of growth in the development and adoption of agricultural technology so that it is now growing faster than demand for food and fiber from agricultural sources. The development and adoption of technology have also made possible instant communication around the world. Instant communication has had profound impacts on forming public opinion and public policies. The oil shocks of the 1970s and related economic impacts were highly publicized. Environmental impacts of human activities on renewable and non-renewable resources are now better understood. Education of the general public on major impacts of the use of fossil fuels, agricultural chemicals, and destruction of forests, among other things, has evoked interest in returning to agriculture as a source of renewable energy.

Scientists have been researching the interactions and interventions of man with nature for centuries. In the early 1960s, Rachel Carson's book, Silent Spring, excited and sensitized the world. This book and other environmental and conservation activities provided the impetus required to protect the Nation's soil, water, and related resources. In addition to the creation of the Environmental Protection Agency, a variety of other actions were taken to protect, conserve, and enhance the Nation's soil, water, and related resources. Of these actions, Public Law 95-195 is of major importance for the purposes of this conference. This Act is called the Soil and Water Resources Conservation Act of 1977 (RCA). It requires the Secretary of Agriculture to assess the Nation's soil and water resources and to develop a national program "for furthering the conservation, protection, and enhancement of the soil, water, and related resources of the Nation..." (U.S. Congress 1997).

The 1985 Food Security Act was the first legislation to link supply control and farm income stability programs to conservation. This Act tied the benefits of all agricultural financial assistance programs to compliance with good stewardship of the land. Producers that have any lands that are classed as highly erodible must have a conservation plan and put it into effect by the end of 1994 in order to participate in any financial assistance program available from the U.S. Department of Agriculture.

Additional research has identified the impact of a wide variety of gases associated with human activities on air quality, acid rain, depletion of the ozone layer, and global climate change. The burning of fossil fuels for the production of electric power, industrial production, agricultural production, and transportation is a major contributor to these problems. Some important actions that are underway to reduce the negative impacts of burning fossil fuels are given below.

The Energy Security Act of 1980 established a goal for agriculture to produce 10 percent of the Nation's annual liquid fuel consumption by 1990. This act also permitted the Secretary of Agriculture to provide technical and financial assistance for a variety of energy-conserving activities.

The Department of Energy has initiated the development of technology to produce biomass for conversion to biofuels for internal combustion engines and for the production of electricity by direct combustion and/or gasification.

The Electric Power Research Institute is also promoting the development and utilization of biomass for producing electricity.

International treaties and/or agreements to reduce the emissions of "Greenhouse Gases" (GHG) have been signed by many nations. The developed nations have initiated a set of country studies to help developing countries determine the actual situation in their countries with respect to the level of production of greenhouse gases and to initiate programs to mitigate negative impacts.

The above concerns provide a very brief overview of why we are here today. Two important questions that need to be answered are first, *do we have the technology to use biomass to produce energy;* and second, *do we have the necessary land resources?* These questions will be answered in the sections that follow.

Biomass: Current Situation

Biomass could play a major role in production of energy and improve environmental qualities in many regions by reducing emissions of GHG and other pollutants into the atmosphere. These gases and pollutants include carbon dioxide, carbon monoxide, nitrous oxide, methane, sulfur dioxide, and suspended particulates. This section will summarize the current situation in the biomass power industry; examine the potential role of cofiring biomass and biomass residues in the production of electricity and their environmental benefits; identify potential energy crops; estimate capacity of plants using biomass; and discuss policies that could enhance use of biomass wastes, biomass residues, and energy crops.

The U.S. agricultural sector has traditionally been a producer of food and fiber. However, through improvement in technologies, more agricultural products are being used for producing electricity and liquid fuel for transportation. Currently the energy generated from biomass (wood and corn) accounts for 2.8 quads or 3.5 percent of total energy production in the United States. Wood is the largest contributor to biomass energy, about 2.7 quads (Turhollow 1993, U.S. Department of Energy 1993 and 1984).

Biomass Types

Currently biomass waste is the primary source of fuel used in biomass power facilities (American Paper Institute 1991, Louisiana State University 1992, 1984a, and 1984b). Biomass for wood-burning power plants is provided from urban wood, fuel wood, wood byproducts, and waste wood (Klass 1984 and USDA and USDOE 1990). Fuel wood is produced on private wood lots, national forests, and state wood lots. Wood byproducts are mainly spent liquor and sawdust (USDA and USDOE 1990, USDOE 1992, USDOE 1993a, USDOE 1993b, and USDOE 1993c). Waste wood includes cull logs, hogged bark, and manufacturing scrap wood. However, at present, a large percentage of waste wood remains unutilized. The Department of Energy estimates that enough biomass waste will be available to allow the biomass power industry to expand modestly throughout the 1990s (USDOE 1991a and USDOE 1993d).

Agriculture and forestry, in addition to their main roles of producing food, fibers, and lumber, have become a source of biomass for energy and other new uses. Large portions of these byproducts are currently either burned in the field or disposed of in landfills. Products such as nutshells, rice hulls, bagasse, cotton gin trash, orchard trimmings, and forestry byproducts have potential as fuels for cofiring or as a supplement in biomass-dedicated plants (Turnbull 1993 and USDOE 1991b).

According to the National Wood Energy Association, about 11 million tons of agricultural waste were produced in 18 states in 1989 (National Wood Energy Association 1993 and USDOE 1991b). Agricultural wastes were also produced in other states for which 1989 annual statistics are not available. Wood and wood waste account for most of the biomass energy used in the United States today (USDOE 1991b and 1993d). More than 140 million tons of wood are used for commercial, industrial, utility, and residential purposes. Sixty-five percent of this wood is used for commercial, industrial, or utility energy production. Thirty-five percent is used to heat homes (table 1).

Table 1 Regional Biomass Data, 1989

	Great Lakes	North-east	North-west	South-east	West-ern	Hawaii	Total
Wood (1,000 tons)							
Commercial	6,404	16,985	20,728	46,806	6,306		97,229
Residential	7,398	14,281	3,739	16,398	3,386		45,202
Agricultural waste (1,000 tons)	350		1,800	5,668	3,138		10,956
Alcohol (1,000 gal.)	918		15	187	151		1,271
Biogas (MMCF/year)	16	54	589,093	6	657,005	0.8	1,241,173

Source: National Wood Energy Association
Great Lakes: IL, IN, IA, MI, MN, OH, WI.
Northeast: CT, DE, MA, MD, ME, NH, NJ, NY, PA, RI, VT.
Northwest: AK, ID, MT, OR, WA.
Southeast: AL, AR, FL, GA, KY, LA, MS, MO, NC, SC, TN, VA, WV.
Western: AZ, CA, CO, KS, NE, NV, NM, ND, OK, SD, TX, UT, WY.

Expansion and development of biomass power depends on environmental and economic incentives provided to utility companies to promote new technologies which lower biomass production cost per ton. New biomass power plants require a long-term, reliable and abundant supply of biomass such as chipped or whole trees. Therefore, waste wood could be used as a supplemental source but not as a primary supply source.

Energy Crops

The United States has a vast supply of biomass that is available for energy production (Keener and Roller 1975). The production of energy crops as a renewable source of energy can generate jobs in rural areas, increase farm income, help reduce the budget deficit by providing alternative sources of income (displacing commodity crops), and help improve the US trade balance (Hall et al. 1993 and Williams 1992). Herbaceous and woody crops have been identified as suitable energy crops for production of electricity. There are varieties of energy crops which can be produced annually in large volume in the United States. Soil types, climate, and land availability are the main determinants of types and volume of energy crops in each region (Turhollow 1993, Wright et al. 1993, and Wright and Ehrenshaft).

Energy stored in the biomass can be used in solid form or can be converted to liquid forms. Direct combustion of energy crops is the easiest way to produce energy. Burning wood has been a source of energy for humankind since prehistoric times. However, direct combustion of energy crops for heat is inefficient and has limited use because of high hauling costs. The introduction of efficient boilers and possibility of gasification of biomass brought new opportunities for energy crops. Energy crops can also be converted to liquid fuels such as ethanol or biocrude. Energy crops are grouped in two large categories: herbaceous and woody crops. Herbaceous energy crops are perennial with the exception of a few annual crops. Land preparation and planting energy crops account for a large percentage of production costs. Therefore, perennial energy crops (herbaceous or woody) are more cost efficient than annual energy crops.

Currently, there are no commercial plantings of herbaceous or woody crops strictly for the production of electricity in the United States. Energy crops are not produced commercially because of lack of demand. In addition, the bulkiness and high transportation cost of biomass curtail biomass use and limit the size of plants.

Herbaceous Energy Crops

Herbaceous energy crops have more variety and greater versatility than woody energy crops. Some are annual crops with thick stems like sorghum, and some are perennial with thick stems like energy cane. Others are perennial with thin stems like switchgrass. Depending on conditions, herbaceous energy crops can be either grown in monoculture or interseeded with more than one species in a stand. They can also be double-cropped with other energy crops or with conventional agricultural crops.

A number of grasses and legumes are being evaluated for their potential as energy crops in the Department of Energy Herbaceous Energy Crop Program (Wright et al. 1993 and Wright and Ehrenshaft 1990). Grasses include Bahia grass, Bermuda grass, eastern gama grass, reed canary grass, napiergrass, rye, Sudan grass, switchgrass, tall fescue, timothy, and weeping love grass. Legumes being tested include alfalfa, bird's-foot trefoil, crown vetch, flatpea, clover, and sericea lespedeza. Field testing is taking place at a number of sites around the country.

There are advantages and disadvantages to growing herbaceous crops for energy production. Many of these crops are already familiar to farmers, and production practices and the equipment used to produce them as energy crops are already part of the farmers' knowledge and capital base. Bulkiness, post-harvest losses, and annual cultivation and other intensive practices required to maintain high yields are common problems with herbaceous energy crops.

Short-Rotation Woody Species

Using wood to produce energy is as old as mankind. Today, tree species suitable for energy crops must produce large quantities of wood in a short period of time. Scientists call such species "short-rotation woody species" because their growth and harvest cycle is relatively short, i.e. 5 to 10 years. The U.S. Department of Agriculture (USDA) and U.S. Department of Energy (DOE) are field testing several short-rotation woody species, including hybrid poplar, black locust, eucalyptus, silver maple, sweet gum, and sycamore. Research projects are being conducted in many regions of the United States, including the Northeast, Southeast, Great Lakes, and Northwest. Results can be used to develop trees that are adapted to specific locations.

Before short-rotation woody species can be used as an economic source of energy, there are various unresolved issues which call for continued investigation and experiment. Among the attainable goals of this research are higher yields per acre, enhanced regrowth which would allow more frequent coppicing, resistance to insects and to weed competition, and improved harvest and handling techniques. Additional problems for short-rotation woody species when compared with herbaceous energy crops include soil erosion, higher costs of production, long-term capital investment in new machinery and equipment and other production inputs. Also, there are high risks associated with the production of woody energy crops, and many farmers are not willing to invest in energy crop production.

Biomass Energy Production

U.S. biomass electric power generation experienced substantial growth as a result of incentives provided by the Public Utility Regulatory Policies Act of 1978 (PURPA) and higher prices of fossil fuels (USDOE 1993a and 1993b). Prior to 1979, there were only 200 megawatts-electric (MWe) reported for biomass energy-based generating capacity in the United States. About 8,400 MWe of installed biomass power generating capacity were reported by Robert Williams and Eric Larson by the end of the 1980s (Williams and Larson 1993). However, according to the Department of Energy in 1992, U.S. power plants fueled by wood and other biomass resources accounted for approximately 6,500 MWe (USDOE 1992).

During the 1980s, national interest grew quickly in wood burning electric generating plants as a direct result of federal tax policy and state utility regulatory actions. During 1980-85, 3,054 megawatts of power from wood-burning generators were reported (USDOE 1992). In 1986 alone, 1,839 megawatts of power from biomass burning went into operation. In 1989 and 1990, according to the National Wood and Energy Association only 614 and 300 megawatts of wood-fueled electricity were brought into operation.

It is estimated that there are nearly 1,000 wood-fired plants in the United States, ranging from one to over 100 megawatts (USDOE 1992). Only a third of these plants offer electricity for sale. The rest are owned and operated by paper and wood products industries for their own use.

Despite rapid growth in the 1980s, active biomass power projects have decreased in number in the 1990s. The biomass power industry is now in a low-growth phase because of low fossil fuel prices (natural gas), competitive bidding for power sales, loss of federal tax credit, and costly permitting procedures.

Competition from natural gas-fired generators has also dampened the market for biomass projects. The price of natural gas peaked in the 1980s and has declined since. Low investment cost per kilowatt hour (KWh), high efficiency in converting natural gas to electricity, lower prices of natural gas due to use of new technology for gas well drilling, availability, and less pollution relative to coal and oil make natural gas an ideal source of energy for production of electricity.

Biomass-fired power plants are either stand-alone or cogeneration (Williams and Larson 1993 and Williams 1992). There are 149 stand-alone biomass plants, reported in 30 states (table 2). Only three states -- California, Florida, and New York -- reported more than 10 biomass-based power plants. The number of biomass-burning plants per state in the rest of the country ranged from 1 to 5. About half of the plants are located in California. Total capacity reported for California is more than 700 MWe. The average capacity varies from 1 to over 100 megawatts of electricity.

There are 367 cogeneration biomass power plants with an average capacity of 16 megawatts located in 36 states. Most of them are located in the Northeast, Northwest, and Southeast. Three states -- Maine, Florida, and New York -- account for 1,600 MWe or 27 percent of biomass-based electric capacity.

Table 2 Electricity Generating Plants Burning Biomass Fuel in the U.S., 1989

	Stand-alone			Cogeneration		
Region[1]	Number	Capacity MWe	Avg. Cap. MWe	Number	Capacity MWe	Avg. Cap. MWe
Great Lakes	14	224	16	60	655.2	11
Northeast	34	771	23	70	1,906	27
Northwest	9	159.2	18	58	761	13
Southwest	21	443.5	21	125	2,062	16
Western	69	791	11	41	438	11
Hawaii	2	70	35	13	129	10
Total	149	2,458.7	17	367	5,951.2	16

Source: Renewable Energy, Sources for Fuel and Electricity, Island Press, 1993

[1] See table 1 for definitions of regions.

More than half of the biomass cogeneration capacity is located in the Southeast (2,069 MWe) and Great Lakes (655 MWe) regions. In contrast, more than half of the stand-alone biomass-burning electric generating capacity is located in the Western (791 MWe) and Northeast (771 MWe) regions.

Potential Plants

In addition to existing biomass-burned stand-alone and cogenerating electric generating plants, there are many coal generating plants which have the potential for cofiring biomass. Cofiring biomass and coal is another alternative for some coal generating plants to reduce SO_2 emissions. Under Title IV: Acid Deposition Control of the Clean Air Act Amendments of 1990, plants must reduce annual SO_2 emissions by ten million tons from 1980 levels (USDOE 1993a).

Cofiring biomass with coal, however, is not currently a viable option for electric utilities due to low heat value, high moisture contents, collection and handling problems, supply availability and costs. Alternatively, many plants are considering near-term solutions such as switching to lower sulfur coals, installing flue gas desulfurization (FGD) equipment, cofiring natural gas, purchasing allowance, reducing output from or retiring plants. Options such as coal cleaning, retrofiring and utilization of clean coal technologies are considered as longer-term options.

Retrofitting a coal plant to burn biomass generally requires boiler modifications and the addition of a separate biomass fuel handling system. However, operation of such a plant is very similar to that of a coal plant. The major drawbacks of cofiring include decreased boiler efficiency due to less Btu and high moisture content of the biomass and boiler derating resulting in part from increased flue gas and air flow rates.

Biomass can also be converted to fuel gas or biocrude which can be used in high efficiency combustion turbine-based power generation cycles such as combined cycles or steam-injected gas turbines (Meridian 1992, Meridian and Antares 1993, and USDOE 1993a). Through gasification, solid biomass can be converted to a low Btu fuel gas. The principal advantage is the high combustion efficiency associated with gaseous fuel. Through fast pyrolysis, biomass can be converted to a biocrude similar to number 6 (bunker c) fuel oil. Biocrude has advantages relative to solid biomass fuels in that it is more easily transported. Biocrude has many disadvantages such as low Btu content (10,000 Btu/lb), low pH.(2.5 to 3.2), and instability in high temperatures (over 40 degrees Celsius).

Cofiring biomass with coal in utility boilers offers many environmental benefits beyond reducing SO_2 emissions (Dyn Corp. et al.). Biomass is a renewable source of energy with sulfur content below 0.1 percent and moderate Btu (8,800 per dry pound). Using wood waste as a fuel reduces landfill materials and consequently extends landfill life. In addition, the use of wood waste in boilers with pollution control, instead of burning waste wood in uncontrolled furnaces, is another means of reducing emissions. Furthermore, biomass has less ash content than coal and offers zero-net CO_2 combustion, therefore lowering the CO_2 emissions and ashes of coal-fired plants.

Section 404 (f) of Title IV of Clean Air Amendments Act (CAAA) includes provisions for earning credits from SO_2 emissions avoided through energy conservation measures or use of renewable energy. These allowances are earned regardless of the emission rate and ceiling for every KWh generated by renewable energy or saved by demand side management. The earned credits will be allocated from 300,000 allowances in the Energy Conservation and Renewable Energy Reserve on a first come, first served basis.

In addition to decreased boiler efficiency, boiler derating, and increased slagging potential, there are other constraints in cofiring biomass with coal. These include long-term availability and reliability of biomass supply, types of coal-fired boilers, plant capacity, and economic and environmental issues related to cofiring biomass. Among the existing coal-fired boiler technologies only stokers, pulverized coal units (PC), and fluidized beds have potential to cofire solid biomass. The advantages and disadvantages of the above boilers are discussed in detail by Piscitello and Demeter (1992).

To identify potential plants for cofiring biomass, resource requirements and technical and economic criteria are applied to the Environmental Protection Agency's National Allowance Database. The 1985 database contains operation information on 3,700 operating units, including location, capacity, heat rate and SO_2 emission rate (Piscitello and Demeter 1992). Based on screening procedures used by the Antares Group on 3,700 operating units, only 24 units are considered candidates for biomass cofiring (table 3). The final screening involved a unit-by-unit review of present cofiring requirements, resource requirements, local biomass availability, and whether the utility operating unit was in Phase I or Phase II utility. Phase I is designed to reduce SO_2 emission rates of the 110 "dirtiest" utility-owned power plants in the 48 contiguous states to 2.5 lb of SO_2/MMBtu by January 1, 1995. Phase II sets an emission ceiling of 1.2 lb/MMBtu for all generating units (both utility and non-utility) larger than 25 MWe by January 1, 2000.

Table 3 Coal-firing Generating Units with Potential to Cofire Biomass

Region[1]	Capacity MWe	Percent biomass heat input	Equiv. biomass capacity MWe	Approx. feedstock required ton/day	Price of coal $/MBtu	Number of units
Great Lakes	423	34	145	4,170	1.98	3
Northeast	200	28	47	1,860	1.90	5
Southeast	1,710	34	566	17,680	2.03	16
Total	2,333	32	758	23,710	2.03	24

Source: Biomass Cofiring Analysis Summary, Scott Piscitello and Christian Demeter, June 1992.

[1] See table 1 for definitions of regions.

More than 2,000 MWe capacities have potential for biomass cofiring. Most of these capacities are located in the Southeast region. The equivalent of biomass capacities will account for about one third of total capacities. Feedstock requirements for these units are about 24,000 tons per day.

Demonstration Pilot Plants

The Electric Power Research Institute (EPRI), Minnesota and Wisconsin power companies, and the Department of Energy are promoting the use of energy crops as a main feedstock for about 10 demonstration electric generating plants (table 4). The main purpose of these pilot plants is to demonstrate the use of energy crops as a feedstock for electric generation (Energy Performance System, Inc. 1991, 1992).

Table 4 Energy Crop Pilot Plants, Location, Size, and Fuel Types

Suggested location	Capacity MWe	Energy crop acreage	Fuel types[1]
Arkansas/Mississippi	25	25,000	SRWC
California	25	25,000	
Georgia/Alabama	25	25,000	SRWC
Hawaii	25	25,000	HEC
Iowa	25	25,000	
Tennessee	25	25,000	HEC
Texas	25	25,000	
Washington	25	25,000	SRWC
Wisconsin/Minnesota	100	100,000	WTB

[1] Type of biomass fuel as identified: SRWC = Short-rotation woody crop, HEC = Herbaceous energy crop, and WTB = Whole tree burner.

Operation of these demonstration plants will help to reduce the existing barriers to using biomass as a dedicated feedstock. In addition, the pilot plants promote cooperation between utilities and farmers, thus reducing the risk and uncertainty for both groups. Feedstocks for these plants are from short-rotation woody crops and/or herbaceous energy crops. Among the pilot plants designed to use woody energy crops, whole-tree burning plants, developed by Energy Performance Systems, Inc., are more practical and cost efficient. Whole-tree burning systems have lower feedstock handling losses and require less capital investment for feedstock handling than those designed to burn processed wood chips.

Agriculture: A Supplier of Biomass

Agriculture has been and may continue to be a major supplier of biomass for energy. This section summarizes agriculture's role as a past, present, and potential future source of renewable energy.

The development and adoption of technology is one of the most important factors that has impacted the supply of energy from biomass originating in the agricultural sector. The development and adoption of agricultural technology was facilitated by legislation designed to promote the public welfare. Some of the key pieces of legislation are summarized below. It is important to note that 1) agriculture was a major supplier of energy from renewable resources prior to the development and adoption of the internal combustion engine; 2) the development and adoption of tractors, related machinery and equipment, and other agricultural production technologies have had a significant impact on land use and availability for production of energy from biomass; and 3) that the development and diffusion of agricultural technology was and is a very successful national policy.

Legislation Promoting the Development of USDA

The development of our agricultural system resulted from specific pieces of legislation designed to promote the public welfare through development, dissemination, and adoption of agricultural technology. Examples of such legislation include the following:

- the Organic Act of 1862 established the Department of Agriculture and gave it authority to acquire and diffuse useful information related to agriculture;
- the Morrill Act of 1862 established the first land-grant university system to promote agriculture, technology, and industry;
- the Hatch Act of 1887 strengthened the land-grant system by providing support to state experimental stations;
- the second Morrill Act of 1890 established the 1890 land-grant colleges to provide agricultural education for blacks; and
- the Smith-Lever Act of 1914 authorized USDA to cooperate with state extension programs in agriculture-related fields.

Other policies designed to stabilize farm income and control the supply of agricultural products have had significant impacts on the adoption of new technology. In general, these policies have tended to reward the adoption of technology.

Impacts Associated with the Development and Adoption of Technology

Until the advent of the internal combustion engine, agriculture was a principal supplier of energy from renewable resources. Animals were a major source of power for transportation in cities, moving agricultural production from farm to local markets, agricultural production, and mining.

The adoption of tractors with associated farm machinery and equipment led to the development of a large set of technologies related to plow depth and seed bed preparation, timing of practices and control of planting depth, the placing of fertilizers, and the application of related agricultural chemicals required for hybrids and other high-yielding crop varieties. These new technologies significantly improved yields. The impacts of adopting these new technologies are noted below:

- a reduction in per capita land requirements for domestic consumption of 2.34 acres in the 1930s to 0.93 in the 1980s;
- a reduction in land requirements to produce feed for animal power from 65 million acres in the 1930s to less than 4 million acres in the early 1960s;
- a reduction in farm labor requirements from an average of 10.4 million worker-years in the 1930s to 1.9 million worker-years in the 1980s (based on 2080 hours per worker-year);
- a significant increase in the use of agricultural chemicals and machinery;
- significant reductions in the relative costs of food and fiber;

- an increase in the acres of row crops; and
- a decrease in acres of close grown crops.

Technological development in livestock production efficiencies has also had a significant impact on land use. In 1989, Robertson et al. reported that the dairy sector produced approximately 40 percent more milk in 1988 than in 1930 with fewer animals and less land. Given 1930s' technology and today's level of demand, we would need an additional 33 million acres for hay and 15 million acres of feed grains (Robertson et al., 1989). Since the 1930s, the decrease in land requirements for animal power and milk production has released over 100 million acres of cropland for other uses.

Availability of Cropland for Biomass Production

Privately owned land in farms in the United States reached its zenith of approximately 1,161 million acres in 1950. Since then, land in farms has decreased to approximately 964 million acres, a 17 percent reduction. Of the 964 million acres, 421 million are classed as cropland and 494 million acres could be converted from other uses to cropland (table 5).

Table 5 Selected Data on Cropland Planted and Land in Farms

Year[a]	Cropland planted (millions) Acres	Cropland planted (millions) Hectares	Land in farms (millions) Acres	Land in farms (millions) Hectares
1930	369.5	149.5	990.1	400.7
1940	347.8	140.7	1,065.1	431.0
1950	353.2	142.9	1,161.4	470.0
1959	329.6	133.4	1,123.5	454.7
1969	291.2	117.8	1,062.9	430.2
1978	336.4	136.1	1,014.8	410.7
1987	304.9	125.2	964.5	390.3

[a] Data are for Ag-Census years at approximately 10-year intervals.
Includes Alaska and Hawaii.

The total potential cropland base in private farms is approximately 915 million acres. This includes the current cropland base and also pasture, range, and forest lands that have a potential for conversion to cropland as identified in the 1987 National Resources Inventory (table 6).

As shown in table 7, a significant amount of land was used to produce power from land prior to the development of the internal combustion engine. By the end of the 1960s, land used for animal power became so insignificant that it was dropped as a category in the Agricultural Statistics series of the Department of Agriculture.

As a result, fewer acres of close grown crops -- hay, oats, rye, and barley -- were required to produce animal power. These acres were shifted into row crops. A shift back to close grown or to short-rotation woody crops would provide more habitat for wild life, reduce erosion, sediment loadings, and agricultural chemical loadings to ground and surface waters. This in turn would help to promote a more sustainable agricultural resource base. Table 8 shows the general trends in the distribution of cropland between row crops and close grown crops.

Table 6 Potential Cropland

	Acres (millions)	Hectares (millions)
Current cropland	421.4	170.5
Potential cropland[1]		
high potential	35.3	14.3
medium	117.6	47.6
low	340.7	137.9
Total potential	915.0	370.3

[1] Land in farms that has a high, medium, or low potential for conversion to cropland.

Table 7 Land Use for Energy, 1920 to 1964

Year/period	Acres (millions)	Hectares (millions)	Percent of cropland
1920	91	37	25
1930s	65	26	19
1940s	32	13	9
1950s	12	5	4
1960s	4	2	1

Source: Agricultural Statistics

Table 8 Distribution of Row and Close Grown Crops, 1939-1989

	Row crops (millions)		Close Grown Crops (millions)	
Decade	Acres	Hectares	Acres	Hectares
1930s	132.9	53.8	174.4	70.6
1940s	126.5	51.2	192.2	77.8
1950s	108.1	43.7	178.6	72.3
1960s	125.4	50.7	147.9	59.9
1970s	150.4	60.9	147.9	59.9
1980s	162.1	65.6	151.3	61.2

Source: Agricultural Statistics

During the last 3 decades, land in annual and long-term set-asides has fluctuated from 0 to 78 million acres. As of the 12th sign-up, there are approximately 36 million acres in the Conservation Reserve Program, a long-term cropland retirement program.

Over the past 50 years, the rate of development of technology has increased faster than the rate of increase in demand for food and fiber. Various projections have been made to estimate land requirements to produce food and fiber for domestic and export demands. If the above historical trend continues through 2030, an average of 190 million acres will be needed to supply projected levels of domestic consumption and exports. Projections on land requirements made for the second RCA Appraisal indicate that average land requirements may range from a low of 218 million acres to a high of 346 million acres. Actual land use may vary as much as 80 million acres above or below the averages due to uncertainties associated with weather and international demand.

In the near term (1990s), the Northern Plains, Corn Belt, Lake States, and Southern Plains are most likely to have land available for biomass production. During the early to mid-2000s, there is likely to be some shifting in land use due to higher water requirements as yields continue to increase. This will shift the relative advantage to the Corn Belt over the Great Plains. Of the land projected to be idled in 2030, up to 40 percent of the excess will come from the Northern Plains, 16 percent from the Southern Plains, and 9 percent from the Lake States.

Other Factors to Consider

A successful biomass program must be developed around the existing and expected structure of the farm sector. The current structure has evolved significantly over time. The structure of agriculture will continue to change as new technologies are developed and as society becomes more aware of the need to protect the Nation's soil, water, and related resources. Over the next 4 to 5 decades, agriculture has the potential to significantly reduce emissions of greenhouse gases and other air pollutants released into the atmosphere from combustion of fossil fuels.

The number of farms has decreased from 6.8 million in 1935 to 2.1 million in 1990. Land in farms has decreased from 1,161 million acres in 1950 to 964 million in 1987. As mentioned above, labor requirements have dropped from around 10 million worker-years in the 1930s to approximately 2 million worker-years in the 1980s. Of the 1.9 million farms that reported sales of agricultural products in the 1897 Agricultural Census, the top 5 percent of the producers accounted for 95 percent of the market value of products sold. For more information, see tables 9 through 11.

Projections on the distribution of farm land for the year 2000 indicate that there will still be a significant change in the structure of the farm sector. Tweeten, Heady, and Lin et al. have projected the following:

- over 1/2 of the farms will have 2,000 acres or more;
- the largest 50,000 farms will operate approximately 1/2 of the land;
- 50,000 farms will produce most of the farm output, next 200,000 will produce next largest share, and the rest will produce the smallest portion.

Table 9 Number of Farms for Selected Census Years, 1935-1990

Year	Million farms
1935	6.8
1945	5.9
1959	3.7
1969	2.7
1979	2.3
1987	2.1
1990	2.1

Source: Agricultural Statistics

Table 10 Distribution of the Value of Products Sold by Farms in 1987

Percent farms	Percent value of production
top 5	55
next 22	34
next 27	10
bottom 46	2

Source: 1987 Census of U.S. Agriculture

Table 11 Distribution of Farm Size, 1987

Farm size	Percent of farms	Percent of land
less than 179 acres	68.8	16.6
180 - 499 acres	20.8	21.3
500 - 1,999 acres	8.9	27.7
2,000 or more	1.5	34.3

Source: 1987 Census of U.S. Agriculture

Summary and Policy Implications

The promotion of biomass production will provide an economic use for current and projected surplus agricultural lands. This assumes that biomass can be produced at a rate of return comparable to alternative crops. If demand for biomass were sufficient, additional land could be converted from the total potential cropland base.

The development of electric power generation from biomass would have positive impacts on the rural sector. First, underutilized land resources could be put to productive use. This would increase on-farm income and employment. Second, because additional equipment would be required as the demand for biomass production increases, additional jobs will be created in the farm services sector. Third, the transformation of biomass into a higher valued product (electricity) in rural areas will also generate employment opportunities and increase income generation in rural areas.

Current policies that promote urban sprawl will limit the amount of land available for biomass production. Land in farms reached its zenith in 1950 at 1,161 million acres. Since 1950, land in farms has decreased 17 percent. As land for food, feedstuffs, livestock, and biomass production becomes limiting, prices of all products will tend to rise.

Policies to promote the development and adoption of agricultural technology at the historical rate could provide up to 150 million acres of the current cropland base for biomass production by 2030.

Policies to promote the production of biomass under long-term contracts and/or a futures market that would assure a market for specific quantities and qualities of biomass would tend to stabilize income and employment for biomass producers.

Policies to promote the production of biomass could include the utilization of commodity set-aside land and CRP land at a reduced payment schedule. This would permit producers to learn how to produce a new product at a lower risk and also reduce the cost of commodity supply control and income stabilization programs.

Policies to promote the production of biomass must consider the changing structure of the agricultural sector. Can producers with limited land resources improve their standard of living by producing biomass?

Policies to promote the production of biomass must be coordinated with policies to protect the Nation's soil, water, and related resources; policies to improve income and employment opportunities in rural areas; and policies to mitigate negative impacts of greenhouse gas emissions.

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PROJECTED WOOD ENERGY IMPACT ON U.S. FOREST WOOD RESOURCES

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Abstract

The USDA Forest Service has developed long-term projections of wood energy use as part of a 1993 assessment of demand for and supply of resources from forest and range lands in the United States. To assess the impact of wood energy demand on timber resources, a market equilibrium model based on linear programming was developed to project residential, industrial, commercial, and utility wood energy use from various wood energy sources: roundwood from various land sources, primary wood products mill residue, other wood residue, and black liquor.

Baseline projections are driven by projected price of fossil fuels compared to price of wood fuels and the projected increase in total energy use in various end uses. Wood energy use is projected to increase from 2.67 quad in 1986 to 3.5 quad in 2030 and 3.7 quad in 2040. This is less than the DOE National Energy Strategy projection of 5.5 quad in 2030. Wood energy from forest sources (roundwood) is projected to increase from 3.1 billion (10^9) ft^3 in 1986 to 4.4 billion ft^3 in 2030 and 4.8 billion ft^3 in 2040 (88, 124 and 136 million m^3, respectively). This rate of increase of roundwood use for fuel -- 0.8 percent per year -- is virtually the same as the projected increase rate for roundwood for pulpwood. Pulpwood roundwood is projected to increase from 4.2 billion ft^3 in 1986 to 6.0 billion ft^3 in 2030 and 6.4 billion ft^3 in 2040 (119, 170 and 183 million m^3, respectively).

Introduction

The Forest Service of the U.S. Department of Agriculture is directed under requirements of the Renewable Resources Planning Act (RPA) of 1978 to make periodic assessments of the current and long-range demand for and supply of renewable resources from forest and range lands in the United States. The Forest Service prepares major assessments each decade and is now completing a mid-decade update. The assessment update has been prepared in draft form (USDA Forest Service 1993). This paper discusses part of the assessment update. It focuses on a part of the timber situation--the analysis of demand for and supply of wood for energy. The results in this paper are an update of the projections prepared for the 1989 RPA Assessment (High and Skog 1990).

The model discussed in this paper, the National Wood Energy Model (NAWEM), projects how much of several types of wood energy will be used by 1) households, 2) pulp/paper/paperboard mills, 3) solid wood products mills, 4) other industries, 5) commercial buildings, and 6) electric utilities in response to projected changes in fossil fuel prices and wood energy supply.

Wood for energy can come from many sources. To assess timber demand, it is useful to sort wood energy supply sources because many sources are not used for sawlogs, veneer logs, or pulpwood. As a result, much wood energy supply (nongrowing stock) may not compete with lumber, panels, and paper for wood input. Wood energy supply sources used to prepare this report include:

Roundwood, in the form of
  Stickwood (primarily for residential use)
  Logging residue (wood that would be left on harvest sites if not used for fuel)
  Chips (made by whole tree harvesting and chipping)

Wood residue from primary wood products mills:
  (wood and bark from pulp and paper mills, sawmills, and panel mills)

Wood residue from secondary wood products mills
  construction waste, demolition waste, and discarded wood products (e.g. pallets)

Black pulping liquor from wood pulp mills

Roundwood, which by definition comes directly from timber, is further subdivided into categories traditionally used to assess timber supply: first, by hardwood and softwood species; second, by land source--timberland, other forest land, and nonforest land; and third, (on timberland only) by type of timber volume--growing stock and other. Timberland produces growing stock growth of 20 ft^3 per acre per year or more; other forest land produces less. The "other" category of timber volume includes tops, branches, cull sections, and saplings. For simplicity, we group roundwood into four categories:

Growing stock volume
  Hardwood
  Softwood
Other sources
  Hardwood
  Softwood

Methods Used to Project Wood Energy Use to 2040

Wood energy demand and supply have been projected through the year 2040 with the use of a computer model (NAWEM) that simulates economic markets, where supply of wood fuels from 15 sources is balanced against demand from six end users for three U.S. regions. The model is constructed using the Price Endogenous Linear Programming framework (PELPS) developed at the University of Wisconsin (Zhang, Buongiorno, and Ince, in preparation).

NAWEM determines the quantities and prices of wood fuels supplied, and quantities and prices of wood energy demanded in various end uses. The model interacts sequentially with other U.S. Forest Service models. It obtains input projections from, TAMM/ATLAS and NAPAP, and provides output projections for TAMM. Through several exchanges of projections, these models provide mutually consistent projections of supply and demand for timber, wood products, and wood energy for the U.S. forest sector. Figure 1 shows projections that are passed between models. TAMM and associated models project sawtimber, lumber and panel production, and end use (Adams and Haynes 1980); ATLAS projects timber growth, inventory and the distribution of timber removals. NAPAP projects pulpwood use; pulp, paper, and paperboard production; and paper and paperboard recycling (Ince, in press).

NAWEM is disaggregated into three independent regional models, North, South, and West. They are run simultaneously. Since transporting wood fuel for long distances is not economical, we assume there is no interregional trade in wood fuel supplies. The regions are shown in figure 2.

Structure of the Model

The model projects wood energy use by solving a series of annual linear programming problems, starting with the base year 1986. In each year, three sets of sector characteristics are specified : 1) a set of raw material (wood fuel) supply equations, 2) a set of technology conversion characteristics, and 3) a set of end-use demand equations. For each year, market equilibrium quantities and prices of wood energy commodities supplied and demanded are calculated by using linear programming to maximize consumer plus producer surplus (in terms of a graph of supply and demand curves, this is the area under demand curves above price plus area above supply curves below price). Between yearly estimates, projected values of exogenous variables are used to update supply equations, technology conversion factors, and demand equations.

Demand and supply equations are of the Cobb-Douglas form with the allowance for possible dynamic partial adjustment of demand or supply by including a lagged independent variable on the right-hand side of equations. This is to accommodate the possibility that demand and supply may be slow to respond to wood energy or fossil fuel price changes. That is, long-run price elasticity may be greater than short-run price elasticity.

Wood Energy Demand Equations

Demand equations are estimated for six end uses: Residential Households, the Pulp and Paper Industry, Other Forest Products Industry, Other Industry, Commercial Buildings, and Electric Utilities. Demand is measured in Btus (joules) of energy content in the wood fuel before conversion to heat, steam, or electrical energy.

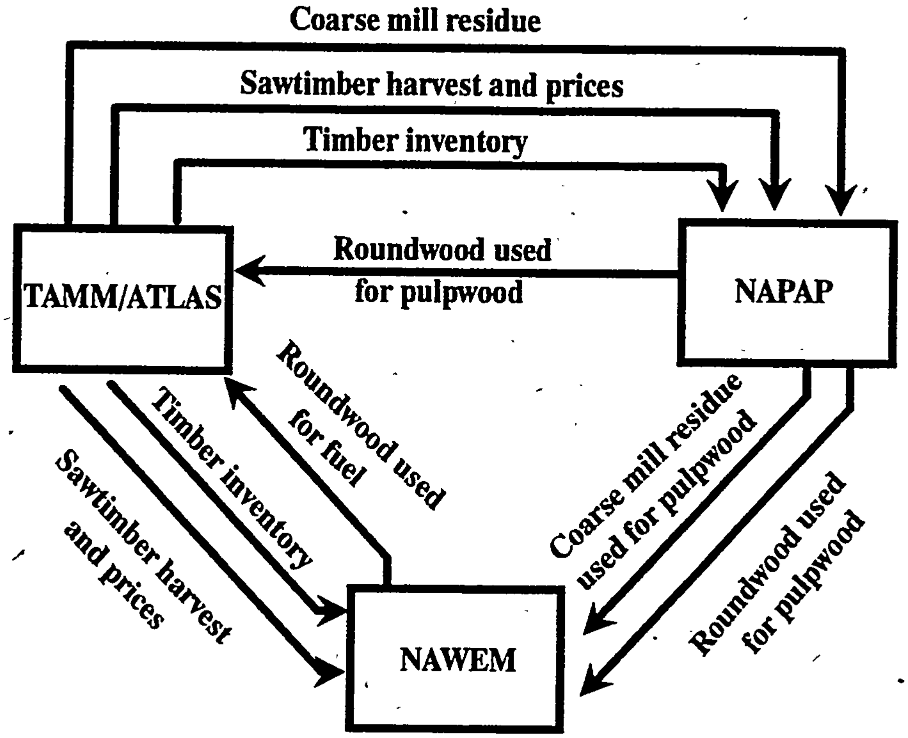

Figure 1.--Data passed between NAWEM, TAMM/ATLAS and NAPAP models

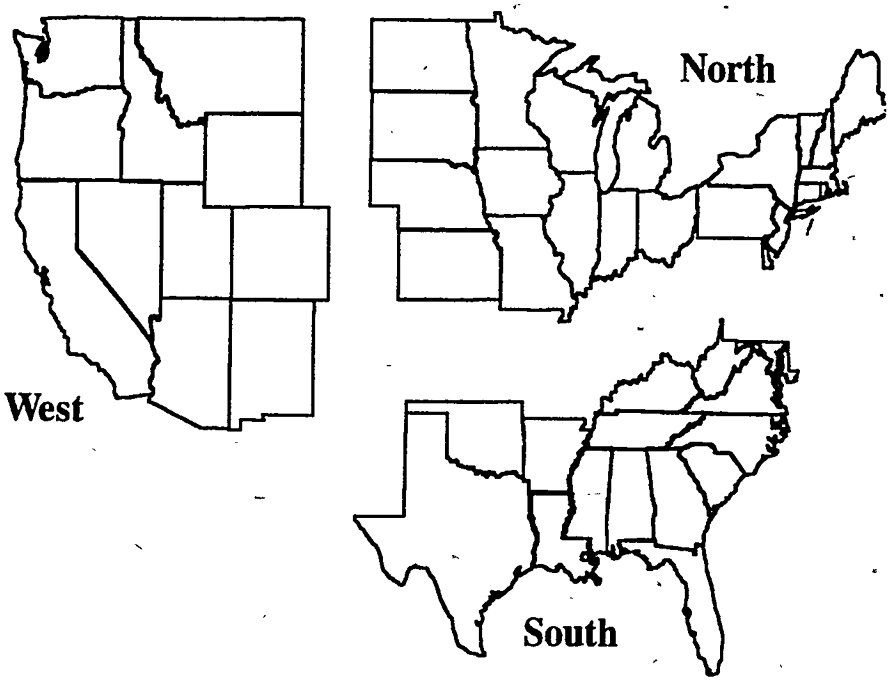

Figure 2.--National wood energy model regions

Demand equations for residential fuelwood use have elasticities estimated from a model using cross-sectional data on fuelwood use in 1980-81 (Skog 1989). The model shows how fuelwood demand per household responds to changes in prices of fuelwood and fossil fuels; household income; population density; heating degree days; and percentage of land in forests. For our long-run projections, we assume heating degree days will remain at the long-run average level and forest land area will remain at the current levels.

Results show that household demand response to fuel price change is slightly inelastic (less than 1) (table 1). Fuelwood use per household declines with increasing population density and increases with increasing income. Demand is adjusted for increasing efficiency of wood and fossil fuel burning between yearly estimates.

Wood energy use in the Pulp and Paper Industry is divided into two parts: use of black liquor, and use of wood and bark. Demand for black liquor for fuel is projected exogenously based on projections of paper and paperboard production from the NAPAP model. Demand for wood and bark for fuel is projected by NAWEM endogenously using estimated demand equations. The wood and bark demand shifters include wood fuel price, fossil fuel price, quantity of purchased fuel, and lagged wood and bark demand (Zhang 1992). Equation estimates indicate demand is determined primarily by previous period (lagged) demand and changes only slowly in response to changing prices and quantity of purchased fuel (table 2) . As for household demand, demand equations are adjusted for expected increasing efficiency of wood and fossil fuel burning.

Demand equations for Other Forest Products Industry and Other Industry were estimated with a single equation using data for all industry (other than Pulp and Paper). Demand shifters include wood fuel price, and fossil fuel price, the level of industrial production, and lagged wood energy demand. Equation estimates indicate demand is determined largely by previous period demand, but to a lesser extent than that for Pulp and Paper (table 2). Changes in prices and production level have a greater short run influence on demand for Other Industry than for the Pulp and Paper Industry. That is, the impact of a given change in prices occurs more quickly for Other Industry.

Separate equations are used in NAWEM for Other Industry. Although the elasticities are the same as for Other Forest Products Industry, different shift variables are used to indicate the trend in the level of industrial production. Roundwood use in the industry is used as a shift variable for Other Forest Products, and the U.S. index of industrial production is used for Other Industry. Demand equations are adjusted between yearly estimates for expected increasing efficiency of wood burning and fossil fuel burning.

Demand equations for Commercial Buildings use shifters including wood and fossil fuel prices, amount of commercial floor space and lagged wood energy demand. Equation estimates suggest demand is more responsive to prices than the Pulp and Paper Industry but less responsive than Other Industry (table 2).

Demand equations for Electric Utilities use shifters including wood and fossil fuel prices, amount of power produced and lagged wood energy demand. Equation estimates suggest demand by Electric Utilities is about as responsive to price changes as demand for Commercial Buildings (table 2)

Note that the demand elasticities in table 2 are short run elasticities. They indicate the change in demand over one year in response to a change in prices or the indicator of production.

Table 1.--Residential fuelwood demand equation elasticities

Own price	Fossil fuel price	Number of households	Household income	Population density
-0.87	0.87	1.00	0.30	-0.55

Source: Skog 1989.

Table 2.-- Wood energy demand equation elasticities

	Demand elasticity with respect to:				
End use	Own price	Fossil fuel price	Sector production indicator	Sector production indicator name	Lagged wood energy demand
North					
Pulp and paper	-.08	.08	.04	Purchased fuel	.96
Other Forest Products	-.39	.39	.19	Roundwood use	.81
Other Industry	-.39	.39	.19	Industry production	.81
Commercial Buildings	-.15	.15	.16	Floor space	.84
Electric Utilities	-.13	.13	.09	Power production	.91
South					
Pulp and paper	-.08	.08	.04	Purchased fuel	.96
Other Forest Products	-.39	.39	.19	Roundwood use	.81
Other Industry	-.39	.39	.19	Industry production	.81
Commercial Buildings	-.15	.15	.16	Floor space	.84
Electric Utilities	-.13	.13	.09	Power production	.91
West					
Pulp and paper	-.08	.08	.04	Purchased fuel	.96
Other Forest Products	-.39	.39	.19	Roundwood use	.81
Other Industry	-.39	.39	.19	Industry production	.81
Commercial Buildings	-.14	.14	.16	Floor space	.84
Electric Utilities	-.10	.10	.29	Power production	.71

Sources: Zhang 1992.

Long run elasticity (response over several years) is calculated as:

$$E_{LR} = (E_{SR} / ((1 - E_{LD}))$$

where E_{LR} and E_{SR} are short run and long run elasticities, respectively, and E_{LD} is the elasticity with respect to lagged wood energy demand.

For example, the long run wood price elasticity for Pulp and Paper wood energy demand (excluding black liquor) is 2.0 (= .08 / (1 - .96)). In the long run demand is highly responsive to prices of wood and fossil fuels. Long run elasticities are 1.4 to 2.1, except for Commercial Buildings and Electric Utilities in the West where elasticities are lower.

Technical Conversion Factors and Technology Improvement

Wood fuel supply quantities in cubic volume are converted to Btus of energy based on 8600 Btu/lb for both hardwood and softwood, and 30.4 lb/ft^3 for softwoods and 34.8 lb/ft^3 for hardwoods.

Projected technology improvements in the efficiency of converting wood to energy have an influence by shifting demand equations and thereby decreasing the amount of demand as efficiency increases. For residential fuelwood use, the improvement in efficiency is estimated to average about 0.9 percent per year; for Commercial Buildings, 0.7 percent per year; and for all industrial sectors, 0.6 percent per year.

Wood Fuel Supply Equations

Supply equations were prepared for 16 categories of wood fuel (tables 3 and 4). Preparation of these equations was more speculative than for wood fuel demand because data are very limited. Supply price is generally the price including delivery to a particular end user. Supply to alternate users may have extra transport costs added.

Sixteen supply sources were identified in an effort to distinguish among characteristics of various sources. The first six sources in table 3 are stickwood sources used only by Residential Households and are supplied by household harvesting or commercial vendor harvesting. Residential Households also use logging residue (in the form of stickwood) and coarse residue from primary wood products mills. Logging residue supply is wood taken for fuel in either combined harvesting operations when sawlogs, veneer logs, or pulpwood are removed, or subsequent to initial harvesting operations.

If black liquor is excluded, Pulp and Paper mills use the same wood fuel sources as Other Forest Products Industry mills: residue from primary wood products mills, logging residue, and other residue (which includes residue from secondary wood products mills).

Other industry, Commercial Buildings, and Electric Utilities are assumed to compete for the same sources as forest products plants but generally incur higher transportation costs. As the price of these residue sources increases we assume they will also use chips from whole tree harvesting. Unlike logging residue harvest, whole tree harvesting only takes wood for fuel. No other products are extracted.

Supply equations in table 3 are specified by several features:

--an elasticity with respect to delivered price,
--an elasticity with respect to the inventory or annual production of the wood source, and
--in some cases, an exogenously given upper limit of supply and reservation price from TAMM.

Table 3.--Wood fuel supply equation elasticities and/or use of an upper limit[a]

Supply equation	Demand elasticity with respect to: Own price	Inventory or production	Inventory or production variable	Upper limit and/or reservation price source
Softwood growing stock	.85	1.00	SW GS inventory	---
Hardwood growing stock	.85	1.00	HW GS inventory	---
Other softwood roundwood	.90	1.00	SW GS inventory	---
Other hardwood roundwood	.90	1.00	HW GS inventory	---
Other forest roundwood	.95	1.00	GS inventory	---
Non-forest roundwood	.95	---	---	---
Logging residue	.95	1.00	Annual logging residue production	TAMM
Softwood coarse residue	1.00	1.00	SWC Residue	TAMM
Hardwood coarse residue	1.00	1.00	HWC Residue	TAMM
Softwood fine residue	1.00	1.00	SWF Residue	TAMM
Hardwood fine residue	1.00	1.00	HWF Residue	TAMM
Softwood bark	1.00	1.00	SW Bark	TAMM
Hardwood bark	1.00	1.00	HW Bark	TAMM
Other wood residue	1.00	---	---	---

Table 4.--Whole tree chip supply equation variables, elasticities and/or use of upper limit or reservation price.

Supply equation/region	Demand elasticity with respect to: Own price	Growing stock inventory	Sawlog price	Bond discount rate	Lagged wood supply	Upper limit projection source
Softwood chips						
North	.903	.250	-.009	---	.75	---
South	.909	.300	.110	---	.70	---
West	---	---	---	---	---	TAMM
Hardwood chips						
North	1.674	.590	.550	.78	.41	---
South	3.618	.350	.550	4.12	.65	---
West	---	---	---	---	---	TAMM

Source: Ince, in press.

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[a] GS is growing stock volume. SWC, HWC, SWF, and HWF are softwood coarse, hardwood coarse, softwood fine, and hardwood fine residue, respectively.

The elasticities in table 3 with respect to delivered price are based on estimates of pulpwood supply equations for the Lake States (Adams 1975). These results suggest an elasticity of about 1. Price elasticities were set lower for growing stock than for nongrowing stock on the premise that owners would be less willing to sell growing stock for fuelwood because it may have an alternate market for pulpwood, or other higher valued products.

Whole tree chip supply equations were developed based on pulpwood roundwood supply equations used in the NAPAP model (Ince, in press). We assume that pulpwood roundwood and whole tree chips would be supplied from the same inventory pool of timber and would be harvested by the same type of harvesting operators. This timber inventory pool includes both growing stock (used for pulpwood) and nongrowing stock (not used much for pulpwood). The NAPAP pulpwood supply equations were adjusted to include the estimated amount of nongrowing stock associated with the growing stock supplied for pulpwood. These adjusted supply equations are included in NAWEM as a source of both pulpwood roundwood supply and whole tree chip supply (table 4). In NAWEM, pulpwood demand from NAPAP (plus associated but unharvested nongrowing stock) is deducted from the supply. NAWEM solves for additional amounts of growing stock and nongrowing stock taken from the supply equations for fuel.

Assumptions and Limitations

The demand equations were constructed using historical data on the assumption that end users would alter wood energy demand in response to changing prices, industry production, and other factors in a manner similar to recent history. No provision was made for government intervention in markets beyond environmental restrictions, which are reflected in the historical data.

We assume, in these base case projections, that economical fuelwood supplies will be restricted to the 16 categories used in the model and that conditions would not develop to allow extensive development of plantations of fast-growing trees for fuel.

Projections of the amount of roundwood that comes from growing stock are strongly influenced by the assumed proportion of whole tree chips that are from growing stock. We assume that as whole tree harvesting expands, harvest methods and composition of harvested stands will decrease the proportion of whole tree chips that come from growing stock over the projection period.

External Inputs

Supply and demand equations are shifted over time by changes in independent variables such as timber inventory or industrial production. These independent variables, with the exception of price, are projected exogenously. Demand equations are shifted by variables which include average fossil fuel prices in various sectors, the industrial production price index, commercial floor space, and electric power production. These projections are from the National Energy Strategy (DOE 1991). Residential demand equations are shifted by additional variables including U.S. population, household income, and population per household (USDA Forest Service 1988). Selected supply equations are shifted by pulpwood roundwood use, pulpwood residue use, and purchased energy in the Pulp and Paper industry from the NAPAP model (Ince, in press). Supply functions are also shifted by hardwood and softwood growing stock inventory, primary mill wood residue production, sawtimber price, and harvest of sawtimber and pulpwood (determinants of logging residue). Except for pulpwood roundwood, these latter projections are from the TAMM model.

Projections of Wood Energy Use 1986 to 2040

Demand for Wood Energy

Overall, NAWEM projects total wood energy use to increase 39 percent between 1986 and 2040: from 2.66 quad in 1986, to 3.40 quad in 2030, and 3.70 quad in 2040 (table 5, figure 3) (1 quad equals 1.055 x 10^{18} joules). In comparison, the National Energy Strategy base case projects higher total use of 5.5 quad by 2030 (DOE 1990). Both NAWEM and NES base case projections exclude use of biomass to make alcohol fuels. It appears the difference between the projections is due to the substantially different projection methods used. The NES projections of wood energy use given in two parts: electric power production (0.5 quad in 2030) and dispersed applications (5.0 quad in 2030). The dispersed applications projections are made using equations linking historical changes in aggregate wood energy use in three sectors (industrial, residential, commercial/utility) to historical changes in GNP, electricity prices, and world oil price. They do not account for projected changes in wood fuel price.

The NES projections for 2030 are probably to high because the projection equations were estimated on data over a period when price was low for residential fuelwood and mill residue was cheap and readily available for use by industry, commercial buildings, and utilities. Mill residue is now almost fully utilized for fuel or products and future increases in industrial/commercial/utility wood energy use must come from more expensive logging residue and whole tree chip sources. The NES projections are to high because they do not account for these projected changes in wood sources and the resultant extra increases in price of wood fuels.

NAWEM projects wood energy use will increase fastest for Other Industry (126 percent), Commercial Buildings (68 percent), and Electric Utilities (56 percent) over the projection period. But the proportion of total wood energy use in these sectors will still be low--7.6 percent in 2040. Residential use will increase 53 percent, Pulp and Paper 27 percent, and Pulp and Paper 2 percent. Pulp and Paper use will increase by 30 percent in the North and South, but will decline by 31 percent in the West due to constraints on timber harvest.

Wood energy use will increase the most over the projection period in the North, 54 percent, followed by the South, 38 percent, and the West, 15 percent. Two key reasons of the differences among regions are differences in projected average fossil fuel prices (each region has a different mix of fuels), and regional differences in the availability of various sources of wood supply.

Supply of Roundwood for Energy

The impact of wood energy use on forest wood resources is determined by the amount of wood fuel that comes in the form of roundwood from forests, either growing stock or nongrowing stock. Use of forest sources are lower to the extent that wood energy is produced from alternate sources, including wood mill residue, black pulping liquor, or waste wood products such as pallets. Although NAWEM projects roundwood and wood residue use for fuel, the following section focuses on roundwood use because of its important impact on forest wood use.

NAWEM projects roundwood use for energy to increase from 3.1 billion ft^3 in 1986 (26 percent from growing stock) to 4.4 billion ft^3 in 2030 and 4.8 billion ft^3 in 2040 (22 percent growing stock) (table 6,

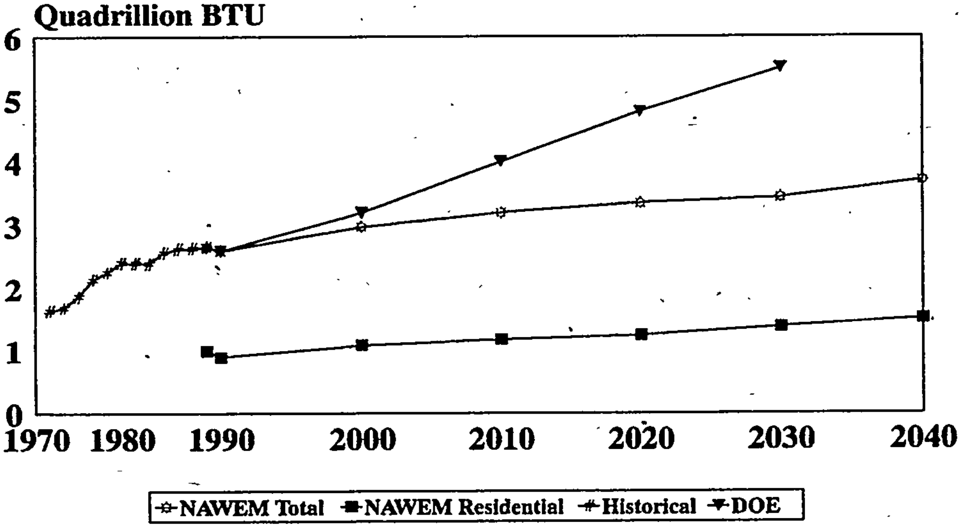

Figure 3.--U.S. Wood energy use, 1972-1986, with projections to 2040. Sources: Klass 1988, DOE 1991. (1 Btu = 1055 joules)

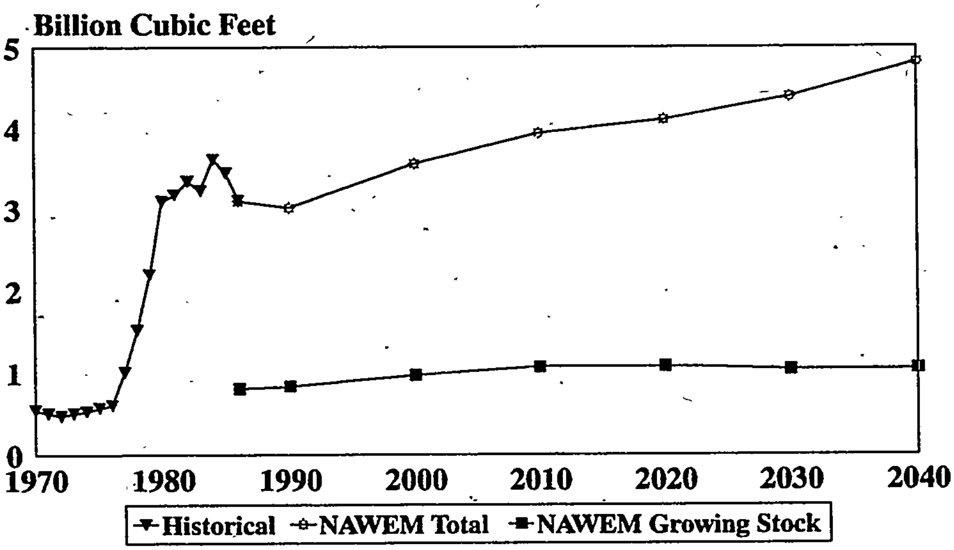

Figure 4.--U.S. Roundwood use for energy, 1970-1986, with projections to 2040. Source: USDA Forest Service 1990. (1 ft^3=0.028 m^3)

Table 5.--Wood energy demand in the U.S. in 1986, with projections to 2040

Region/ Year	Total	Residential	Pulp and Paper		Other Forest Products	Other Industry	Commercial	Utilities
			Black Liquor	Wood and Bark				
	Quadrillion Btu[a]							
North								
1986	0.849	0.570	0.100	0.070	0.045	0.048	0.011	0.004
1990	0.807	0.529	0.107	0.068	0.045	0.044	0.011	0.004
2000	0.977	0.665	0.124	0.066	0.048	0.057	0.013	0.005
2010	1.067	0.724	0.127	0.069	0.053	0.072	0.015	0.006
2020	1.126	0.770	0.131	0.070	0.055	0.078	0.016	0.006
2030	1.218	0.856	0.116	0.073	0.056	0.092	0.018	0.006
2040	1.309	0.933	0.106	0.076	0.058	0.110	0.020	0.006
South								
1986	1.288	0.242	0.650	0.261	0.094	0.035	0.006	0.000
1990	1.292	0.215	0.694	0.252	0.092	0.032	0.006	0.000
2000	1.494	0.261	0.825	0.253	0.107	0.041	0.007	0.000
2010	1.611	0.285	0.867	0.273	0.125	0.053	0.008	0.000
2020	1.680	0.301	0.901	0.277	0.136	0.057	0.008	0.000
2030	1.666	0.331	0.815	0.293	0.152	0.067	0.009	0.000
2040	1.782	0.357	0.859	0.357	0.123	0.076	0.010	0.000
West								
1986	0.526	0.175	0.146	0.060	0.116	0.019	0.005	0.005
1990	0.500	0.150	0.161	0.060	0.102	0.018	0.004	0.005
2000	0.508	0.158	0.196	0.061	0.060	0.021	0.005	0.007
2010	0.525	0.166	0.200	0.064	0.055	0.027	0.006	0.008
2020	0.544	0.175	0.206	0.065	0.055	0.029	0.006	0.008
2030	0.558	0.197	0.184	0.067	0.061	0.033	0.006	0.008
2040	0.604	0.222	0.170	0.072	0.080	0.045	0.007	0.008
United States								
1986	2.663	0.987	0.897	0.391	0.255	0.102	0.022	0.009
1990	2.600	0.894	0.963	0.380	0.239	0.094	0.022	0.009
2000	2.979	1.084	1.144	0.381	0.215	0.119	0.025	0.011
2010	3.203	1.174	1.195	0.406	0.233	0.152	0.029	0.013
2020	3.350	1.245	1.239	0.412	0.247	0.164	0.030	0.014
2030	3.441	1.384	1.115	0.433	0.270	0.193	0.033	0.014
2040	3.695	1.512	1.135	0.505	0.261	0.231	0.037	0.014

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[a] 1 Btu = 1005 Joules.

Table 6. -- Roundwood used for fuel in the U.S.in 1986 with projections to 2040 (excludes logging residue use)[a]

	Roundwood			Growing Stock		
Year	Total	HW	SW	Total	HW	SW
				Million cubic feet[b]		
North						
1986	1825	1705	121	241	223	18
1990	1748	1636	112	264	247	18
2000	2189	1952	236	326	268	58
2010	2441	2095	346	363	276	87
2020	2530	2209	322	371	295	76
2030	2674	2404	271	356	299	57
2040	2898	2668	230	377	332	45
South						
1986	739	682	57	329	286	43
1990	758	702	57	344	301	43
2000	800	743	57	365	323	42
2010	864	747	116	399	325	74
2020	875	773	102	384	319	65
2030	914	849	65	361	311	49
2040	998	926	73	354	299	55
West						
1986	531	192	340	228	86	142
1990	513	183	330	227	84	143
2000	575	200	375	272	95	177
2010	644	230	414	297	107	190
2020	708	254	455	315	113	203
2030	799	295	504	312	114	198
2040	914	302	612	314	119	195
United States						
1986	3096	2578	518	798	595	202
1990	3019	2521	498	835	632	203
2000	3563	2895	667	963	686	277
2010	3949	3072	877	1058	708	350
2020	4114	3235	878	1070	727	343
2030	4388	3548	840	1029	724	304
2040	4810	3896	914	1045	750	295

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[a] HW is hardwood and SW is softwood.

[b] 1 $ft^3 = 0.0283\ m^3$

figure 4) (88, 136 and 124 million m^3, respectively). The increase is 55 percent over the projection period. NAWEM projections are consistent with the 1989 Forest Service fuelwood projections of 5.1 billion ft^3 by 2040 (High and Skog 1990). Our current projections are lower primarily because projected fossil fuel prices are now lower. In 1989 DOE projected world oil prices to increase to $61 (1990$/barrel) by 2030. Currently the National Energy Strategy projects world oil price to increase to $49 (1990$/barrel) by 2030. The rate of increase of roundwood use for fuel, 0.8 percent per year, is virtually the same as that the projected rate of increase of roundwood use for pulpwood. Pulpwood roundwood is projected to increase from 4.2 billion ft^3 in 1986 to 6.0 billion ft^3 in 2030 and 6.4 billion ft^3 in 2040 (119, 170 and 183 million m^3, respectively) (Ince, in press). This rate of increase in greater than for total roundwood harvest which is projected to increase from about 18 billion ft^3 and 25 billion ft^3 between 1990 and 2040, or 0.68 percent per year.

The proportion of roundwood used for fuel that is from growing stock is a critical factor in determining the impact of wood energy use on forest wood sources. Most timber products (sawlogs, veneer logs, and pulpwood) come predominantly from growing stock - 70 percent or more. But only 26 percent of fuelwood comes from growing stock. If this proportion from growing stock declines to 22 percent as projected by NAWEM then the wood energy drain from growing stock will increase about 31 percent through 2040, much less than 55 percent increase for all wood energy from roundwood, and less than the 40 percent increase for all roundwood harvested.

Conclusions

Wood energy use is projected to increase 39 percent, which is modest in comparison to the large increases in the 1970's and early 1980's. This is based on projected increases in fossil fuel prices from the National Energy Strategy, the aggregate increases in residential and industrial energy consumption, and the supply response, including price increases, from wood energy sources.

Roundwood use for fuelwood is projected to increase about 55 percent over the projection period, which is faster than for the projected use of wood residue and black liquor sources.

Roundwood use for fuelwood is projected to remain a significant factor in forest management and harvesting at about 75 percent the volume of roundwood used for pulpwood. But, unlike pulpwood roundwood, fuelwood roundwood is projected to use only 22 percent from growing stock volume by 2040. Pulpwood roundwood is 74 percent from growing stock. Therefore, fuelwood use has a much lower impact on drain of growing stock than pulpwood.

These projections would be altered by changes in key assumptions; a change in the trend in fossil fuel prices; major advances in technology which reduces the cost to convert wood to energy; an increase in the proportion of fuelwood roundwood from growing stock; advances in reducing the cost of producing short rotation woody crops; and changes in government regulations or incentives such as those that would restrict harvesting to maintain ecosystem features or that would promote tree planting to sequester atmospheric carbon.

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SOME ECOLOGICAL GUIDELINES FOR LARGE-SCALE BIOMASS PLANTATIONS

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Abstract

The National Audubon Society sees biomass as an appropriate and necessary source of energy to help replace fossil fuels in the near future, but is concerned that large-scale biomass plantations could displace significant natural vegetation and wildlife habitat, and reduce national and global biodiversity. We support the development of an industry large enough to provide significant portions of our energy budget, but we see a critical need to ensure that plantations are designed and sited in ways that minimize ecological disruption, or even provide environmental benefits. We have been studying the habitat value of intensively managed short-rotation tree plantations. Our results show that these plantations support large populations of some birds, but not all of the species using the surrounding landscape, and indicate that their value as habitat can be increased greatly by including small areas of mature trees within them. We believe short-rotation plantations can benefit regional biodiversity if they can be deployed as buffers for natural forests, or as corridors connecting forest tracts. To realize these benefits, and to avoid habitat degradation, regional biomass plantation complexes (e.g. the plantations supplying all the fuel for a powerplant) need to be planned, sited, and developed as large-scale units in the context of the regional landscape mosaic.

Introduction

As the world seeks alternatives to fossil fuels to slow global warming, attention has naturally focused on a variety of solar energy sources, including biofuels. Since the carbon accumulated in the biomass of growing plants through photosynthesis is almost entirely derived from atmospheric CO_2, the combustion of that biomass does not, if the resource is used sustainably, cause a net input of CO_2 to the atmosphere. Advances in the extraction of this energy make the deliberate farming of biomass crops a realistic addition to our energy budget in the near future.

Clearly, any technology that will produce energy without adding to the planet's atmospheric carbon budget should be examined carefully. Yet, without proper management, large-scale dependence on biofuels would bring its own major environmental problems. Of special concern to ecologists is the prospect that increasingly intensive land usage to grow biomass for energy will further reduce natural biodiversity (Cook et al. 1991). Moreover, by making bioenergy more competitive with other alternatives to fossil fuels, the application of biotechnology and other new technologies may increase its ecological impacts.

If bioenergy becomes a major contributor to our national (or global) energy budget, the land needed for production of the biomass involved will be very substantial (Beyea et al. 1991). It is therefore critical to understand the impacts that biomass plantations have on wildlife habitat values in the affected landscapes. We see the possibility of immense tracts of land being converted to short-rotation monocultures of rapidly growing plants. These may replace croplands, pasturelands, prairies, forests and degraded lands.

Biomass plantations are likely to provide habitat that is more suitable for a wider range of species than the habitat provided by typical row crops. Likewise, they are likely to provide better habitat than do degraded lands that are poorly vegetated or dominated by weedy vegetation. Conversely, it is unlikely that biomass plantations will represent habitat improvements compared to forests or prairies, although their relative value will depend on their design and management.

Biomass plantations are typically envisioned as monocultures that will be intensively managed for maximal production with little or no concern for their value as wildlife habitat, i.e., like agricultural row crops. As monocultures, such plantations will have greatly reduced plant species diversity, and will probably provide good habitat for only a fraction of the fauna that would occupy the site with its natural vegetative cover. Among vertebrates, widespread generalist species that are least at risk are most likely to prosper in monocultural biomass plantations. Conversely, with some exceptions, those species that are habitat specialists or have restricted ranges are unlikely to prosper in such plantations.

It may be possible to design and manage plantations to provide higher quality wildlife habitat without unacceptable losses in biomass productivity. Determinants of agricultural and forestry practices that maintain natural biodiversity and are sustainable on a long-term basis are emerging in such disciplines as sustainable agriculture, agroforestry, new forestry and landscape ecology (Harris 1984, Gliessman 1990, Probst and Crow 1991). It appears that long-term sustainability entails the management of complex natural ecosystems and successional sequences, or the use of crop management systems modeled on such natural processes.

We support the development of a biofuels industry, provided that the industry is developed in an environmentally sensitive manner. Biomass plantations should be integrated into landscapes in ways that enhance rather than degrade the regional (gamma) biodiversity. This paper discusses ways to enhance natural regional biodiversity while developing biomass plantations. We propose here some guidelines for designing and siting biomass plantations in ways that enhance regional biodiversity.

We believe that restoring the natural biodiversity in agricultural landscapes will require a more regional approach to land-use decisions. In choosing the appropriate crop in a given field, for example, consideration should be given not only to the soil and moisture conditions of the field and the market conditions, but also to the field's surroundings. For example, a woody biomass crop might be the most appropriate crop from a biodiversity perspective to plant in a field occupying a gap in an expanse of more natural forest, or in a field separating two tracts of forest. Field sizes and surrounding habitats greatly affect habitat value of agricultural landscapes (Best et al. 1990), and can be altered to enhance biodiversity.

Ecological Guidelines

Suitable Lands

From a biodiversity perspective the most suitable lands for biomass plantations are currently or recently cultivated farmland. Such land generally supports only minor components of the historic natural flora, and the more adaptable fauna. We do not favor converting existing forest lands to short-rotation biomass crops, as that is likely to displace portions of the forest biota. We also oppose breaking natural prairie or other native grasslands to plant biomass crops.

Conservation Reserve Program (CRP) lands are often suggested as appropriate sites for biomass crops. These are areas of farms that are particularly susceptible to erosion, and that are enrolled in a government program that pays the landowner to remove them from cultivation and keep them vegetated, often with perennial grasses. Perennial biomass crops require less soil disturbance than cultivation of annual crops, and so may be suited to these lands. Use of these lands for biomass crops presumably would terminate the subsidy program, and return them to economic productivity.

Many bottomland areas, particularly in eastern North America, have rich soil but often crops are lost because the fields are too muddy to negotiate at planting or harvest time. These areas may be well suited to woody perennial biomass crops, where harvest can be delayed without loss of a crop. These areas typically were wetlands before conversion to agriculture, at least by liberal wetland definitions, and many of them abut surviving wetlands. Proposals for biomass plantings on these lands should be assessed carefully to ensure that they do not degrade the adjacent wetlands. In particular, soil conditions and hydrology need to be studied to determine whether the water needs of the biomass crop would affect the water table in adjacent wetlands. In some cases restoration to wetland status will be the most appropriate use for these lands.

Native tallgrass prairie has become a rare habitat in North America. Clearly prairie remnants are not appropriate land for planting biomass crops. On the other hand, plantations of switchgrass (*Panicum virgatum*), a native prairie grass, may provide some of the habitat value of prairie, and thus benefit prairie wildlife.

Target Species

If the goal is to enhance natural regional biodiversity while establishing biomass plantations, the most effective strategy will be to concentrate on preserving or restoring habitat for the habitat specialist species, including those that need large expanses of relatively uniform habitat (obligate prairie species, for example). The species that occupy edge habitats, and are comfortable in mosaics of disparate patch types, will be able to survive and reproduce in a variety of landscapes. It is counter-productive, from a regional biodiversity perspective, to manage landscapes for maximum numbers of deer, rabbits, quail, or other such habitat generalists. Instead, concentration on providing habitat for prairie specialists, forest-interior species, wetland biota, wide-ranging carnivores, and so on will contribute the most to the regional biodiversity. The others generally are capable of taking care of themselves, at least insofar as population persistence is concerned.

Ecological Scale

It is becoming increasingly obvious that the quality of landscapes as habitat for wildlife depends on the scale of patchiness in them (e.g. Wiens et al. 1987). Animals that are patch specialists may need patches of their preferred habitat of a particular minimum size, or a particular minimum density of patches within the landscape.

The responses of wildlife to habitat patchiness involve not only patch sizes, but also the nature of the differences among patches. From the animals' perspective these differences define patch quality. A forest interior animal might prefer oak-dominated patches over beech groves, for example, because the former produces more or better food, or better nest sites, but may be willing to travel through the beech, and use it when necessary. A patch of cleared land, on the other hand, might be perceived as totally unsuitable, and perhaps dangerous habitat, to be avoided at all costs. Most animals will respond very differently to a mosaic of patches of different forest types than to a mosaic of forested and open patches.

The scale of the landscape mosaic in North America has generally been set by political, economic, and labor considerations, rather than by biological ones, and the scales chosen were not necessarily optimal for maintaining natural biodiversity. The primary tools for land development and management in most of the United States west of the original 13 colonies were the Homestead Acts. Similar land-granting acts were employed in Canada. These policies resulted in the conversion of much of the low elevation upland forests in temperate eastern North America into a mosaic of pastures, cultivated fields, and remnant woodlots. Large tracts of forest persisted mainly at higher elevations in the Appalachians and in areas of low-fertility soil and poorly drained soil in the southeastern United States and around the Great Lakes. Much of the Canadian boreal forest survived because it occupies areas where growing season are too short for much agriculture, and where soil conditions are generally poor for cultivated annuals.

In the United States, the Homestead Acts generally gave land to settlers in 80-acre units, with the requirement that a certain percentage of each farm be cleared and farmed for five years. This provision determined the scale of landscape patchiness over great areas of the east: woodlots were generally 40 acres or less, and at least half of the landscape was cleared for pasture or cultivation, except where the soil was unsuitable for farming. In the Western United States, much of the more fertile mesic areas were cleared and farmed at the same scale. Substantial areas of land were ceded to industrial interests to foster development (primarily railroad land grants). These grants were generally in units of square miles (640 acres) or more.

In the future, before major changes in land-use patterns are made, such as large-scale conversion to short-rotation biomass plantations, we suggest that the consequences for biodiversity of the various possible scales of implementation be explicitly investigated. We suggest further that such explorations can (and in the case of biomass plantations, will) lead to discovery of actual environmental benefits at some scales, rather than just ways to minimize degradation. As a first approximation, we would expect the natural biodiversity to be most secure in landscapes with patch sizes (or aggregates of structurally similar patches) of the same magnitude as the pre-agricultural landscapes. More realistically, research can be directed toward determining the scales of patchiness needed by various wildlife.

In predominantly forested landscapes, filling forest gaps with woody biomass plantations should increase the effective size of the forest tracts, and thus make the landscape more suitable to forest-interior wildlife. Plantations arranged as broad bands around forest tracts may increase effective patch size for forest-interior birds. Similarly, extensive plantings of herbaceous biomass crops may provide habitat for prairie specialist species (e.g. Greater Prairie Chickens, *Tympanuchus cupido*) that do not do well in farmland mosaics. Switchgrass is probably the most benign possible crop to plant adjacent to remnant natural prairies.

One relatively easy habitat enhancement strategy would be to use woody biomass plantations to provide habitat corridors connecting forest fragments. Recently (Simberloff et al. 1992) the value of corridors has been questioned, but we do not find these arguments convincing. Instead, we see the claimed lack of rigorous experimental evidence for the value of corridors more as a reflection on the status of landscape-level ecological studies than on the value of the corridors themselves. Further, while Simberloff et al. questioned corridors largely from the point of view of cost-effectiveness in nature-reserve systems, biomass plantations sited as corridors should be economically viable in their own right.

Boundary Conditions

The nature of plantation boundaries will have major implications for their value as wildlife habitat. Where woody plantations abut more natural forests, we recommend planting right to the edge of the forest, without any unvegetated buffer or gap. We think that as the plantation matures forest interior wildlife will treat the forest/plantation edge as if it were a boundary between patches of forest of different types, rather than as a forest edge. Whether or not they use the plantation, they should use the forest right up to the boundary, rather than avoiding an edge zone. Our studies in the Domtar fiber plantations in Ontario (Hoffman, Cook, and Beyea unpub. manuscript) indicate that some forest-interior birds (Ruffed Grouse, Ovenbird) ranged into a plantation embedded in a second-growth forest, and others (Veery, Red-eyed Vireo, Chestnut-sided Warbler) used the forest and plantation edges, but were not detected in the plantation interior.

Choice of Biomass Crops

We strongly recommend using as biomass crops species, cultivars, or hybrids that have genetically close relatives in the region. Thus, poplars, cottonwoods, and their hybrids in temperate to boreal North America share landscapes with several native *Populus* species, and plantations may provide habitat to the wildlife that uses stands of the natives. Perennial switchgrass is a dominant component of native tallgrass prairies. Several trees under consideration in the southeastern United States (black locust, sycamore, sweet gum) are natives. Most emphatically, we recommend that genetically alien species not be used. *Eucalyptus* and *Casuarina* should not be used for biomass plantations outside of Australia. A study of bird use of *Eucalyptus* and *Casuarina* plantations in central California (Kelly et al. 1990) found little use by forest birds, although the plantations were used as nesting sites by ground-feeding birds (House Finch, *Carpodacus mexicanus*; Mourning Dove, *Zenaida macroura*; Brewer's Blackbird, *Euphagus cyanocephalus*) that presumably fed in the surrounding fields. Poplars should not be used in Australia. Switchgrass and other native grasses should be used in North America in preference to African, Asian, or Australian grasses.

The use of crops with close relatives present locally also may have economic advantages. The dominant components of any natural flora have a history of co-evolution with their pollinators, their herbivores, and their herbivores' predators, and with soil micro-organisms. As successful dominants they will have evolved relationships with these organisms that keep herbivory at manageable levels. Alien plants brought in for cultivation are likely to be distasteful to the native "background" populations of herbivorous insects that provide the basis for many terrestrial food webs, so plantations of these aliens are unlikely to provide much food for spiders and insectivorous birds and mammals, and are likely to have slower leaf decomposition rates than native species. At first glance, the aliens' lower losses to herbivores might seem beneficial from a production perspective, but such crops are very susceptible to outbreaks of diseases and herbivorous insects imported from their native habitats. Pests that cause minor losses in the native habitat can be devastating in a foreign plantation situation, where their predators are absent. The history of agriculture is full of instances of devastating imported crop pests, that must have been no more than annoyances to the crops' ancestors. In the long run it will be healthier to develop crops from locally native groups, and to tolerate a moderate background loss to herbivory, than to risk catastrophic losses to imported pests.

Some of the hybrid poplar plantations we studied in Ontario are bounded by overgrown fencerows containing mature trees. We regard these as contrasting habitat inclusions, and discuss them below.

Exclusion of Noxious Organisms

In agricultural landscapes we commonly see organisms, plants and animals, that we regard as pests. These tend to be species, introduced or native, that are pre-adapted to take advantage of the habitat conditions created by agricultural disturbance and food crops. Switching from annual food crops to perennial biomass crops should reduce populations of some weedy plants, by reducing the extent and frequency of soil disturbance through cultivation. Conversion from livestock and food-crop agriculture to biomass crops should reduce populations of some of the animal pests by removing their attractants, such as waste grain and spilled feed.

The Brown-headed Cowbird (*Molothrus ater*) is a special case that deserves further discussion. Cowbirds are brood parasites, and lay their eggs in the nests of other birds. The nestling cowbirds are aggressive competitors of the other nestlings and the host parents generally end up raising the cowbirds rather than their own offspring.

We see opportunities to use the development of short-rotation tree plantations for biomass energy projects as a tool for managing landscapes to reduce the effects of cowbirds on breeding songbirds. Several aspects of cowbird biology are relevant to this conclusion. Brown-headed Cowbirds apparently evolved from neotropical ancestors, and invaded temperate North America by exploiting a relationship with bison (Bison bison). Cowbirds followed the great herds of bison on the American prairies and plains, and fed on insects flushed by the animals, and on insects attracted to the dung of the bison.

Since the disappearance of the great bison herds, cowbirds have switched to feeding in agricultural situations, particularly around cattle. Historically, they apparently were limited to open prairie habitats, where they used grassland and marsh birds as their primary hosts. These hosts evolved defense mechanisms that keep parasitism rates at tolerable levels. With the fragmentation of the eastern (and western) forests and the development of the dairy industry and other agricultural practices cowbirds have expanded their range in several directions, and have been using many new host species. This range expansion appears to be continuing, and cowbird populations have been increasing throughout much of their new range.

In these areas, cowbird courtship and feeding continue to be mostly limited to developed and open habitats — pastures, lawns, mowed roadsides, plowed fields, barnyards and so on. Females, however, fly considerable distances, even into forests, in search of nests to parasitize. In the fragmented landscapes of eastern North America, the forest songbirds provide new and naive hosts that have not evolved the defense mechanisms that allow the prairie birds to survive cowbird parasitism.

If woody biomass plantations were established in the currently open areas of a forest/farmland mosaic, they should displace much of the foraging and courtship habitat for cowbirds, thus locally reducing their populations. Broad buffers of woody biomass plantations surrounding forest fragments might reduce the frequency with which the females penetrate into the forest in search of nests.

Depredation of songbird nests in temperate North America tends to be more severe in small forest fragments than in larger forest blocks (Wilcove 1985). The primary predators (omnivorous mammals such as raccoons, opossums, skunks, and squirrels; jays and crows; and snakes) use forest-edge habitats extensively, and tend to be very successful in fragmented forest landscapes. Woody biomass plantations connecting and surrounding forest fragments might reduce the attractiveness of the landscape to these predators.

Contrasting Habitat Inclusions

Within forests, small areas of contrasting forest type can add greatly to wildlife use and diversity. Patches of cedars in deciduous forest can be very important as winter roost and den sites for a variety of wildlife. Brushy stream-courses can also greatly increase overall species diversity. Inclusions of mature trees left within short-rotation woody plantations can add greatly to habitat value. The hybrid poplar plantations we studied in Ontario occupied complexes of formerly cultivated fields, separated by fencerows with heavy brush cover and some mature trees. These fencerows were left in place within and along some edges of the plantations. The mature trees provided suitable sites for woodpecker holes, and thus allowed a variety of hole-nesting birds (various woodpeckers, Black-capped Chickadee, *Parus atricapillus*; Great-crested Flycatcher, *Myiarchus crinitus*, possibly Eastern Bluebird, *Sialia sialis*) to occupy the plantations. Song sparrows (*Melospiza melodia*) were abundant throughout the younger plantations, but tended to concentrate their activity in and near the fencerows in the more mature plantations. If the fencerows had been removed we think Song Sparrows would have been much less common in the older plantations.

Weed Control

In woody plantations weed control is generally necessary, at least in the early stages of growth, to reduce competition for light, water, and/or nutrients. Without weed control, plantation productivity is generally reduced. In later stages, the trees are generally able to outcompete the weeds by shading them, so less weed control is necessary. Unfortunately, this weed control reduces the value of the plantations as wildlife habitat. In the Ontario plantations, the annual weeds that persisted seemed to contribute greatly to the value of the plantations as habitat for songbirds. We suspect that a majority of the insect food, and any seeds consumed by the birds were produced on the weeds rather than on the poplars.

Cultivation for weed control avoids possible toxicity problems associated with chemical weed control, but may be inappropriate on lands susceptible to erosion. Cultivation may also be very disruptive to small mammal populations. We recommend coppicing or pollarding woody biomass crops whenever possible, because we think that the need for weed control will be reduced. Coppice generations will have far larger root systems than newly established trees, and with their multiple trunks should be able to compete more successfully for light with the weeds. Pollarded woody crops will overtop most weeds immediately and have even less need for weed control.

We suspect that weed control will be far less of an issue with herbaceous perennial biomass crops such as switchgrass. Switchgrass is a prairie species, adapted to growing in dense stands, with a variety of other herbaceous perennials, and it appears to be a superior competitor. In any case "contamination" of the biomass with other species should be inconsequential, as the other biomass should burn or ferment as well as the switchgrass.

Monoculture versus Polyculture

To date, most of the biomass crop development programs have concentrated on developing single crops to be planted as monocultures. Monocultures are much simpler to work with experimentally. Differences in productivity are easier to measure and understand, and causes of failure are more readily apparent. On the other hand, monocultures are likely to be less attractive as wildlife habitat than mixtures of different species. We see the development of monocultural biomass crops as a necessary step in the evolution of the industry, but we believe that in the long run they should be replaced by polycultures. We think that research efforts to develop competitive polycultures should be undertaken as the industry develops. It is worth noting that biomass crops need not aspire to the standards of uniformity we expect of food crops, although some technical problems with burning mixtures of different tree species may need to be overcome.

One experiment in Hawaii involved planting alternating rows of *Eucalyptus* and the legume *Albizzia*: higher yields were obtained than in monocultures of either species ( ). We do not advocate using these alien species together, but mixtures of appropriate native-derived crops may increase yields as well as improve the habitat value of the plantations. On a finer genetic scale, the differences in branching structure of different hybrid poplar clones affected their use as nest sites by birds in E.A. Hansens's clonal trials (E.A. Hansen pers. comm. and WH pers obsn.), so mixing clones in single-crop plantations may enhance biodiversity.

With perennial herbaceous crops the potential of polyculture may be even greater. The current favorite herbaceous biomass candidate in temperate North America is switchgrass. This is a native prairie grass, adapted to growing and prospering in multispecies prairie communities. We suspect that multispecies plantations of prairie plants will produce yields comparable to those of switchgrass monocultures, and we propose that direct trials be conducted to test this question. Perhaps, restored species-rich prairie will be as suitable for biomass production as switchgrass monocultures. Proponents of switchgrass as a biomass crop plan a single annual harvest to follow the growing season (i.e. between late August and October). This late harvest should be much less disruptive to wildlife than traditional haying activities in monoculture or in prairie polyculture, as it follows the end of the breeding season for most birds and many mammals. It also follows seed maturation for many prairie plants, so it should not greatly affect prairie species composition. Again, some technical problems with optimizing yield from mixed biomass (particularly for ethanol production) may need to be overcome.

Conclusions

Biomass energy croplands are likely to provide better habitat for the native biota than annual rowcrop agriculture, but lower-quality habitat than natural systems. Considerable opportunity exists for substantially restoring the natural biodiversity of agricultural landscapes by replacing annual rowcrops with perennial biomass crops. However, we believe the actual habitat value of a landscape containing biomass plantations will be very sensitive to the details of location, culture, and crop selection in the plantations. The ecological guidelines we have proposed should serve to direct research into the most ecologically sensitive ways to integrate biomass plantations into landscapes. Because many of the consequences for biodiversity are highly scale-dependent, adequate tests of our proposals may not be possible until industrial-size plantations are actually established. We strongly urge that the first industrial-scale woody plantations be explicitly set up to test our recommendations about use of plantations as corridors and buffers, and for exclusion of noxious organisms. We also urge that explicit tests be conducted of the yield and economics of switchgrass monocultures versus prairie polyculture systems. We urge that research efforts worldwide on biomass crop development concentrate on identifying and culturing promising local plants, rather than on adapting alien species.

Finally, we stress that much of the loss of regional biodiversity that has occurred in North America and elsewhere can be attributed to the scale of land-use decision-making. Typically decisions about crop selection and cultivation are made on a field-by-field or parcel-by-parcel basis. Successful restoration of regional biodiversity will require such decision-making on a landscape scale, with biodiversity as an explicit goal. Decisions about the best use of each parcel should consider not only its potential for yield, but also its relationship to the whole landscape.

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ENERGY FROM WOOD BIOMASS: THE EXPERIENCE OF THE BRAZILIAN FOREST SECTOR

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Abstract

Wood biomass is one of the most significant renewable sources of energy in Brazil. Fuelwood and charcoal play a very important role not only for household energy consumption but also for the cement, iron and steel industries. Wood is used as an energy source by the pulp and paper, composite board and other industries of the country, mainly for steam and electricity generation. Ethanol, lignin-based coke and methanol from wood were produced at experimental units in Brazil but were not implemented on a commercial scale. Currently a new experimental plant using a technology developed in the United States is being built in the state of Bahia to generate electricity from **Eucalyptus**. This technology is a Biomass Integrated Gasification/Gas Turbine process which is expected to make the use of wood biomass economically feasible for electricity generation. Forest plantations are the main source of wood biomass for energy consumption by the Brazilian industrial sector. Fiscal incentives in the 1960's helped the country to begin a massive reforestation program mainly using **Eucalyptus** and **Pinus** species. A native species, bracatinga (Mimosa scabrella) has also been used extensively for wood energy plantations in southern Brazil. Technical, economic, social and environmental impacts of these plantation forests are discussed along with a forecast of the future of wood energy utilization in Brazil.

Introduction

Wood as an energy source (fuelwood and charcoal) in the Brazilian economy decreased from 43% in 1970 to 15% in 1990. This was caused by the substitution of subsidized liquid petroleum gas for domestic fuelwood as the population moved from rural areas to urban centers. In terms of tons of oil equivalent (**toe**) this change corresponded to a consumption of 32 million **toe** in 1970 compared to 27 million **toe** in 1990. Although wood's use decreased dramatically percentage-wise, the shift from domestic to non-domestic utilization increased energy efficiency and kept the oil equivalent values nearly the same.

The oil embargo of the 70's forced Brazil to look for alternative sources of renewable energy. To meet this need a large scale biomass program using sugar cane and wood received special attention in terms of fiscal incentives for both production and consumption. At that time, wood became a very important source of raw material for charcoal, liquid fuels, steam, and thermoelectricity generation. These energy products were used by the cement, pulp and paper, iron and steel, and grain dryer industries as well as other industrial sectors of the country.

In the early 1980's native forests accounted for 80% of the total supply of charcoal while forest plantations contributed the remaining. By 1991, the use of wood from the native forests decreased to 60% while the use wood from forest plantations doubled to 40%. Thus the forest plantation program helped alleviate the timber harvesting pressure on the native forest ecosystems resulting in positive environmental impacts. In 1991, the pulp and paper industry alone consumed 5 million steres of wood for energy as a substitute for fuel oil. This wood came from their own plantation forests as well as from small private ownerships. Wood's use for energy amounted to almost 13% of the industry total wood consumption. Of this, **Eucalyptus** accounted for 63% and **Pinus** for 17% (**ANFPC 1991**).

In the southern Brazil, most of wood used (66%) by the forestry sector is obtained from forest plantations (**Eucalyptus sp**, **Pinus sp**, **Mimosa scabrella**, and **Acacia mearnsii**). The native forests account for the rest. In that region, the second largest use of wood is for energy generation. In 1991, in the state of Paraná, wood biomass for energy production accounted to 18% of all energy consumption. In the industrial sector wood was the second largest energy source accounting for 33% of the energy supply (**COPEL 1992**).

An extreme case of fuelwood dependence is exhibited by the state of Minas Gerais. The largest Brazilian producers of iron and steel are located in that state. In 1989, fuelwood and charcoal satisfied 38% of the state's total demand for energy and 45% of its industrial demand. In that year, fuelwood was the major source of energy with plantation forests accounting for 27% of the total supply of this raw material (**CEMIG 1989**).

Now, there is a growing trend to adopt agroforestry systems, ranging from small to large-scale ventures. These systems are based on short-rotation tree species, such as **Eucalyptus sp**, **Pinus sp**, **Mimosa sp**, and **Acacia sp**. These type of plantations could gain the interest of new landownerships and add a considerable amount of wood biomass for energy supply in the country.

This paper will explore the importance of wood biomass for energy in Brazil and point out the experiences of the Brazilian forest sector in dealing with energy production issues. There will be special emphasis placed on discussing two key wood-energy plantation species - the exotic Eucalyptus sp and the native bracatinga (Mimosa scabrella).

The Wood-Based Energy Programs

There are four main industrial users of wood: steel and cement, steam generation, liquid fuels and thermoelectricity. Household use of wood is declining due to the increased consumption of liquid petroleum gas. Charcoal is very important as an energy input for the iron and steel industries and as a fuel oil substitute in the cement industry. The thermochemical process of wood pyrolysis to supply fuel to boilers, kilns and engines is also an important energy use. Wood-based liquid fuels such as ethanol and methanol were also produced at pilot level but not implemented commercially.

The Charcoal and Fuelwood Energy Programs

Brazil's reserves of oil and coal are relatively small considering the extent of its territory. Further, Brazilian coal is of low quality for producing iron and steel due to its high sulphur and ash content. Thus, opposed to most of the industrialized countries of the world, charcoal as a substitute for coal played a very important role in the development of the Brazilian iron and steel production sector. The use of wood placed a heavy burden on Brazil's native forests and also contributed to the development of the large-scale short rotation plantation forestry over the last 25 years. According to the **F.A.O. (1991)** in 1989 Brazil consumed 182.806 million cubic meters of fuelwood and charcoal and this is projected to continue at that level until year 2010. In 1991 the charcoal-based iron and steel industry in Brazil contributed US$3 billion to the country's economy generating 189,500 jobs and paying US$485 million in tax revenues to the government (**ABRACAVE 1992**).

Over the last ten years utilization of native forest-based charcoal increased 119% while forest plantation-based charcoal utilization increased 351%. This is a positive trend both from the environmental and economic point of view. Currently the Brazilian government has removed some fiscal incentives from the forest sector of several charcoal-based industries. This has caused some to switch to imported coal. Decrease in use of charcoal will alleviate the pressure on the native forests. Plantations may be used for other purposes such as woodpulp. The environmental, social and economic impacts of these changes will need to be monitored in the future.

A government program called **Our Nature** was created in 1989 to generate 100% self sufficiency in the charcoal-based industries within a seven-year period. In the Amazon region those goals would be attained by sustained yield management of the native forests while in the other states of the country they would be accomplished through plantation forestry.

Fuel oil is utilized as a fuel by industries to produce thermal energy, mechanical energy and electricity. Most of these industries can promote partial or total substitution of fuel oil by biomass-based fuels. Among them, woody biomass has all the necessary conditions to substitute for fuel oil if used directly (firewood, chips and logging residues) or transformed (charcoal brickets, tar, etc...). Charcoal and wood tar played a very important role as a fuel oil substitute in the cement and steel industry in the 1980's. Thermochemical processes of pyrolysis and gasification for supply of fuel to boilers, kilns and engines also attracted the attention of large companies such as Nestlé and Petrobrás. Nestlé initiated a US$40 million program to convert fuel oil use to biomass over its nationwide network of factories.

Copene, a subsidiary from Petrobrás also started a project to replace 200 thousand barrels of fuel oil annually by using wood at the Camaçari petrochemical complex in the state of Bahia. An extensive area of **Eucalyptus** plantations was established by Copener, the forest division of Copene. The plantations were close to the area in order to guarantee the supply of wood for the large energy generation complex. The wood was pulverized and burned in the boilers for steam generation. Low costs of fuel oil caused the project to be discontinued by Copene which is now exporting the plantation's wood and pursuing joint ventures with national and international pulp and paper companies.

In 1981, the cost (as a percentage of oil price) to produce a gigacalorie of fuel oil by using charcoal was 43.8%, by using debarked wood 34.9% and by using logging residues only 9.6%. In 1991 the pulp and paper sector alone consumed 4.3 million steres of wood for energy as a substitute for fuel oil. Of this wood, **Eucalyptus** accounted for 61.5%, **Pinus** for 19.6% and 18.9% from other forest species. To supply their needs for fuel oil substitution and for producing pulp and paper, the Brazilian pulp and paper sector has established 1.4 million hectares of forest plantations and is planning to establish an additional 855 thousand hectares plantation by the year 2000.

Studies conducted by Shell, Chesf and Eletrobras have shown that *ceteris paribus* energy production from biomass cannot presently compete in price with energy generated from oil, coal and natural gas. The only way it can compete is by generating a more valuable form of energy *viz* electricity. This is possible by using a technology developed in the United States. This new technology is the Biomass Integrated Gasification/Gas Turbine (**BIG/GT**). In this technology the gas is used to power a turbine which produces electricity. The exhaust gases from the turbine are captured for additional energy production. Compared to the traditional 20% efficiency in the steam-based electricity production systems this new technology has a 40% conversion efficiency. In 1992 Brazil submitted a technical proposal to the Global Environmental Facility to build an experimental **BIG/GT** plant and to study the economic feasibility of the process. The project was approved and is now underway (**Carpentiere et al. 1992**).

The Ethanol Program

In 1979, the Brazilian Congress approved the creation of Coalbra (Brazilian Company for Wood Ethanol and Coke Production) whose shares were owned by the Brazilian government (51%) and by private investors - mainly equipment producers and forest plantation owners. The program goals involved much more than simply increasing ethanol's physical production. The program had broad social objectives such as: to minimize environmental impacts, to use marginal agricultural lands, to develop local research and development, to generate jobs, to decrease oil and coal imports, and to increase equipment production.

Initial studies dealing with acid hydrolysis of wood in Brazil began in 1976 at the National Institute of Technology in Rio de Janeiro. Several pilot experiments were conducted in its laboratories which tested ethanol and lignin-derived coke from **Eucalyptus sp, Pinus sp, Gmelina arborea**, native tree species and other cellulose material suitable for acid hydrolysis (**Longo and Araujo Neto 1980**). The pilot experiments in Rio de Janeiro showed the estimated cost of one liter of wood-based ethanol was US$0.34. This was twice the cost of ethanol derived from sugar cane. However, due to the social, environmental and economic importance placed on the forest plantations, the Brazilian government proceeded with the program. It also was thought there would be a possibility of reducing the production cost of the ethanol. Since the wood raw material accounted for 60% of the total cost using logging residues could lower that cost. Further, by-products such as lignin tar, lignin-based coke, calcium sulphate, methanol, furfural and single-cell proteins could be produced and sold, increasing the revenue from the wood-based ethanol production. For every 100 liters of ethanol produced it is possible to obtain 3.5 kg of furfural, 7.5 liters of methanol and 60 kg of lignin-based coke. Revenues from these by-products can amount to 75% of the price of ethanol (**Kling 1980**).

In 1984, Coalbra began production at a 11 billion liters per year pilot plant located close to Uberlândia, Minas Gerais. The production was based on a Russian dilute acid hydrolysis technology using **Eucalyptus.** In addition to ethanol it was to produce lignin-based coke, furfural and one-cell proteins for animal feed. Despite the success of obtaining the required production at the experimental level, the process was not implemented commercially. In this case, like the pilot experiments in Rio de Janeiro, the costs were too high. The cost was 10% to 20% higher than sugar cane-based ethanol. The process was also capital intensive and required a large quantity of wood (**Rosillo-Calle 1987**). In 1988 the plant was closed and the company was disbanded.

In producing ethanol from wood it is necessary to take into consideration the investment level, the energy input-output balance and the possibility of generating by-products. The capital investment for wood-based ethanol production is 2-3 times higher than that required to produce a similar product from sugar cane, manioc, and sorghum. Investments in this process are high because the equipment has to be resistant to corrosion by sulphuric acid. In Brazil, a plant to produce 100 thousand liters of wood-based ethanol per day would require US$20 to US$30 million of capital investment. Further, energy consumption in the wood-based ethanol process is also higher than for the sugar cane-based product. Almost 50% of the wood in wood-based ethanol process must be used to generate energy. Table 1 shows the energy efficiency of different sources of biomass.

Table 1. Energy Efficiency of Different Sources of Biomass

BIOMASS SOURCES	NET ENERGY in Mcal.ha^{-1}.year^{-1}
Sugar Cane (ethanol)	17.224
Manioc (ethanol)	7.091
Eucalyptus (ethanol)	11.822
Eucalyptus (methanol)	17.856

Source: Cesp

Even though wood-based ethanol has had its problems it still warrants consideration. Advances in the technological aspects of the production process such as continuous hydrolysis and high temperatures could improve economic performance. Wood also presents some advantages relative to sugar cane, manioc and other crops since forest plantations are less sensitive to changes in climatic conditions. Wood has a more stable market price in the long run. Finally forest plantations are usually established on marginal lands that could not be used for food production whereas sugar cane and manioc often are produced using prime agricultural land.

The Methanol Program

Methanol from gasification of **Eucalyptus** was the endeavor of a five-year US$80 million program developed by Cesp a São Paulo state-owned company (**Trindade 1989**). The company chose **Eucalyptus** because of its high yields over a short 7-year rotation. **Eucalyptus** also grows well on marginal lands like the savanna region of the country, and has a large number of species adaptable to the different climatic and edaphic conditions of Brazil. Finally, it grows 365 days per year (there is no dormant period) and has relatively low costs of production.

Cesp began it's wood-based methanol production in Corumbataí (São Paulo state) with two pilot plants producing methanol from charcoal. In Jupiá between the states of São Paulo and Mato Grosso do Sul, Cesp built three experimental wood gasification units located near 300,000 ha of **Eucalyptus** plantations. Each plant was designed to use a different technology in order to determine the best one for industrial wood gasification (**Bueno 1980**).

Cesp used methanol as a substitute for gasoline in Otto-cycle engines and the company operated several methanol-fueled vehicles during the tests. A substitute for diesel engines was also studied using additives to make the methanol suitable for that type of engine. For fuel oil substitution Cesp modified an oil-fired boiler which drove a turbine generator producing 15,000 Kw. This equipment was manufactured in Brazil and used for steam generation. Methanol was also used to substitute for propane gas for thermal treatment of metal and alloys. The pilot studies showed that methanol requires fewer inputs than wood and sugar cane-based ethanol production but the energy efficiency of the process is low (**Rosillo-Calle 1987**). The production cost of this fuel would be around US$0.23 per liter which at that time was not competitive with sugar cane-based ethanol, gasoline, and diesel (**Zagatto 1980**).

Technical Aspects of the Short Rotation Eucalyptus and Bracatinga Forest Plantations

Timber Yields

The short rotation large-scale **Eucalyptus** plantations in Brazil, exhibited a dramatic increase in timber yield over the last 23 years. From 1970 to 1993 the average annual yield in some regions rose from 35 $m^3.ha^{-1}.year^{-1}$ to 70 $m^3.ha^{-1}.year^{-1}$ (**Betters et al. 1991**). At the experimental level, even higher yields have been obtained by both forest companies and research institutions. This increase in **Eucalyptus** stand productivity in the country is a result of a substantial forest research effort, in particular in genetics and biotechnology. Genetic gains were reinforced by better silvicultural and management practices.

The initial growing stock for the short rotation coppicing-stands generally ranges from 1100 to 2200 seedlings per hectare. Plantings normally are established on a 3 m x 3 m or 3 m x 1.5 m spacing. It has been found that the mean annual increment of the stand increases somewhat with wider spacing. Wider spacing is used to facilitate harvesting and weed control and to reduce wind damage. It also allows intercropping of agriculture crops when this is desired (**Betters et al. 1991**).

For short rotation **Eucalyptus** plantations, weed control is done twice a year and considered critical during the first two years before canopy closure. Where labor is cheap and plentiful the weeding is done by disking between the tree rows and hand hoeing in the rows. Some forest companies use herbicides such as glyphosate at a rate of 3 to 4 liters per hectare before planting and tractors to disk between tree rows after stand establishment. Others are using cattle and sheep to reduce grass competition in plantations and to lessen the fire danger. Small-scale plantations are also being intercropped, in the first year, with corn and beans as a way to off-set plantation establishment costs. The most recent advance in this area is the use of herbaceous legume species planted at the time of stand establishment to offset the growth of undesirable weeds.

The control of leaf-cutting ants is an expensive cultural treatment in **Eucalyptus** plantations. Once established in a stand they can destroy a young plantation in few days, so it is necessary to have careful monitoring of the plantations to detect the colonies at an early stage. Until last year, dodecachlor-based baits were used to control ant population. The use of this product is now forbidden and a sulfluramid-based bait is used instead.

Bracatinga (**Mimosa scabrella**), a native nitrogen-fixing tree cultivated in southern Brazil (mainly in Parana state), usually is reforested by natural regeneration. Fire is used to prepare the land for planting. The initial growing stock of those stands can sometimes reach 20,000 seedlings per hectare. Farmers generally reduce the number of plants to 3,000 to 4,000 per hectare through thinnings. This reduction in stand density allows intercropping with corn and beans in the first year of the seven-year rotation. The average timber yield of the bracatinga is about 13 $m^3.ha^{-1}.year^{-1}$ and can be double that on higher quality sites (**EMBRAPA 1988**). Although bracatinga has a lower average yield than **Eucalyptus viminalis** (19 $m^3.ha^{-1}.year^{-1}$) it remains the key forest plantation species in the cold highlands of the southern Brazil. Bracatinga is preferred because it can be grown at a much lower cost (**Graća et al. 1986**) and the rural landholders usually do not have capital for large investments. Further, as opposed to **Eucalyptus**, there is no need for fertilization, tending and control of leaf-cutting ants.

Growing Stock and Stand Establishment

Australia is the main source of genetic material for the **Eucalyptus** plantations in Brazil. South Africa, New Zealand and the Timor Island in Indonesia also contributed with several species and provenances. The most widespread **Eucalyptus** species introduced in Brazil is **Eucalyptus grandis**, along with species such as **Eucalyptus saligna, Eucalyptus urophylla, Eucalyptus camaldulensis, Eucalyptus citriodora, Eucalyptus viminalis**, and others.

A national genetic improvement program is carried out by state and federal research institutions. Forest companies can be directly associated with it or have their own independent tree improvement programs. The use of vegetative propagation techniques (cuttings and micropropagation) is becoming widespread among large companies. This has resulted in considerable gains in timber yields in large-scale forest plantations. The nursery process takes 70 to 80 days, where the plants stay under shade half of the time and the other half in the sun before going to the field for planting.

Most of the planting is done by hand and the trees are watered immediately and then again after one week if no suitable rainfall occurs. After harvest, logging slash is burned or used for energy purposes. The area between the rows is disked and the site is broadcast fertilized. Stump sprouts normally appear within 2 to 3 weeks. If the existing stand is to be replanted, the stumps are covered with soil, and the new trees are planted in the same row between the old stumps. Otherwise, stumps are removed either using a "root rake" or heavy chains pulled between crawler tractors. The stands renewal depends on individual coppice yields and its costs. Although most of Brazilian companies ordinarily adopt 2 coppices, some companies are lowering the number of coppices and even choosing not having coppice at all. This occurs in cases where new genetic improvements make a replanting a better financial option.

Since bracatinga is a native species, the genetic material has been collected locally by provenances and submitted to genetic improvement trials at EMBRAPA-CNPFlorestas. This facility is located in Colombo in the state of Paraná. In places where bracatinga does not exist direct planting (by seed or by seedlings) is required. The recommended density is 3000 to 4000 seedlings per hectare. Once the bracatinga plantation is established, seeds will be naturally incorporated into the soil by the time of clearcutting and there will no need to plant again.

Logging and Transportation

In **Eucalyptus** plantations, most of the forest companies do their own harvesting. However, there is an increasing trend towards subcontracting such operations. Plantation harvesting involves manually felling the trees using chain saws, where the average operator cuts 120 trees per day. The crowns are lopped off and the trees bucked or left whole depending on the equipment used to move the logs to the landing. Grapple loaders are used to pick up the logs. Close to 70 percent of log transportation to the mill is done by trucks, the remainder by rail. The average haul distance is about 75 km one way, with a maximum of 200 to 300 km. Transportion costs have been of primary concern to the companies since they are dependent on expensive transport fuels.

Since bracatinga is a farm-operated activity some of the harvesting operations are still done by ax. The logs are cut at a length of 0.8 to 1.2 m with a minimum diameter of 4 cm. The wood is carried out using either horse carriers or tractor trucks and is piled close to the roads where it is sold to prospective buyers.

The Economic, Social and Political Aspects of Forest Plantations

Plantation Costs

Plantation, cultural and administration costs for one hectare of **Eucalyptus**, over a seven-year rotation period, can vary substantially depending on the region, soil fertility, species, and technology (Table 2). The data observed for São Paulo (SP) and Rio Grande do Sul (RS), are typical of **Eucalyptus** plantations used for pulp and biomass energy production. While data from Minas Gerais (MG), represent plantations used for charcoal and fuelwood. For bracatinga, the data is from Paraná (PR).

Table 2 Plantation Costs and Yields for **Eucalyptus** and Bracatinga in US$ per Hectare for a 7-year Rotation

Genus	State	Planting US$.ha^{-1}	Cultural US$.ha^{-1}	Administrative US$.ha^{-1}	Yield st.ha^{-1}
Eucalyptus	RS	856.90	136.30	371.20	323.8
Eucalyptus	SP	722.70	225.10	321.30	455.0
Eucalyptus	SP	783.69	285.00	232.07	273.0
Eucalyptus	MG	584.19	137.36	384.83	210.0
Eucalyptus	MG	1171.37	281.92	522.81	360.0
Eucalyptus	MG	518.00	278.00	162.80	108.0
Eucalyptus	MG	684.00	859.00	162.80	150.0
Eucalyptus	MG	646.27	236.80	132.46	180.0
Mimosa	PR	64.00	38.40	210.50	182.0

Source: Information gathered by the authors

Table 2 indicates the cost advantage of bracatinga. It is important to note that for **Eucalyptus**, coppicing costs must be lower than replanting costs since coppicing yields decrease after the first harvest. Forest companies which deal with large **Eucalyptus** plantations have almost unanimously reported reductions in coppice yields. Coppicing net revenues can offset the high initial planting costs making the whole cycle (21 years) profitable.

For the state of Minas Gerais, it is common to have coppicing costs amounting to only 10% of planting costs. At the same time, yields are reduced by 15% and 30% for the first and second coppices, respectively. Some companies have reported that it is more profitable to replant their plantations after the first or second harvesting. This depends on renew costs and future yields of more productive genetic material (**EMBRAPA 1989**).

Logging and Transportation Costs

In the state of Minas Gerais, logging and transportation costs can reach US\$1,190.00 ha^{-1} for flat areas and up to US\$1,674.00 ha^{-1} for steeper regions. For a 21 year, 3-coppice **Eucalyptus** plantation, this represents 60% and 51% respectively of all operational costs (**Tecflor 1989**). In other states and regions, these costs are reported to make up 70% of the total delivered wood costs.

For bracatinga, due to its lower planting and cultural costs, the logging and transportation costs, can reach US\$190.00 per hectare which represents 93% of the total operational costs (**Graça and Mendes 1987**). In order to save time and money, bracatinga farmers often prefer to sell standing trees. This leaves the logging and transportation costs for the buyer or to contractors. As part of payment, contractors are often allowed to plant corn and beans for themselves in the following cycle.

Economic Incentives and Forest Legislation

With the passage of the Forestry Code of 1965 and Public Law 5106 in 1966, Brazil implemented several important incentives including: a) Reforestation incentives to include tax breaks amounting to the planting and maintenance costs of a plantation for the first four years (land costs not included). Those eligible included reforestation companies, individual landowners, or individuals or companies operating through third parties (reforestation companies). A tax rebate up to 50% of income tax due was allowed if applicable in forest projects; b) Income from sale of manufactured wood products could be reduced up to 25% from tax credits based on reforestation expenses; c) Credit agencies could give preferential rates to individuals or companies purchasing reforestation equipment; d) Plantations and native forests were exempt from land tax increases due to an increase in land value (**Betters et al. 1991**). This incentive program generated a major new timber supply source via the establishment of short-rotation tree plantations.

Currently, a large wood products industry is in place and wood energy (charcoal, fuelwood, etc) supplies have been augmented substantially. The area of plantations is now over 6.5 million hectares. The main forest species are of the genus **Eucalyptus** and **Pinus** with 52% and 32% of total area, respectively. These plantations provide 39% of wood consumed for industrial purposes. Rural employment opportunities have improved greatly, and Brazil has become a net exporter of short-rotation-based wood products that are competitive worldwide. These products include plywood, hardboard, pulp and paper and pine lumber. Exports from the iron and steel industry also have increased.

In 1988 the fiscal incentive program was terminated. Without such incentives there are now concerns about future supplies and competition from world markets. As a result several state level initiatives, such as Pro-Florestas (financed by IDRB) and FLORAMINAS (an ongoing project) in Minas Gerais have recently provided financial help for small land ownerships interested in establishing plantations.

In both social and economic terms, the forest sector has achieved national importance, as it contributes 5.6% of total Gross Domestic Product (GDP) and 4% of total exports. It generates a total of 2.5 million of jobs in factories and in the field.

It is interesting to note that no fiscal incentives were provided for bracatinga. It was considered unsuitable for large-scale plantations, had a limited growing area and had only one major use, fuelwood. Thus, it was not included in the incentive program.

Environmental Aspects of Forest Plantations

The critics of **Eucalyptus** have mentioned that these monocultural plantations create problems in biodiversity, generate soil erosion, reduce soil nutrients, and compete with the production of food crops. Some discussion is necessary in order to put these concerns in the right perspective. First, with the fiscal incentives, **Eucalyptus** became the most planted species, having 2.2 million hectares in the state of Minas Gerais alone. This all happened very quickly which caused some of the problems. There was little professional expertise available to monitor the planting. The first school of forest sciences was created in 1960 and the first graduate program (M.Sc.) in 1974. Thus at that time little was known about the silvicultural aspects of the species in order to effectively deal with the negative impacts on the environment. At the time it was thought that **Eucalyptus** could be grown in any type of soil. This was not the case and many stands had low yields and poor survival on certain sites. There was some poor decisions made about species and provenances, resulting in major insect damage, less vigorous coppices and a low rate of survival. Inadequate management practices, mainly linked to soil preparation, contributed to erosion. The fact that the program moved ahead so quickly contributed to some of those problems.

Biological diversity (plant, animal or both) generally suffers when using a pure monoculture short-rotation species. Although these effects have not been quantified, many companies are now trying to increase biodiversity by keeping areas of natural forests along side the **Eucalyptus** plantations. One large forest company in the state of Paraná, has been preserving an area of over 40 thousand hectares of natural forests adjacent to its **Pinus** and **Eucalyptus** plantations. This example has been followed in other states. In addition the more widespread use of agroforestry systems with **Eucalyptus** will enhance biodiversity.

Erosion is another concern, since the use of heavy mechanization for soil preparation and intensive weed control have contributed to soil erosion. Moreover, the short rotations cause more nutrient loss since the young **Eucalyptus** plants have a higher nutrient uptake. Although **Eucalyptus** is an efficient nutrient user, it is not unlike any agricultural crop, such as soybean or sugar cane, as far as nutrient depletion is concerned. The same can be said about the depletion of the water table where any monocultural cultivation, be it forest, agriculture or pasture, generate a similar pattern of water usage.

Sorting out causes and effects in complex subject like this requires a great deal of research. **Reis (1993)**, has advocated the following approach in order to minimize the environmental impact caused by **Eucalyptus** plantations. She states that there is a need for ecological zoning, considering species and adequate management practices. Future management needs to intensify biodiversity by mixing of forest and agricultural plants (agroforestry systems). There needs to be more use of biological control as opposed to pesticides. On steeper areas less mechanization should be used to conserve soil. Research needs to be done on ecological systems of native forest species as substitutes for **Eucalyptus**. Further, in the near future, an institutionalized process for environmental impact assessment, should be implemented. Many of companies, such as, Cenibra, Pains, Belgo-Mineira, Aracruz, Mannesmann, Klabin, Riocell, Duraflora, Ripasa and others, have already developed specific departments to deal with environmental questions.

Bracatinga has multiple purposes: nitrogen fixing, good nutrient cycling, soil protection, biological diversity, production of honey in mid-winter. In the case of bracatinga, there has always been intense public scrutiny regarding its use. Only mature stands can be harvested and only on a sustained yield basis. Widespread clearcutting is not allowed in order to preserve water tables and reduce soil erosion. This policy has contributed to stabilizing fuelwood supply in times of increasing demand and causes bracatinga's real price to increase making thousands of small farmers better off. Thus, besides its positive environmental contribution, bracatinga has provided a reliable and stable source of income.

Future Trends for the Forest Plantations

There is no doubt that environmental issues will continue to be a primary concern with **Eucalyptus** plantations, not only in terms of its negative aspects but also with its positive side as a CO_2 sequester. There will be greater demand for the use of agroforestry systems with **Eucalyptus**, to offset plantation costs and increase supply of agricultural and animal products. Fuelwood will continue to have an important role because it is a cheap, renewable raw material source and provides a great deal of stable employment. Research will be devoted to find alternative short-rotation forests (involving better species and management alternatives) for **Eucalyptus**, in order to minimize its monocultural aspects.

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EVALUATING A BIOMASS RESOURCE: THE TVA REGION-WIDE BIOMASS RESOURCE ASSESSMENT MODEL

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Abstract

The economic and supply structures of short rotation woody crop (SRWC) markets have not been established. Establishing the likely price and supply of SRWC biomass in a region is a complex task because biomass is not an established commodity as are oil, natural gas and coal. In this study we project the cost and supply of short-rotation woody biomass for the TVA region - a 276 county area that includes all of Tennessee and portions of 10 contiguous states in the southeastern United States. Projected prices and quantities of SRWC are assumed to be a function of the amount and quality of crop and pasture land available in a region, expected SRWC yields and production costs on differing soils and land types, and the profit that could be obtained from current conventional crop production on these same lands. Results include the supply curve of SRWC biomass that is projected to be available from the entire region, the amount and location of crop and pasture land that would be used, and the conventional agricultural crops that would be displaced as a function of SRWC production.

Finally, we show the results of sensitivity analysis on the projected cost and supply of SRWC biomass. In particular, we examine the separate impacts of varying SRWC production yields.

Introduction

Wood is an alternative fuel for electric power generation at coal-fired plants in the Tennessee Valley Authority (TVA) region. Short rotation wood energy crops (SRWC) could provide a source of this woody biomass. The amount of wood (biomass yield) that can be produced by SRWC in a region (for example, a county) is a function of the 1) amount of crop and pasture land in the county, 2) soil quality of this land, 3) current use of crop and pasture land in the county, 4) management practices used to grow SRWC, and 5) regional climate characteristics. The price paid by power plants for SRWC biomass is a function of the cost of production, harvesting and transportation and therefore the price that farmers must receive in return for growing SRWC biomass.

The objective of this study was to project quantities of SRWC biomass that could be produced in a 276 county region and the cost of producing the wood. Cost of production here refers to the price paid to farmers. Using a schedule of projected quantities and prices, we derived a supply curve of SRWC biomass for the 276 county region.

The economic supply structure of a market for SRWC biomass has not been established for this region. Because SRWC biomass is not an established commodity as are oil, coal and natural gas, projecting the yield, production cost and thus supply of SRWC biomass in the TVA region is based on a comparison with conventional agricultural and pasture land conversion options. A basic assumption was that price system incentives would determine the margin at which farmers would be induced to convert currently used conventional agricultural land to SRWC biomass production. This margin or economic incentive, called the breakeven price (BEP) is the price that farmers would need to receive for growing biomass that assured them of equal or greater profit levels than they would receive if they planted the same land with the most profitable conventional crop or maintained pasture land in pasture. Profit to farmers is considered a function of the 1) expected yields of conventional agricultural crops (determined by soil quality, management practices, and weather), 2) market price, which in this analysis was assumed to be set by a national market and thus insensitive to local supply and demand, 3) production cost, which is affected by management practices and soil quality, and the existence of government commodity programs. We did not consider government commodity programs in this study.

The rest of this paper is organized as follows. Section two describes the methodology by outlining the geographic scope and modeling approach including economic assumptions about production trade-offs and decisions. In section three, we present the results in the form of a supply curve and discuss an interpretation of this cost-supply curve. The final section concludes the paper by discussing some implications and expanded research work.

Methods

In order to produce a supply curve for biomass for the 276 county region, both quantities and prices had to be derived. Since no biomass is currently grown in organized markets in this region, neither prices nor quantities were available. Derivation from the quantity side relied on the assumption that farmers of agricultural lands would convert their land to biomass production when the price per unit of biomass harvested would meet or exceed their current profit margins. Therefore, information about yields, costs of production and market prices would have to be determined for both conventional agricultural crops and SRWC crops. Knowledge of these numbers would give information about physical properties and factors regarding economic decision making. The breakeven price was calculated using the following equation:

(1) $$(YLDc * PRICEc) - COSTc = (YLDw * BEP) - COSTw$$

where YLDc was the particular conventional crop yield expected, PRICEc was the expected market price of the conventional crop, COSTc was the cost of conventional crop production, YLDw was the yield of woody biomass, BEP was the breakeven price of SRWC to the farmer to be calculated, and COSTw was the cost of production of SRWC woody biomass. The left-hand side of the equation may be considered land rent or the returns to land, labor, capital and management as a result of growing conventional crops on cropland. We considered land rent, similarly, as a result of keeping pasture land in pasture production. The right-hand side of the equation, therefore, is land rent received as a result of growing biomass crops on either conventional crop land or pasture land.

The notion of a breakeven price (to be calculated) was that a farmer would convert his conventional crop agricultural production lands to woody biomass production when it became profitable enough for him to do so. Based on available information on the remaining five coefficients in the above equation, we could solve for BEP. Figure 1 shows a diagram by which information flows through each stage of our analysis.

Land Base Characterization

Figure 2 demonstrates the span of counties across the 11 state area. For the purposes of our study we selected eight subregions within the TVA region. The boundaries of the subregions were based on current land use and physiographic features and largely followed the boundaries of the United States Department of Agricultural (USDA) Major Land Resource Areas in this region (United States Department of Agriculture 1981).

In order to adequately and completely describe the geographic region, national agricultural data bases were used to characterize soil types, agricultural crops grown, and the acres of crop and pasture land for each county. Information on soil types was derived from the national resource inventory (NRI) (Soil Conservation Service 1984) and the SOILS5 data base (United States Agricultural Stabilization Conservation Service 1989). SCS soil classes were aggregated into nine categories for each of the eight subregions so a representative SCS soil class code could be used. The NRI was then scanned to determine the most common soil type for each soil class. Soil names were cross referenced with NRI soil codes using the SOILS5 database. Finally the SOILS5 data base was accessed by soil name to provide all information possible about different horizons, slope characteristics and other information for each of nine soil categories.

In order to determine the dominant agricultural crops grown in a particular region, the National Agricultural Statistics (NAS) were accessed by county to determine, by acreage, the three dominant conventional crops grown in each of the eight subregions United States Department of Agriculture 1988, 1989). Each of the subregions would then have three crops which represented at least 80 percent of the region's agricultural land base considered. The trio of dominant crops for each region were some combination of corn, cotton, soybeans or wheat. The Agricultural Census data provided information about the crop and pasture acreage for each county United States Department of Commerce 1989).

Conventional Agricultural Crop Yields

Crop yields were available from the NAS. The 1988, 1989 and 1990 data for the three dominant crops for each subregion provided data on average yield. However, since we wanted to make the yields more sensitive to the soils within a subregion, we used the Erosion Productivity Impact Calculator (EPIC) model (Sharpley and Williams 1990) to simulate yields using soil information directly available for each soil type associated with each soil category for each subregion. EPIC is a widely used productivity and erosion simulation package. EPIC required a physiology characteristics module for each conventional crop grown, the SOILS5 soil name specific module, wind and weather data, and a crop management scenario. The subregion's wind and weather data module selected was that national weather service (NWS) weather and wind station data which was closest to the geographic center of the subregion. Management scenario information for the EPIC module was taken from state crop budget data information available from agricultural extension offices. For subregions which included counties from two or more states, information from the dominant state was used to characterize both crop budget and management practices. Tillage practices considered predominant for each state were used; the dominant tillage practices considered for most states was no-till, except for cotton acreage which was predominantly conventional till. A total of 216 EPIC simulations were completed, providing information on yields about three crops on nine soil categories in eight different subregions.

To provide more accurate yield information, an index of the ratio of NAS crop yield and EPIC simulated crop yield was produced. This index was used in Equation 1 and would be more representative of the true yield for a subregion. A more detailed explanation of this index is found in Graham and Downing (1993) in these proceedings.

Conventional Crop Market Prices and Production Costs

Conventional crop market prices were assumed constant across the entire study region. These were taken from Johnson (1990).

Each state crop budgeter provided an accurate production budget for each of three dominant crops in each subregion. Management scenarios were important determinants of the cost of production as were tillage practices. In order to determine overall investment and trade-offs, a discount rate of 6 percent was used.

Pasture rent values were determined on the state level as well. Pasture rent values considered were from the average gross cash rent per acre statistics from selected states for 1986-1990 (United States Department of Agriculture 1990). These values were estimated cash rent as a percent of the per-acre value of rented pasture.

SRWC Yields

There are several common SRWC varieties considered capable of reasonably fast growth, good quality for conversion, or resistant to disease. The varieties selected for growing in the subregions were sweetgum, poplar, sycamore, and black locust. SRWC wood was considered to grow better on some SCS soil classes than others, so each variety was tailored to the particular soil category. As displayed in Table 1, poplar was projected to grow on only the first and fourth soil categories, sweetgum was projected to grow best on the second and third. Black locust was expected to grow best on soil categories 5 and 6 and sycamore on soils 7 categorization. No SRWC wood was considered capable of growing on soil categories 8 and 9.

There have been numerous field trials conducted in the United States to evaluate SRWC yields (Bransby 1990, and Parrish 1990). There is little or no field data on SRWC yields in the 276 county study region. Therefore, expected yields for the 276 county region were assembled based on the best possible information from experts in the field (Cherney 1990, and Dobbins 1990). Yields were projected to range from 3.5 to 5 dry tons per acre across all subregions and were sensitive only to soil category, not subregion. Yields on pasture land of the same soil category were considered to be lower by an average of 20 percent because of conversion transition problems such as soil compaction and previous cropping and fertilization practices. EPIC does not yet contain an SRWC simulation module for any of the SRWC species we wished to model, so it was not used to simulate yields.

Table 1

SCS Soil Classes	Soil Categories	SRWC Species
1	1	Poplar
2w	2	Sweetgum
2e	3	Sweetgum
2s	4	Poplar
3w, 4w	5	Black locust
3e	6	Black locust
4e	7	Sycamore
3s, 4s	8	—
5–12	9	—

SRWC Production Costs

Each biomass crop species had a different rotation length based on knowledge of optimal rotation as seen in field trials in other parts of the country. Individual budgets for each rotation for each species were constructed to reflect the 6 percent discount rate, custom harvesting, and variable and fixed costs of production. Harvesting, for example included chipping costs, which would more accurately reflect the total cost of the final product. Losses for shrinkage were included, but transportation costs to move the product from the field to the utility plant were not.

BEP solution

The result of solution of Equation 1 for all subregions (8), across all soil categories (9) and for each conventional crop for crop land and pasture land, was a file containing 144 observations. We were thus able to calculate the breakeven prices for each crop as well as the maximum breakeven price for each subregion and soil category. The conventional crop corresponding to the maximum-breakeven price was also identified. The maximum breakeven price was not allowed to imply a negative land rent. There were many instances in which none of the conventional agricultural crops were profitable. This may not be unrealistic as it is clear from discussions with the agricultural extension offices that farmers are going out of production in many of the counties examined.

Results

The solid supply curve shown in Figure 3 represents the SRWC biomass supply curve for the entire region of 276 counties. The total dry chipped tonnage of biomass projected to be supplied is shown to be 74 million tons. The price per dry chipped ton of SRWC biomass is shown to range from $28 to $93. Each step of this aggregate supply curve demonstrates a change in the price. For example, approximately 25 million tons are available at a price of about $43 per ton. Two concepts of this additive supply curve are noteworthy. First, the steeper portions of the curve represent smaller groups of biomass available while the flatter portions of the curve represent more abundant quantities of biomass, at particular prices.

Based on how the breakeven prices for biomass were calculated, we showed that each county included in the study region had an individual quantity of biomass projected to be supplied at individual prices. The particular species of SRWC wood were also identified, as well as the acres and particular conventional agricultural crop displaced. The percentage of crop land and pasture land for each county was identified also.

An economic interpretation of the curve shows that movements along the curve (known as changes in quantity supplied) can only be made by either a change in price or quantity. Shifts in the curve itself would be due to changes in other determinants of supply such as changes in production technology or changes in the discount rate. For example, the broken curve in Figure 3 would represent the supply curve if production yields are increased by 25 percent. The supply curve appears shifted out and to the right as a result of costs of production decreasing on a per acre basis per unit of yield.

Figure 4 shows the conversion of the solid supply curve in Figure 3 from dollars per ton ($/Ton) to dollars per million British Thermal Units ($/MBtu). This curve can be used to compare the $/MBtu of coal, or other energy inputs to conversion for electricity production. TVA currently pays about $1.20/MBtu for coal (Gold, 1993). This curve is also useful in determining the trade-offs in using wood for production of ethanol as an end product vs production of electricity. Thus, woody biomass may be seen as having competing uses; for electricity production and conversion to ethanol.

Spatial distributions of the range of available quantities of woody biomass available at different prices are portrayed in the Figure 5. Each of the three maps represent the distribution by county for the quantities of woody biomass projected to be available at $2.00, $2.50 and $3.00 per MBtu. The land that currently produces more profitable conventional agricultural crops would tend to produce greater amounts of biomass, but at higher prices. Information such as this is important because it indicates something about the quality of land in certain areas, especially along the Mississippi River and in some of the corn growing regions of southern Illinois and Indiana. By the same logic, forested areas in the Virginia and North Carolina counties would tend to produce less quanities of biomass.

Discussion and Conclusions

The supply schedule (list of quantities available at certain prices) can be useful as inputs to a geographic information system (GIS). Modeling efforts currently underway using these data include determining optimal hauling distances and transportation routes for SRWC biomass from production location(s) to existing coal-fired power plants in the TVA region. Data needs for assisting in these kinds of decisions as well as decision making about future optimal location of electric power generating plants and other conversion facilities using GIS as a tool may include this supply information by county and information on geographic road location networks. Other information useable by GIS as "overlays" may be digitized maps showing the location of wetlands or other environmentally sensitive areas, major power transmission lines, location of population centers, and location of specific cropland usage areas (Noon 1993).

Extensive EPIC crop simulation modeling of conventional crops provided baseline information on level of fertilizer use, the effect on soil runoff, and evapotransporation levels of plants. This information is useful in determining the environmental effects of growing conventional agricultural crops vs other biomass crops as a landscape alternative. These effects have been outlined and modeled in Graham and Downing (1993) focusing on herbaceous energy crops in particular.

This analysis includes no information about the effect of crop reduction program lands (CRP), livestock production areas, or agricultural reduction program (ARP) lands. In major agricultural areas, these considerations would be important in determining the BEP and for estimating the environmental effects. Data are available on ARP and CRP lands, by farm contract, and could be used in a resource analysis that included a linear program to solve for the optimal quantities of biomass to be produced (English, et al. 1992).

A parallel study is in process to determine the BEP of herbaceous energy crops (HEC) on the same production lands. It would not be determined if SRWC and HEC would be in competition on these lands, but relative BEP and production supply curves could be generated by the same modeling technique. An EPIC simulation module for switchgrass as well as sorghum is available, representing two crops commonly considered as HEC crops.

Risk has been analyzed by McCarl, et al. (1919) to determine the possible presence of risk (in the form of a risk coefficient) assumed by farmers in agriculture. Our analysis does not attempt to attach a risk coefficient, but it is apparent that there is probably some differential price that may have to be added to the BEP in order to actually induce farmers to switch from short rotation conventional agricultural crops to longer rotation biomass crops such as poplar and sweetgum. Further work in this areas is need to assess the particular associated risk coefficient associated with these trade-offs.

Further analyses needed relate to the nonmarket benefits that may accrue to society regarding the growing of biomass in lieu of agricultural crops. This has to do with the environmental analysis (Graham and Downing 1993) but considers some very important trade-offs to do with the environmental degradation and costs and benefits to society (Downing and Graham 1993).

Our analysis takes into account only the supply side of SRWC production of biomass for conversion to electricity. The other side of the total analysis would be from the demand side, where demand for biomass wood could be derived to establish an equilibrium price in the options for trade-offs for energy inputs.

Acknowledgements

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Economic Modeling Approach

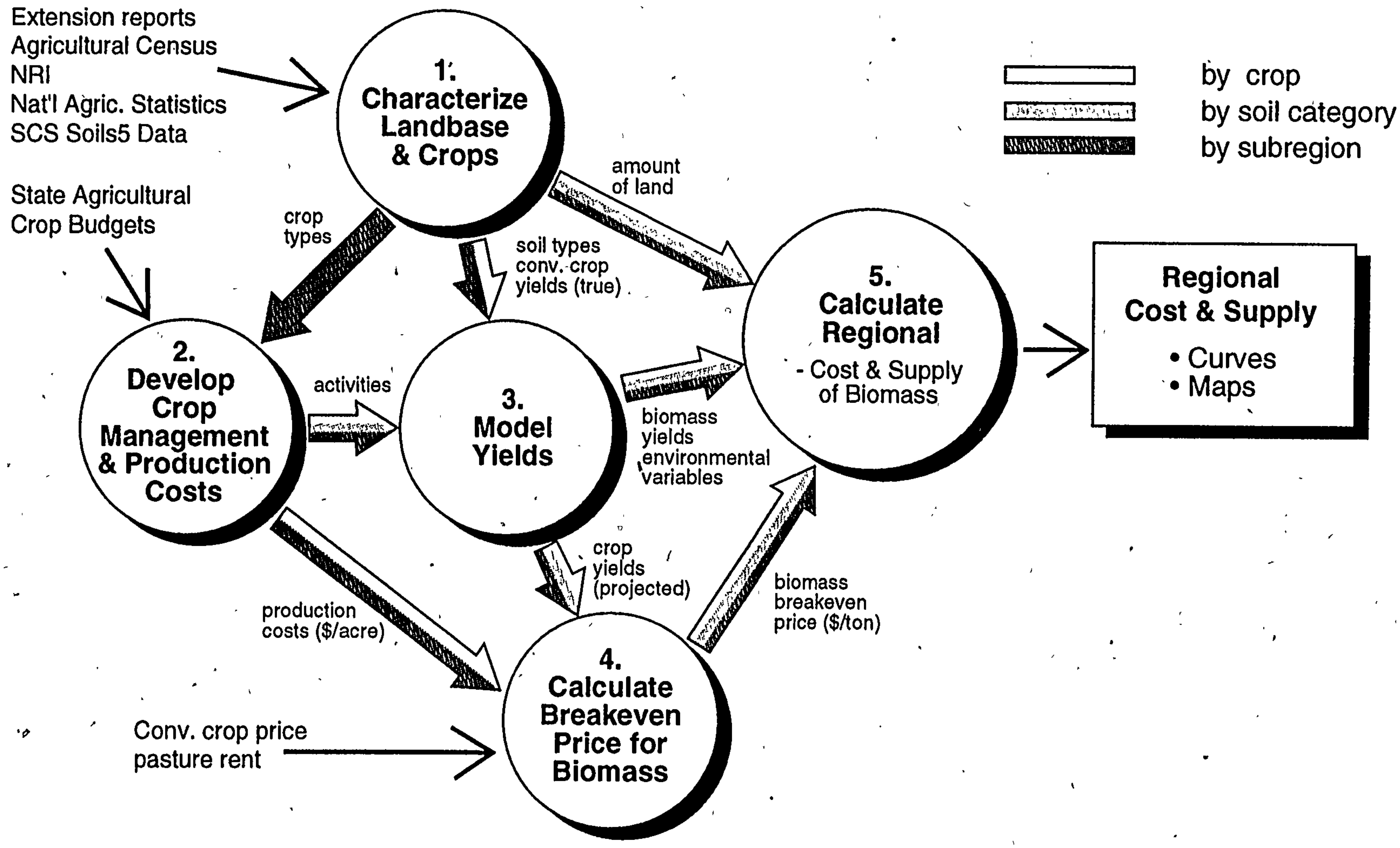

Figure 1 - Economic Modeling Approach

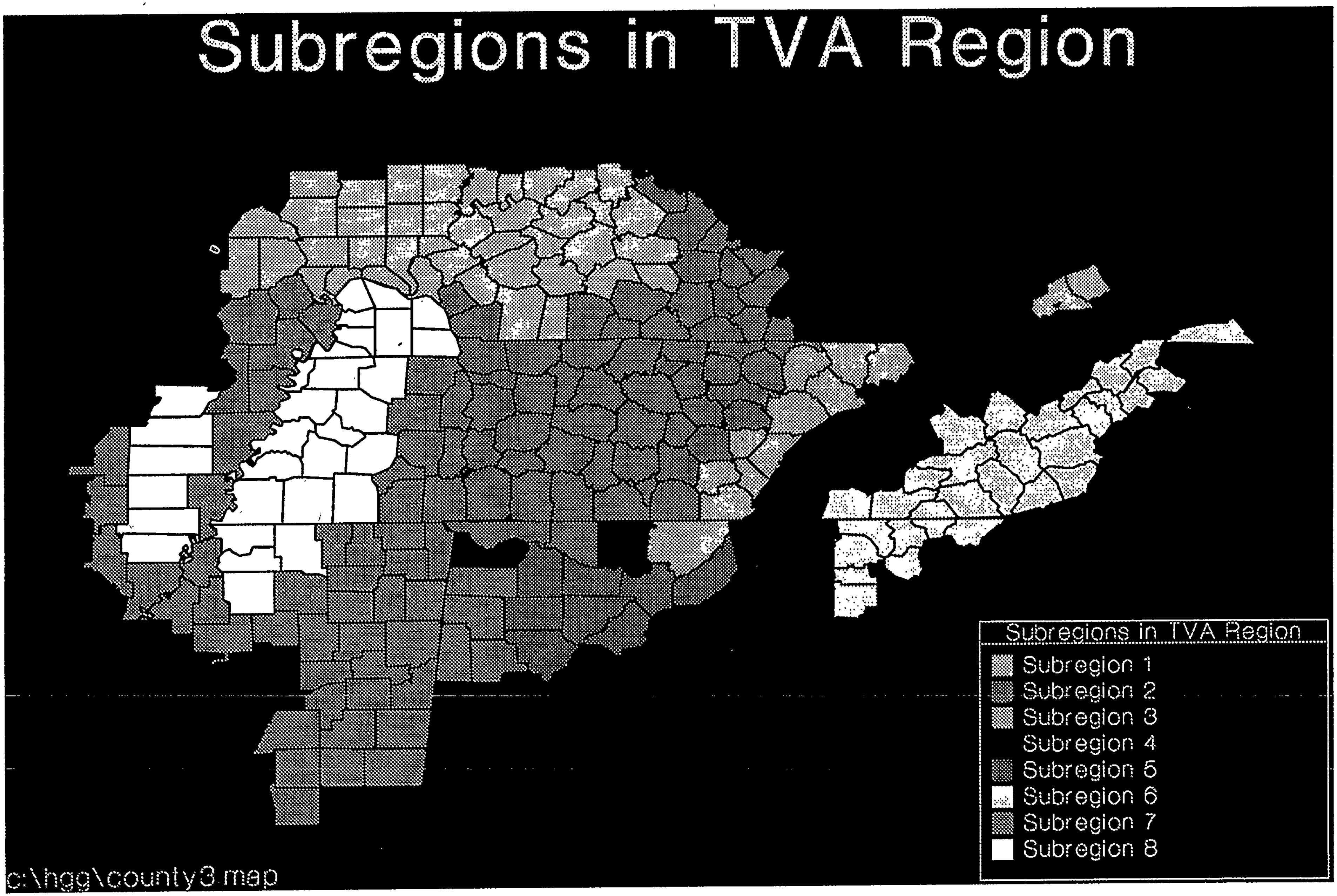

Figure 2 - Subregions in the TVA Region

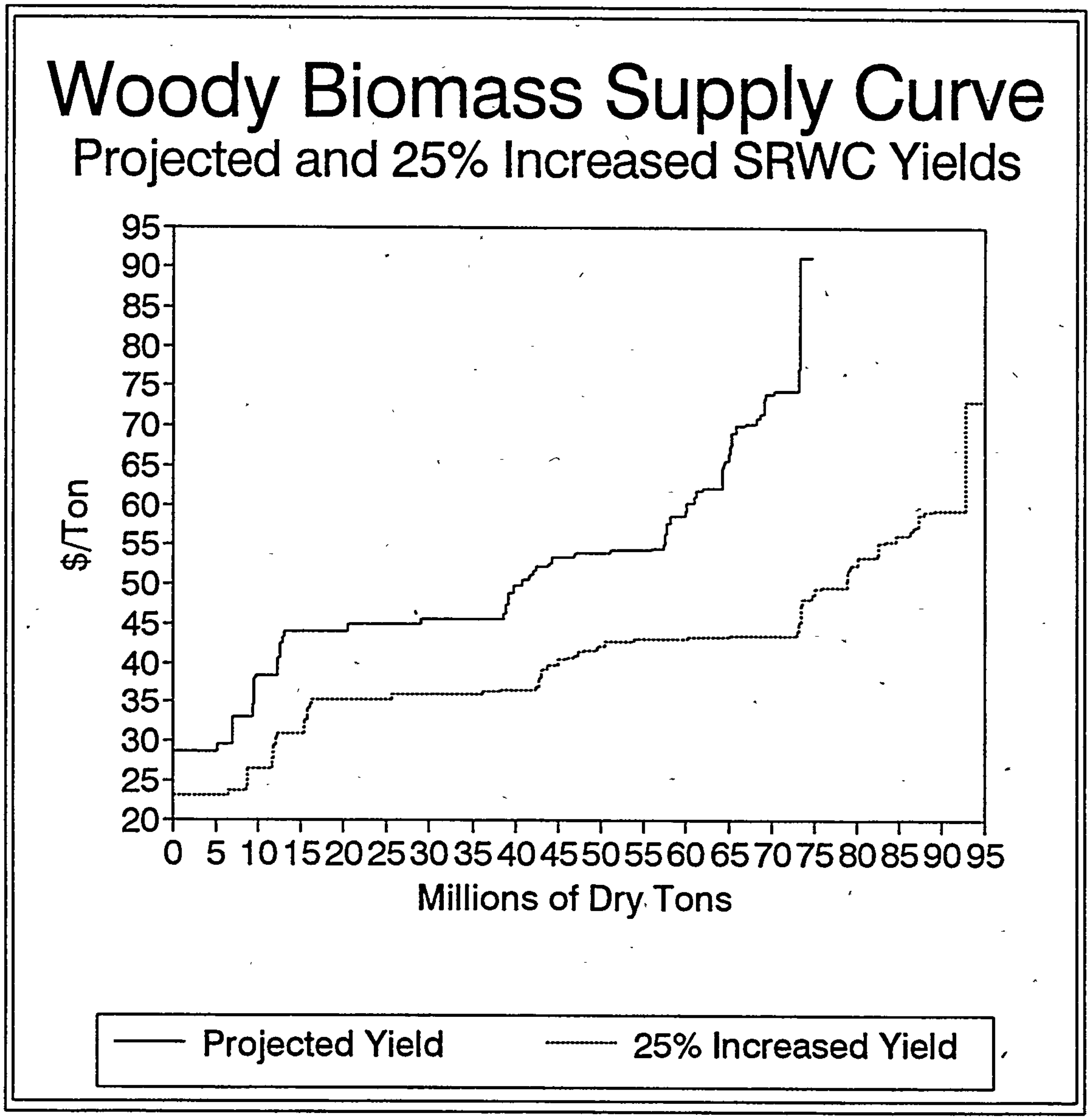

Figure 3 - Woody Biomass Supply Curves in $/Ton

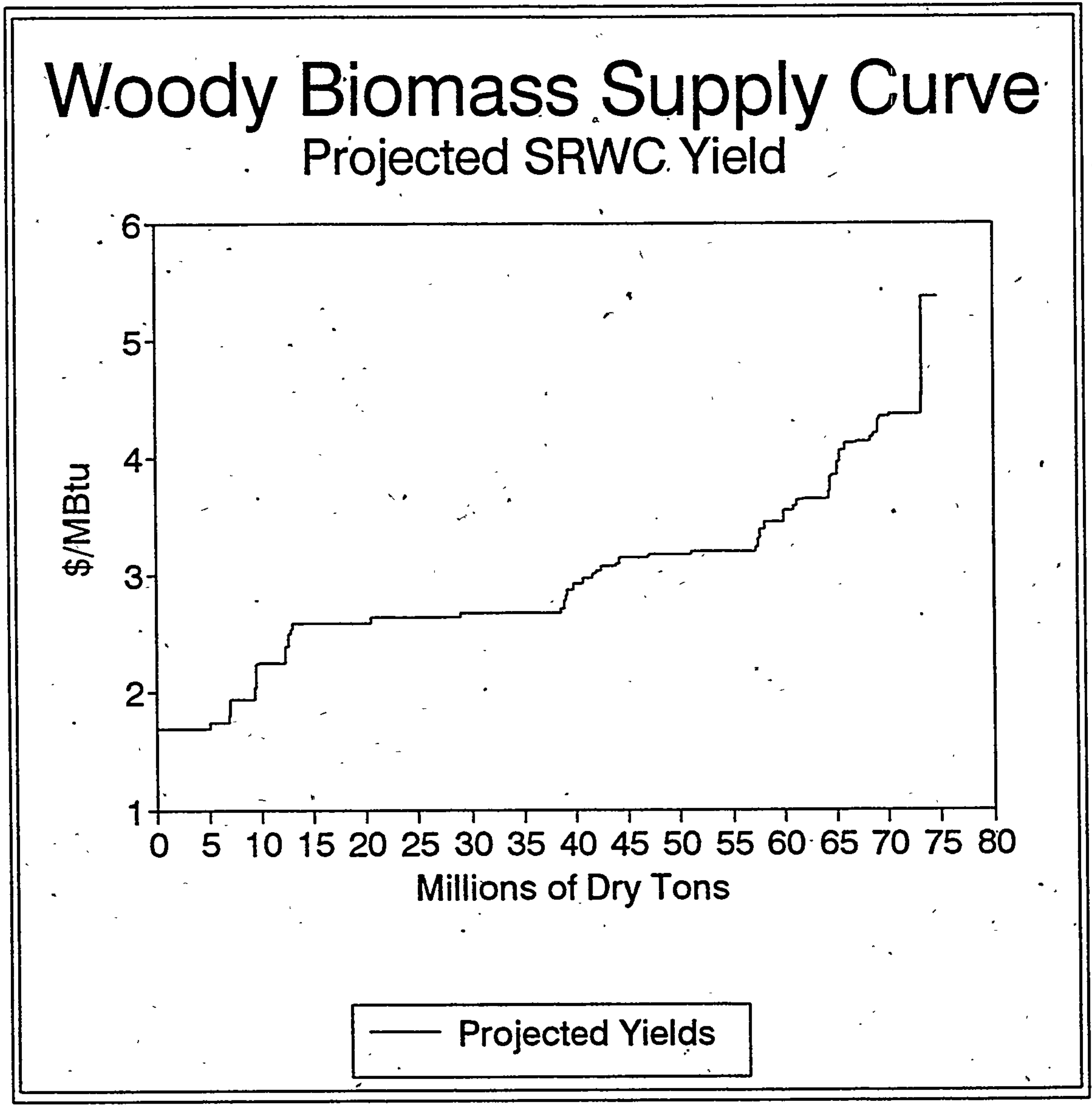

Figure 4 - Woody Biomass Supply Curve in $/MBtu

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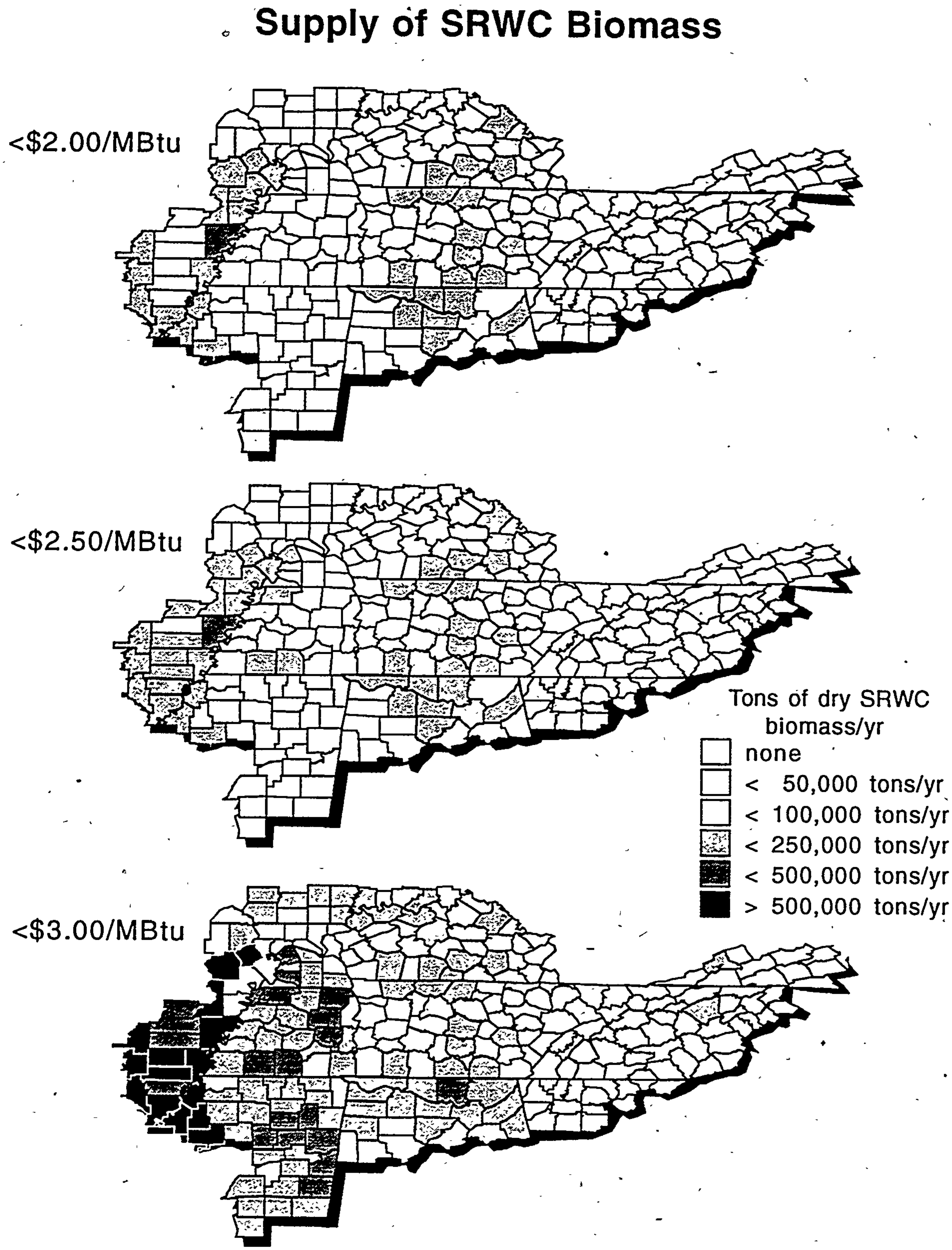

Figure 5 - Regional Maps of Biomass Distribution in Tons of Biomass by $/MBtu

SHORT-ROTATION FORESTRY FOR ENERGY PRODUCTION IN HAWAII

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Abstract

In Hawaii, imports of fossil fuels continue to accelerate and now provide over 90% of the total energy supply at a cost exceeding \$1 x 10^9 annually exported from the local economy. Concurrently, sugarcane and pineapple crops, the traditional mainstays of the state's economy, have declined such that as much as 80,000 hectares of agricultural land are now available for alternative land uses. The feasibility of short-rotation forestry for sustainable energy production on these former sugarcane and pineapple plantation lands is being evaluated using species- and site-specific empirical models to predict yields of *Eucalyptus grandis*, *E. saligna*, and *Leucaena leucocephala*, a system model to estimate delivered costs, and a geographic information system to extend the analysis to areas where no field trials exist and to present results in map form. The island of Hawaii is showcased as an application of the methodology. Modeling results of methanol, ethanol, and electricity production from tropical hardwoods are presented. Short-rotation forestry appears to hold promise for the greening of Hawaii's energy system and agricultural lands for the benefit of the state's citizens and visitors. The methodology is readily transferable to other regions of the United States and rest of the world.

As traditional plantation crops such as sugarcane and pineapple continue to decline in Hawaii, landowners and other decision-makers are considering short-rotation forestry for energy production as an alternative enterprise. To provide useful information to interested parties, our research team at the University of Hawaii developed a decision support system featuring three integrated components: (1) empirical SRIC yield models of three promising tropical hardwoods, *Eucalyptus grandis, E. saligna,* and *Leucaena leucocephala,* constructed using growth data, site characteristics, and management variables from field trials in Hawaii; (2) a SRIC biomass system model of production costs, including establishment, maintenance, harvesting, transport, and storage; and (3) a geographical information system to extend the analysis to areas where no field trials exist and to enhance the communication of results visually (Phillips *et al.*, 1993). In this paper, three sites on the island of Hawaii were analyzed using the above methodology to estimate yield and delivered cost of feedstocks for conversion to ethanol, methanol, and electricity. Estimates of capital, O&M, feedstock, and production costs at the plant gate ($/liter and $/kWh) are presented for one site.

Because *E. saligna* demonstrated the highest yields and lowest delivered costs at all three sites modeled, we present results for only this species. Using an optimum SRIC management strategy of approximately 7 m^2 of growing space and 7 years of age at harvest for Hilo coast *E. saligna* plantations, the average cost of chips delivered to a bioconversion facility located at Pepeekeo is ≈ $36/dry Mg (Fig. 1). A potential biomass supply curve of *E. saligna* from the Hilo coast indicates that 200,000 dry Mg/year could be produced at ≈ $36/dry Mg (Fig. 2). Yield (dry Mg) and cost estimates ($/dry Mg) of delivered chips were calculated for three sites on the island of Hawaii. The Hilo coast site was the most productive one modeled and could provide more than 1,600,000 dry Mg over 7 years with most of the feedstock costing under $35/dry Mg (Tables 1 and 2). Hilo coast *E. saligna* yield and delivered cost maps are showcased in Figs. 3 and 4.

Table 1. Potential SRIC Production E. saligna Based on Optimized Management Strategy at Three Sites on the Island of Hawaii.

	Hamakua coast[a]		Hilo coast[a]		Ka'u[b]	
Yield Range (dry Mg/ha)	Area (ha)	Biomass Production (10^3 dry Mg)	Area (ha)	Biomass Production (10^3 dry Mg)	Area (ha)	Biomass Production (10^3 dry Mg)
< 100	1,322	108	22	2	4,524	253
100 - 150	1,852	231	1,830	238	501	58
150 - 200	1,859	320	5,468	975	14	2
> 200	2,745	725	2,113	449	741	265
Total	7,778	1,384	9,433	1,664	5,780	578
Average Yield	178 (dry Mg/ha)		176 (dry Mg/ha)		100 (dry Mg/ha)	

[a] Growing space = 7 m^2, rotation age = 7 years, nitrogen fertilizer application = 0.15 kg/tree;
[b] Growing space = 12 m^2, rotation age = 9 years, nitrogen fertilizer application = 0.15 kg/tree.

Table 2. Cost Estimates of E. saligna Chips Delivered to Specific Bio-conversion Plants on the Island of Hawaii.

Cost Range	Hamakua coast plantations to Hamakua Sugar Co. mill at Haina (15 km)[a]	Hilo coast plantations to Hilo Coast Processing Co. mill at Pepeekeo (11 km)	Ka'u plantations to Ka'u Agribusiness Co. mill at Pahala (15 km)
($/dry Mg)		(10^3 dry Mg/yr)[b]	
≤ 35	98	114	25
35 - 40	24	57	1
> 40	46	31	29

[a] Average distance from plantations to mill; [b] includes 15% feedstock handling and storage loss.

These feedstock results were then used with specific bioconversion processes for estimating the costs of manufacturing energy products at a plant capacity of 95 x 10^6 liters per year (25 x 10^6 gallons per year) for ethanol and methanol fuels and 25 MWe for electricity. The technology and assumptions for each of the bioconversion processes used to estimate costs are described by Hohmann and Rendleman (1993) for ethanol, Wyman *et al.* (1993) for ethanol and methanol, and the U. S. Department of Energy (1992) for electricity. Preliminary levelized cost estimates are $0.32/liter for ethanol, $0.21/liter for methanol, and $0.071/kWh for electricity (Table 3). Short-rotation forestry for energy production appears to hold promise for the greening of Hawaii's energy system and agricultural lands.

Table 3. Cost Estimates of Biomass Energy Products Manufactured at a Hypothetical Bioconversion Facility at Pepeekeo, Hawaii.

	Energy Product		
Cost Estimates[a]	Ethanol[b]	Methanol[c]	Electricity[d]
		(10^6 $)	
Capital costs	56.2	55.0	38.2
O & M costs	7.7	7.9	2.2
Feedstock costs	9.1	4.4	3.3
Levelized cost	$0.32/liter ($1.21/gallon)	$0.21/liter ($0.80/gallon)	$0.071/Kwh

[a] 1991 US $; [b] simultaneous saccharification and fermentation system, capacity = 95 x 10^6 liters per year; [c] low-pressure indirect gasifier with hot-gas conditioning and MEOH synthesis, capacity = 95 x 10^6 liters per year; [d] fixed-bed gasifier coupled to open cycle turbine, capacity = 25 MWe.

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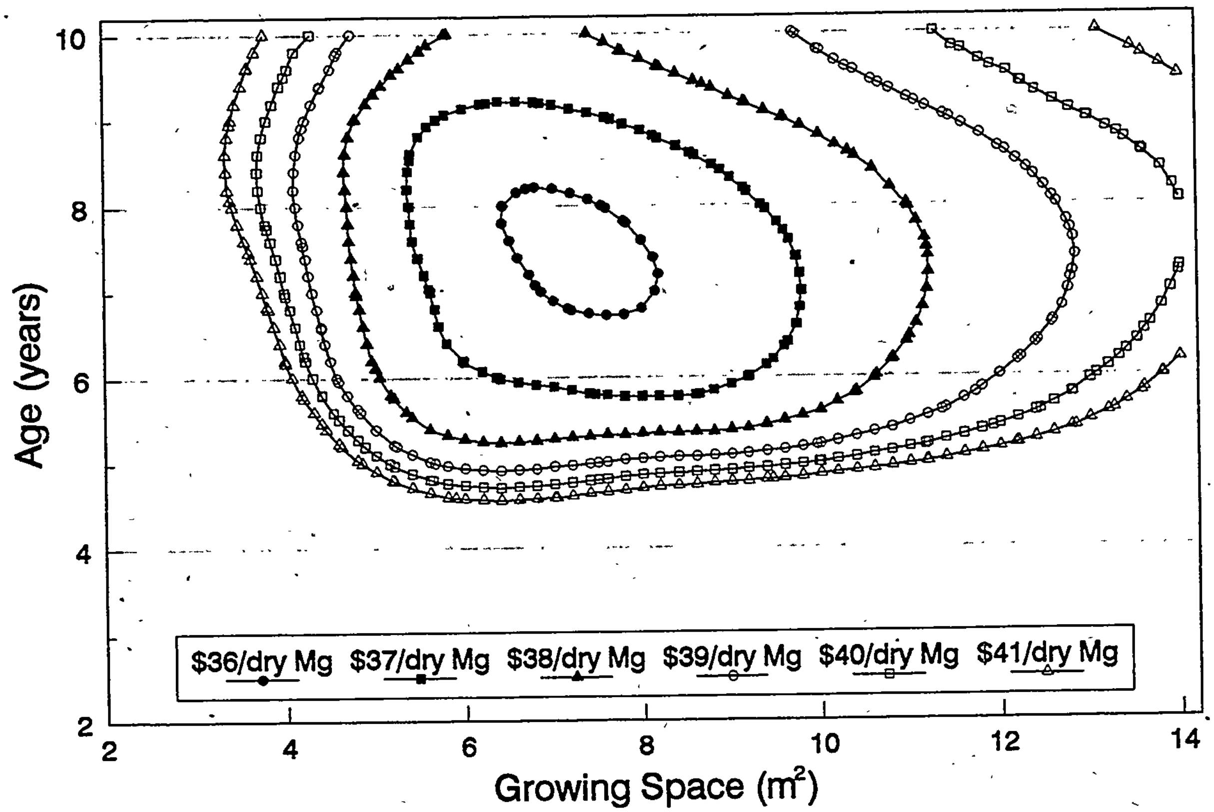

Fig. 1. Optimum SRIC management strategy for *Eucalyptus saligna* plantations, Hilo coast, Hawaii.

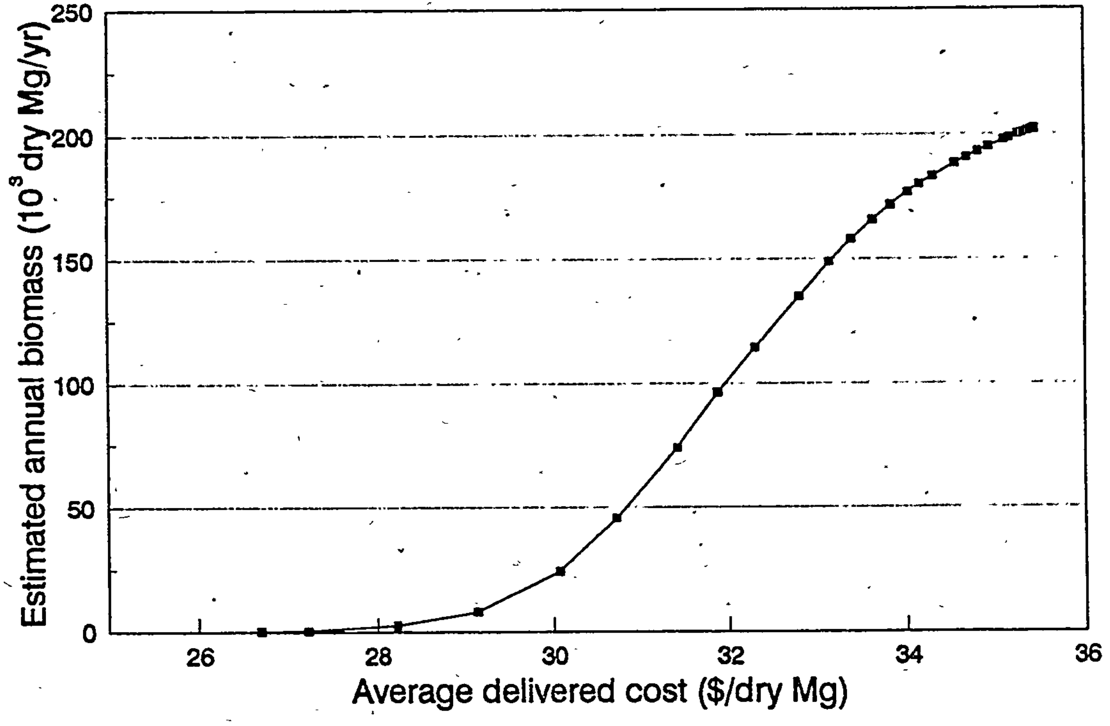

Fig. 2. Potential biomass supply curve of *Eucalyptus saligna* based on optimized management strategy for Hilo coast plantations with delivery of chips to Hilo Coast Processing Co. mill at Pepeekeo, Hawaii.

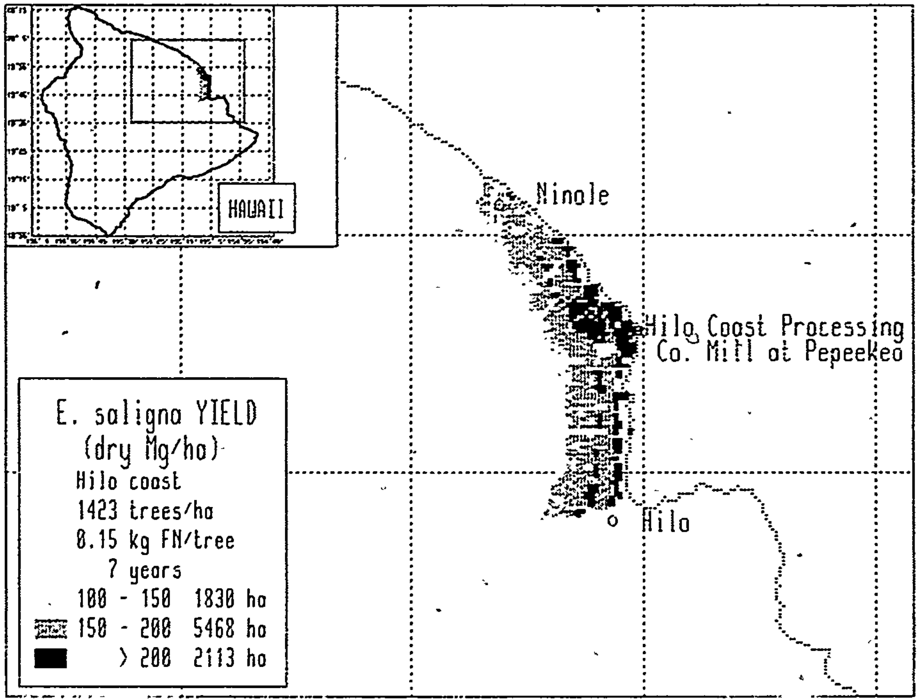

Fig. 3. Estimated *Eucalyptus saligna* yield based on optimized management strategy, Hilo coast plantations, Hawaii.

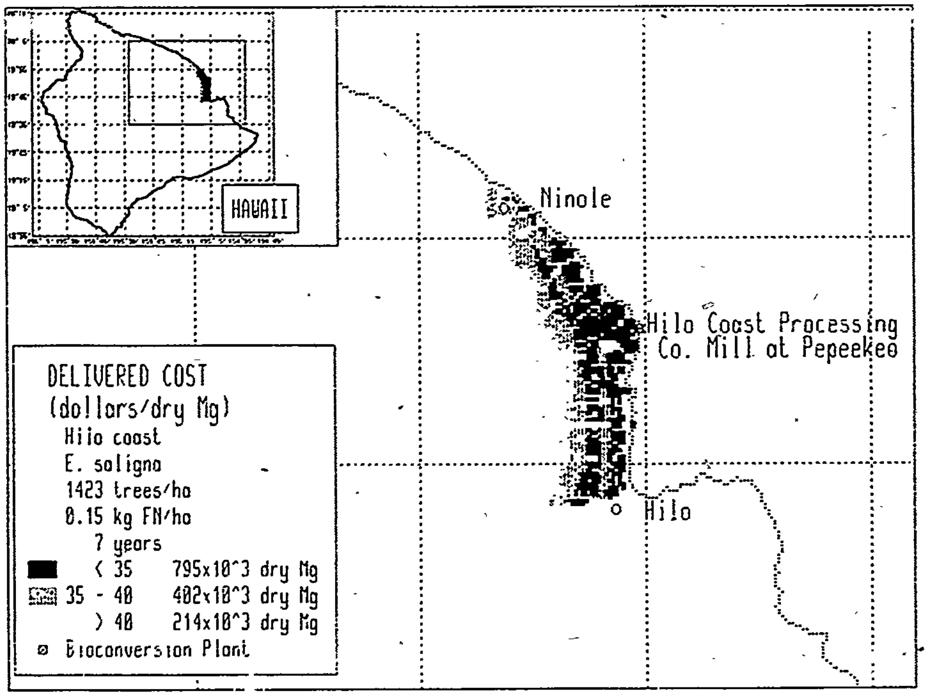

Fig. 4. Cost estimates of *Eucalyptus saligna* chips delivered from Hilo coast plantations to Hilo Coast Processing Co. mill at Pepeekeo, Hawaii.

TVA GIS-BASED BIOMASS RESOURCE ASSESSMENT

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Abstract

The focus of this paper is a computer-based system for estimating the costs of supplying wood fuel. The system is being developed for the Tennessee Valley Authority and is referred to as the Biomass Resource Assessment Version One (BRAVO) system. The main objective in developing the BRAVO system is to assist TVA in estimating the costs for supplying wood fuel to any one of its twelve coal-fired power plants. The BRAVO system is developed within a Geographic Information System (GIS) platform and is designed to allow a user to perform "what if" analyses related to the costs of wood fuel supply. Three types of wood fuel are considered in the BRAVO system: mill residues, logging residues and short-rotation woody crops (SRWC). Each type of wood fuel has unique economic and supply characteristics. The input data for the system includes the specific locations, amounts, and prices of the various types of wood fuel throughout the TVA region. The system input is completed by data on political boundaries, power plant locations, road networks and a model for estimating transportation costs as a function of distance. The result is a comprehensive system which includes information on all possible wood fuel supply points, demand points and product movement costs. In addition, the BRAVO system has been designed to allow a user to perform sensitivity analysis on a variety of supply system parameters. This will enable TVA to thoroughly investigate the financial impacts of issues such as increased competition for wood fuel, environmental policies, fuel taxes, and regional economic cycles.

For logging residues, we assume future logging practices will be similar to recent practices with respect to general location, terrain, type of harvest and potential for residues. The estimated logging residue amounts are computed from U.S. Forest Service data and assigned to forest plot locations with each plot location representing approximately 5000 acres. Figure 2 displays the plot point locations for the Colbert 40-mile radius. The prices associated with logging residues represent estimates of the incremental cost to a logger to recover residues during merchantable tree harvests.

The data for the short-rotation woody crops (SRWC) is provided by the Energy Crop Development Program at Oak Ridge National Laboratory. For each county, a cost/supply curve is developed which gives the quantities available within the county at specific price intervals. The prices represent payment levels necessary to induce a farmer to produce SRWC in place of conventional crops.

The system input is completed by data on political boundaries, power plant locations, road network and a model for estimating transportation costs as a function of distance. The road network is a digitized version of TVA's 1:633,000 scale regional wall map. Figure 3 shows the road network over the Colbert 40-mile radius. BRAVO is designed to run on a UNIX-based workstation. The system procedures and user interface are written in ARC Macro Language (AML) which is part of the GIS software ARC/INFO, a product of Environmental Systems Research Institute (ESRI).

System Usage

With the input data, BRAVO is a comprehensive system which includes information on all possible wood fuel supply points, demand points and product movement costs. With this information, the system can then estimate the total costs to supply a power plant with varying levels of wood fuel. Figure 4 displays an example output. The chart shows the marginal and average cost curves for supplying wood fuel to a particular location. Obviously, the marginal cost per dry ton increases along with an increase in demand at a particular location. However, the rate of marginal cost increase is highly demand location dependent within the TVA region.

In addition, the system is designed to allow a user to easily specify and analyze "what if" scenarios with respect to supply, demand and transportation costs. For example, the user can specify that only half of the potential logging residues are available and that mill residues can be obtained only from large mills. As another example, the user can specify a $.50 per gallon tax on diesel fuel and examine its effects on total cost and procurement. From its inception, the BRAVO system has been designed to allow a user to perform sensitivity analysis on a variety of supply system parameters. This will enable TVA to thoroughly investigate the financial impacts of issues such as increased competition for wood fuel, environmental policies, fuel taxes, and regional economic cycles. Finally, the BRAVO system is designed to be methodologically portable and expandable. Additional resource layers or alternate transportation networks can be readily incorporated into the system.

Background and Motivation

The focus of this paper is a computer-based system for estimating the costs of supplying wood fuel. The system is being developed for the Tennessee Valley Authority and is referred to as the Biomass Resource Assessment Version One (BRAVO) system. The main objective in developing the BRAVO system is to assist TVA in estimating the costs for supplying wood fuel to any one of its twelve coal-fired power plants which are located in Tennessee, Kentucky, and Alabama. Burning wood in lieu of coal has the advantages of reducing sulphur-dioxide emissions and helping decrease the flow of wood residue into landfills. TVA's short-term strategy for using biomass as an energy resource includes cofiring wood at a coal-fired plant rather than construction of a new, dedicated wood-burning facility. The cofiring strategy will allow TVA to gain experience in wood procurement, handling, and combustion without excessive capital risk. In addition, the cofiring facility can be easily reconverted into coal-only which protects TVA during periods of unfavorable wood fuel supply.

The task of estimating wood fuel costs is particularly challenging due to the fact that wood fuel is not an established commodity and that wood fuel availability and price are often dependent on conditions that are external to TVA. In contrast to conventional fossil fuels, geographic proximity to supply is a main determinant in the cost of wood fuel at a power plant. For example, the cost per MBtu-mile for transporting wood is three times that of coal based on weight alone. As a consequence, BRAVO is being developed within a Geographic Information System (GIS) platform. The GIS platform allows for the efficient storage, retrieval and display of data and results. Further, the GIS platform allows analysis to be performed on transportation networks so that accurate estimates of hauling distances and costs can be determined.

System Design

The system is designed to estimate the total purchase and transportation costs of wood fuel under various levels of demand. Three types of wood fuel are considered in the BRAVO system: (1) mill residues, (2) logging residues and (3) short-rotation woody crops (SRWC). Each of the three types of wood fuel has unique economic and supply characteristics. The system considers mill residues as any unused bark, fines, shavings, etc... available from either primary (lumber mills, paper mills) or secondary (eg., furniture manufacturers) industries. Logging residues are defined as tree crowns, tops, or boles that would otherwise be left on-site during a logging operation. Short-rotation woody crops are intensive culture woody crops which are grown on land that would otherwise be used for growing traditional agricultural crops.

The data for mill and logging residues is provided by TVA's Forest Resources Program. For each primary or secondary mill in a seven state region, the data includes the mill location and the quantity, type and current usage of wood residues. As an example, Figure 1 displays the counties and mill locations within a 40-mile radius of TVA's Colbert Steam Plant (denoted by a star) located in the northwest corner of Alabama. Mill residue prices are based on Timber Mart-South estimates.

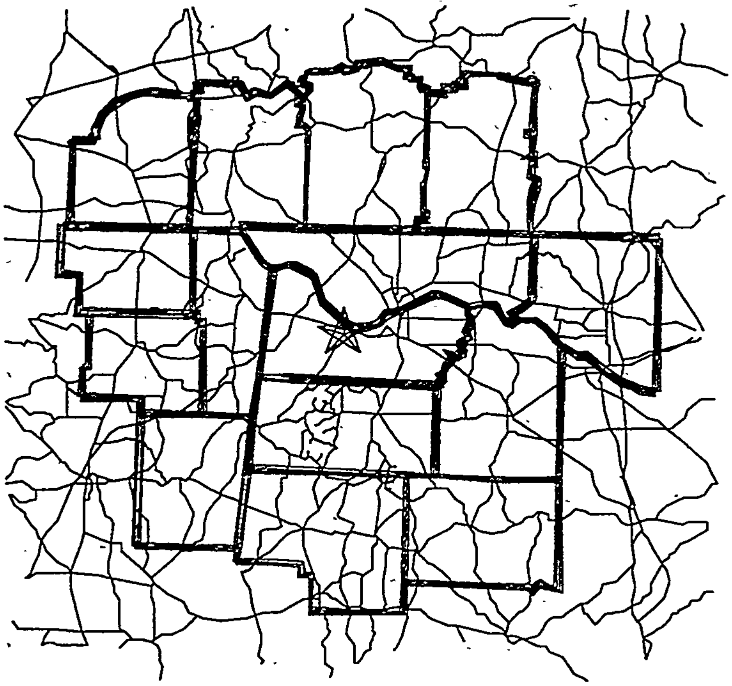

Figure 3. Road network for Colbert procurement zone.

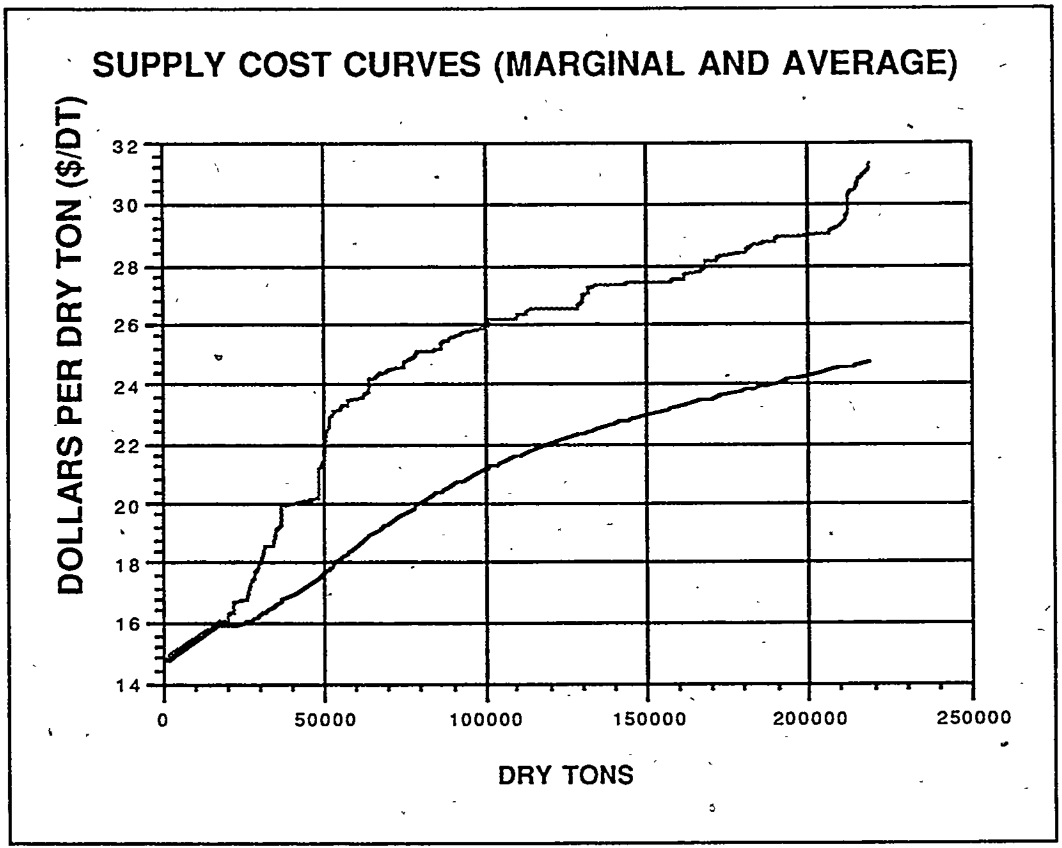

Figure 4. Example supply cost curves (top curve is marginal).

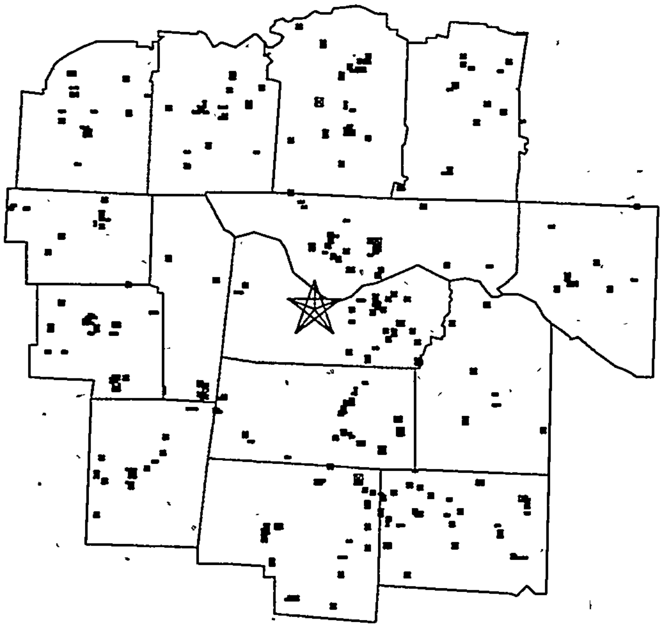

Figure 1. Counties and mills for Colbert 40-mile procurement zone.

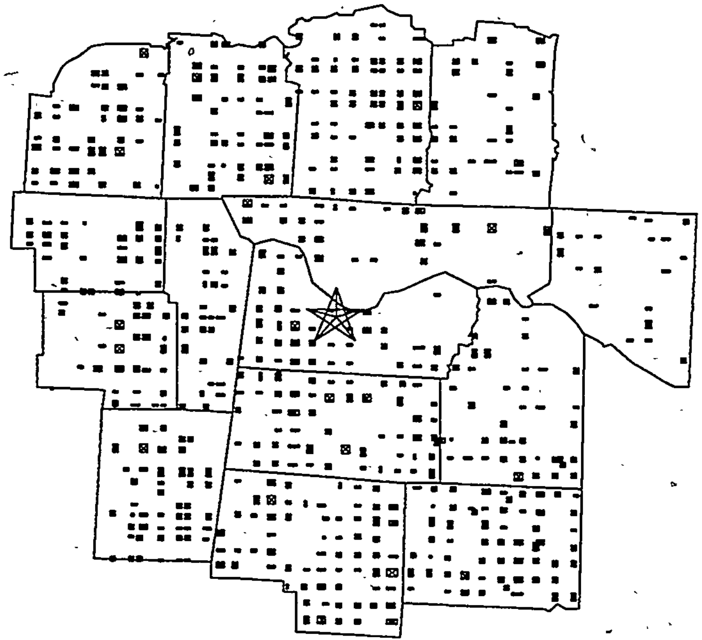

Figure 2. Forest plot locations for Colbert procurement zone.

Introduction

This paper provides estimates of the amount of woody biomass that is present on timberland in the Southern United States--the 12 States from Virginia to Texas. Interest in the woody biomass of the South is high for several reasons. First, this region is rapidly becoming the most important in the Nation for timber production. Tree growth is relatively rapid and major markets for timber and paper products are nearby. Second, the rapidly growing economies of Southern States provide promising markets for woody biomass that is unsuitable for traditional wood products.

The estimates presented here are based on the most recent published data from the statewide forest inventories that are conducted by the Forest Inventory and Analysis (FIA) Units at the Southern and Southeastern Forest Experiment Stations. Inventories of the individual States were completed between 1987 and 1993. The published data sources are included in the list of references.

General Resource Description

Land area in the 12 Southern States totals 329 million acres. About 185 million acres (56.2%) are classed as timberland. Alabama, Georgia, South Carolina, and Virginia have more than 60% of their land area classed as timberland while Florida has the lowest (43.2%) (table 1).

Table 1. Total Land and Commercial Timberland Area for 12 Southern States

State	Total area	Commercial timberland	Proportion in timberland
	- - - Thousand	acres - - -	- - Percent - -
Alabama	32,491.3	21,932.0	67.5
Arkansas	33,320.0	17,246.6	51.2
East Oklahoma	10,103.8	4,895.5	48.4
East Texas	22,192.1	11,565.3	52.1
Florida	34,652.8	14,982.6	43.2
Georgia	37,140.5	23,631.2	63.6
Louisiana	26,265.4	13,782.8	52.5
Mississippi	30,228.9	16,981.6	56.2
North Carolina	31,228.2	18,710.4	59.9
South Carolina	19,320.6	12,178.8	63.0
Tennessee	26,447.0	13,265.2	50.2
Virginia	25,409.8	15,447.6	60.8
South	328,800.4	184,619.6	56.2

Nonindustrial private landowners, which include farmers and other private individuals who do not engage in forest products manufacturing, own two-thirds of the South's timberland (table 2). Forest industry owns 23% of the timberland acreage. In terms of industry holdings, Georgia, Alabama, and Florida rank first, second, and third.

Table 3 shows the division of each Southern States' timberland among major forest types. Ninety percent of the timberland is in four forest types: 35% is in oak-hickory, 25% is in loblolly-shortleaf pine, 15% is in oak-pine, and 15% is in oak-gum-cypress. In terms of stand-size classes, 44% of the South's timberland is occupied by sawtimber stands, 27% by poletimber stands, and 27% by sapling-seedling stands (table 4). Two percent of timberland is classes as nonstocked.

FOREST BIOMASS AND ENERGY-WOOD POTENTIAL IN THE SOUTHERN UNITED STATES

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Abstract

Timber resource data were compiled from the most recent USDA Forest Service inventory data for the 12 Southern States from Virginia to Texas. Timber resource inventories traditionally include only trees 5 inches dbh and greater and their volumes to the prevailing merchantable top diameter expressed in cubic feet, board feet, or cords. For this paper, conversion factors were developed to express timber inventories in weight and to expand the inventories to include the crowns of merchantable trees and trees less than 5 inches dbh. By so doing, the total aboveground biomass is estimated for the timberlands in the South.

The region contains 185 million acres of timberland. Some 14.6 billion green tons of woody biomass are present on southern timberland--about 79 tons per acre. When mature stands are harvested, the average acre in the South has 22.2 tons of woody material left in crowns and sapling, and 5.1 tons in cull stems. Thus, an average of 27.3 green tons per acre of potential energy wood are left after conventional harvests. Conversion factors that are presented permit estimates for specific tracts, areas, counties, or states.

Estimating Biomass

Reports of timber inventories have traditionally included only trees 5 inches dbh and greater and their volumes to the prevailing merchantable top diameter expressed in cubic feet, board feet, and cords. For the purpose of this report, conversion factors were developed to express timber inventories in weight (CF-1) and to expand the inventories to include the crowns of merchantable trees (CF-2) and trees less than 5 inches dbh (CF-3). By so doing, the total aboveground biomass was estimated for trees greater than 1-inch dbh in the Southern region. Conversion factors used are as follows:

CF-1. Green weight of wood and bark per cubic foot of wood

Softwoods = 73 lbs/cu.ft.
Soft Hardwoods = 71 lbs/cu.ft.
Hard Hardwoods = 83 lbs/cu.ft.

CF-2. Crown percent in trees greater than 5.0 inches dbh

	Sawtimber	Poletimber
Softwoods =	15%	25%
Soft Hardwoods =	18%	30%
Hard Hardwoods =	25%	35%

CF-3. Percent of total cubic foot volume in trees less than 5.0 inches dbh

Softwoods = 10%
Soft Hardwoods = 17%
Hard Hardwoods = 16%

Conversion factors 1 and 2 are based on total-tree weight and volume data collected at this laboratory from over 6,000 trees of the major species in the South. These data are published in numerous individual species or species group reports and summarized largely in the following reports. (Saucier et al., 1981 and Clark et al., 1986). Conversion factor 3 was derived from forest inventory data collected by the Forest Inventory and Analysis Unit of the Southeastern Station found in the references listed.

Results

The estimates of the total Southern timber resource are presented in table 5 and on a per-acre basis in table 6. The estimates are given for each of the 12 Southern region States and by the species group categories of softwoods, hard hardwoods, and soft hardwoods. Table 5 shows that the 185 million acres of commercial forest land in the Southern region contain 14.6 billion green tons of woody biomass. North Carolina and Georgia lead with 1.8 billion tons each, followed by Virginia, with 1.6 billion tons.

Average amounts of biomass per acre vary considerably by state. Commercial forest lands of Virginia have the highest average per-acre biomass, with 103.0 green tons, while East Oklahoma is lowest, with 45.8 green tons (table 6). Four factors obviously influence the biomass of a forest acre: age, stocking, species composition, and site productivity. The average biomass per acre in the Southern region is 79.3 green tons.

Estimates of biomass fuel can be made from data in table 6. For example, in the final harvest, the average acre in the Southern region has 22.2 tons of crown material and saplings, and 5.1 tons of cull stems, for a total of 27.3 green tons of potential energywood. Estimates for specific tracts can be made if the merchantable volume in cubic feet is known by application of the conversion factors used in this analysis.

Table 2. Area of Commercial Timberland by Ownership for 12 Southern States

State	Total commercial timberland	National forest	Other public	Forest industry	Farmer	Other private
	- - - - - - - - - - - - Thousand acres - - - - - - - - - - - -					
Alabama	21,932.0	605.4	556.7	5,499.5	4,764.6	10,505.8
Arkansas	17,246.6	2,296.8	778.8	4,376.3	2,926.0	6,868.7
East Oklahoma	4,895.5	222.7	359.5	1,047.3	1,097.1	2,169.0
East Texas	11,565.3	610.3	152.7	3,820.8	1,369.8	5,611.7
Florida	14,982.6	990.2	1,452.9	5,446.4	1,114.9	5,978.2
Georgia	23,631.2	751.8	893.6	5,870.1	4,877.7	11,238.0
Louisiana	13,782.8	495.7	743.1	4,472.1	724.9	7,346.9
Mississippi	16,981.6	1,212.1	707.2	3,332.9	4,171.5	7,557.9
North Carolina	18,710.4	1,082.4	920.3	2,420.4	5,041.9	9,245.5
South Carolina	12,178.8	576.5	596.8	2,706.6	3,136.4	5,162.5
Tennessee	13,265.2	556.0	953.0	1,143.9	3,848.9	6,763.4
Virginia	15,447.6	1,468.1	515.2	1,554.8	3,870.4	8,039.1
South	184,619.6	10,868.0	8,629.8	41,691.1	36,944.1	86,486.7

Table 3. Area of Commercial Timberland by Forest Type for 12 Southern States

State	All species	Loblolly-shortleaf pine	Oak-pine	Oak-hickory	Oak-gum-cypress	Longleaf-slash pine	Other hardwood types	Other softwood types
	- - - - - - - - - - - - - - - - Thousand acres - - - - - - - - - - - - - - - -							
Alabama	21,932.0	6,259.9	4,521.8	7,661.4	2,258.9	1,197.5	16.3	16.2
Arkansas	17,246.6	4,185.4	3,049.9	7,264.6	2,582.5	-	164.2	-
East Oklahoma	4,895.5	1,098.6	702.2	2,590.8	409.9	-	94.0	-
East Texas	11,565.3	3,936.7	2,401.8	3,369.3	1,519.1	279.9	58.5	-
Florida	14,982.6	1,376.6	1,210.8	1,890.4	4,271.1	6,149.9	83.8	-
Georgia	23,631.2	6,833.7	3,063.9	5,917.6	3,245.2	4,178.0	318.4	74.4
Louisiana	13,782.8	4,165.1	1,891.0	2,107.9	4,352.9	849.1	401.8	14.9
Mississippi	16,981.6	3,930.8	3,522.9	5,477.2	3,051.7	841.5	157.5	-
North Carolina	18,710.4	5,604.5	2,580.2	7,008.0	2,490.4	411.1	369.4	246.2
South Carolina	12,178.8	4,656.9	1,543.7	2,644.2	2,300.9	769.6	252.8	10.7
Tennessee	13,265.2	1,333.8	1,591.5	9,476.5	639.3	-	154.4	69.7
Virginia	15,447.6	3,135.8	1,941.2	9,377.1	392.3	-	384.3	216.9
South	184,619.6	46,517.8	28,020.9	64,785.0	27,514.2	14,676.6	2,455.9	564.4

Table 4. Area of Commercial Timberland by Stand Size Classes for 12 Southern States

State	Total commercial timberland	Sawtimber	Poletimber	Sapling and seedling	Nonstocked
	- - - - - - - - - - - - - - Thousand acres - - - - - - - - - - - - - -				
Alabama	21,932.0	7,639.4	5,912.5	8,336.0	44.1
Arkansas	17,246.6	7,450.1	5,769.7	3,830.2	196.6
East Oklahoma	4,895.5	1,496.6	2,004.3	1,394.5	0.0
East Texas	11,565.3	5,715.1	2,813.3	2,778.5	258.4
Florida	14,982.6	4,926.6	3,882.8	4,401.6	1,771.6
Georgia	23,631.2	9,285.4	6,294.3	7,388.5	663.0
Louisiana	13,782.8	8,137.3	2,165.1	3,409.8	70.6
Mississippi	16,981.6	8,116.8	4,203.9	4,458.9	202.0
North Carolina	18,710.4	9,117.2	4,939.1	4,500.9	153.2
South Carolina	12,178.8	5,511.2	3,085.9	3,307.7	274.0
Tennessee	13,265.2	6,521.2	4,397.5	2,340.8	5.7
Virginia	15,447.6	7,599.4	4,710.0	3,034.0	104.1
South	184,619.6	81,516.3	50,178.4	49,181.4	3,743.3

Table 5. Green Weight of Aboveground Tree Biomass (Excluding Foliage) on Commercial Timberland in the South, by State and Species Group --Continued

Southern region by state and species group	Biomass			Growing stock			Cull			Saplings
	Total	Stem	Crown[a]	Total	Stem	Crown	Total	Stem	Crown	Total
	- - - - - - - - - - - - -	- - - -	- - - -	- - - -	Million tons	- - - -	- - - -	- - - -	- - - -	- - - -
Mississippi:										
Softwoods	475.7	372.8	102.9	412.7	356.1	56.6	19.8	16.7	3.1	43.2
Hard hardwoods	511.7	350.0	161.7	353.5	282.0	71.5	87.6	68.0	19.6	70.6
Soft hardwoods	283.7	200.2	83.5	200.3	165.8	34.5	42.2	34.4	7.8	41.2
Total	1,271.1	923.0	348.1	966.5	803.9	162.6	149.6	119.1	30.5	155.0
North Carolina:										
Softwoods	605.1	461.1	144.0	538.7	457.4	81.3	4.4	3.7	0.7	62.0
Hard hardwoods	681.0	459.3	221.7	524.7	410.4	114.3	63.6	48.9	14.7	92.7
Soft hardwoods	561.8	391.7	170.1	447.2	366.4	80.8	31.4	25.3	6.1	83.2
Total	1,847.9	1,312.1	535.8	1,510.6	1,234.2	276.4	99.4	77.9	21.5	237.9
South Carolina:										
Softwoods	446.9	349.8	97.1	401.1	345.4	55.7	5.2	4.4	0.8	40.6
Hard hardwoods	304.6	207.9	96.7	227.8	181.2	46.6	34.8	26.7	8.1	42.0
Soft hardwoods	308.2	218.5	89.7	231.2	192.3	38.9	32.2	26.2	6.0	44.8
Total	1,059.7	776.2	283.5	860.1	718.9	141.2	72.2	57.3	14.9	127.4
Tennessee:										
Softwoods	150.9	117.2	33.7	132.7	113.4	19.3	4.5	3.8	0.7	13.7
Hard hardwoods	716.8	489.6	227.2	556.3	442.0	114.3	61.6	47.6	14.0	98.9
Soft hardwoods	247.3	175.2	72.1	191.5	159.1	32.4	19.9	16.1	3.8	35.9
Total	1,115.0	782.0	330.0	880.5	714.5	166.0	86.0	67.5	18.5	148.5
Virginia:										
Softwoods	320.9	246.1	74.8	287.7	242.7	45.0	4.0	3.4	0.6	29.2
Hard hardwoods	877.3	589.8	287.5	675.5	527.6	147.9	80.8	62.2	18.6	121.0
Soft hardwoods	392.4	274.4	118.0	308.5	252.9	55.6	26.9	21.5	5.4	57.0
Total	1,590.6	1,110.3	480.3	1,271.7	1,023.2	248.5	111.7	87.1	24.6	207.2
Total softwoods	5,342.3	4,152.8	1,189.3	4,739.7	4,060.3	679.4	109.8	92.5	17.4	492.5
Total hard hardwoods	5,867.0	3,980.2	1,841.8	4,321.0	3,409.8	911.2	738.2	570.4	167.8	762.8
Total soft hardwoods	3,426.0	2,407.1	1,018.9	2,585.2	2,129.6	455.6	341.2	277.5	63.7	499.6
Total South	14,635.3	10,540.1	4,050.0	11,645.9	9,599.7	2,046.2	1,189.2	940.4	248.9	1,754.9

[a] Includes total sapling weight.

Table 5. Green Weight of Aboveground Tree Biomass (Excluding Foliage) on Commercial Timberland in the South, by State and Species Group

Southern region by state and species group	Biomass			Growing stock			Cull			Saplings
	Total	Stem	Crown[a]	Total	Stem	Crown	Total	Stem	Crown	Total
	- - - - - - - - - - - - - - - - Million tons - - - - - - - - - - - - - - - -									
Alabama:										
Softwoods	536.4	413.9	122.5	477.0	405.2	71.8	10.5	8.7	1.8	48.7
Hard hardwoods	478.7	320.1	158.6	359.7	279.3	80.4	53.0	40.8	12.2	66.0
Soft hardwoods	295.5	204.6	90.9	229.9	186.2	43.7	22.7	18.4	4.3	42.9
Total	1,310.6	938.6	372.0	1,066.6	870.7	195.9	86.2	67.9	18.3	157.6
Arkansas:										
Softwoods	511.2	402.0	109.2	455.8	394.6	61.2	8.9	7.4	1.5	46.5
Hard hardwoods	622.9	424.0	199.0	469.0	371.4	97.6	68.0	52.6	15.4	85.9
Soft hardwoods	182.6	129.1	53.5	139.3	114.9	23.7	17.5	14.2	3.3	26.5
Total	1,316.7	955.1	361.7	1,064.1	880.9	182.5	94.4	74.2	20.2	158.9
East Oklahoma:										
Softwoods	73.7	52.4	21.3	65.2	50.9	14.3	1.8	1.5	0.3	6.7
Hard hardwoods	129.3	85.7	43.6	70.4	54.1	16.3	41.1	31.6	9.5	17.8
Soft hardwoods	21.8	15.1	6.7	13.1	10.7	2.4	5.5	4.4	1.1	3.2
Total	224.8	153.2	71.6	148.7	115.7	33.0	48.4	37.5	10.9	27.7
East Texas:										
Softwoods	409.6	321.8	87.8	358.4	310.0	48.4	14.0	11.8	2.2	37.2
Hard hardwoods	267.4	182.6	84.8	167.3	133.4	33.9	63.2	49.2	14.0	36.9
Soft hardwoods	119.9	84.2	35.7	81.1	66.8	14.3	21.4	17.4	4.0	17.4
Total	796.9	588.6	208.3	606.8	510.2	96.6	98.6	78.4	20.2	91.5
Florida:										
Softwoods	477.4	370.0	107.4	427.1	364.2	62.9	6.9	5.8	1.1	43.4
Hard hardwoods	220.8	151.0	69.8	130.4	104.6	25.8	60.0	46.4	13.6	30.4
Soft hardwoods	218.9	154.6	64.3	161.9	134.2	27.7	25.2	20.4	4.8	31.8
Total	917.1	675.6	241.5	719.4	603.0	116.4	92.1	72.6	19.5	105.6
Georgia:										
Softwoods	790.1	615.3	174.8	712.0	610.0	102.0	6.3	5.3	1.0	71.8
Hard hardwoods	560.5	382.7	177.8	427.5	340.0	87.5	55.7	42.7	13.0	77.3
Soft hardwoods	463.2	326.6	136.6	361.4	298.7	62.7	34.5	27.9	6.6	67.3
Total	1,813.8	1,324.6	489.2	1,500.9	1,248.7	252.2	96.5	75.9	20.6	216.4
Louisiana:										
Softwoods	473.4	368.8	104.6	421.3	361.2	60.1	9.1	7.6	1.5	43.0
Hard hardwoods	328.0	221.5	106.5	234.9	184.5	50.4	48.1	37.0	11.1	45.3
Soft hardwoods	265.9	185.8	80.1	191.6	156.5	35.1	35.7	29.3	6.4	38.6
Total	1,067.3	776.1	291.2	847.8	702.2	145.6	92.9	73.9	19.0	126.9

(Continued)

Table 6. Average Per Acre Green Weight of Aboveground Tree Biomass (Excluding Foliage) on Commercial Timberland in the South, by State and Species Group--Continued

Southern region by state and species group	Biomass			Growing stock			Cull			Saplings
	Total	Stem	Crown[a]	Total	Stem	Crown	Total	Stem	Crown	Total
	- - - - - - - - - - - - - - - - - - - -	- - - -	- - - -	- - - -	Tons	- - - -	- - - -	- - - -	- - - -	- - - -
Mississippi:										
Softwoods	28.0	22.0	6.0	24.3	21.0	3.3	1.2	1.0	0.2	2.5
Hard hardwoods	30.1	20.6	9.5	20.8	16.6	4.2	5.2	4.0	1.2	4.2
Soft hardwoods	16.7	11.8	4.9	11.8	9.8	2.0	2.5	2.0	0.5	2.4
Total	74.8	54.4	20.4	56.9	47.4	9.5	8.9	7.0	1.9	9.1
North Carolina:										
Softwoods	32.4	24.7	7.7	28.8	24.5	4.3	0.3	0.2	0.1	3.3
Hard hardwoods	36.4	24.6	11.8	28.1	22.0	6.1	3.4	2.6	0.8	5.0
Soft hardwoods	30.0	20.9	9.1	23.9	19.6	4.3	1.7	1.3	0.4	4.4
Total	98.8	70.2	28.6	80.8	66.1	14.7	5.4	4.1	1.3	12.7
South Carolina:										
Softwoods	36.7	28.7	8.0	32.9	28.4	4.5	0.4	0.3	0.1	3.3
Hard hardwoods	25.0	17.1	7.9	18.7	14.9	3.8	2.9	2.2	0.7	3.4
Soft hardwoods	25.3	17.9	7.4	19.0	15.8	3.2	2.6	2.2	0.4	3.7
Total	87.0	63.7	23.3	70.6	59.1	11.5	5.9	4.7	1.2	10.4
Tennessee:										
Softwoods	11.4	8.8	2.6	10.0	8.5	1.5	0.3	0.2	0.1	1.0
Hard hardwoods	54.0	36.9	17.1	41.9	33.3	8.6	4.6	3.6	1.0	7.5
Soft hardwoods	18.6	13.2	5.4	14.4	12.0	2.4	1.5	1.2	0.3	2.7
Total	84.0	58.9	25.1	66.3	53.8	12.5	6.4	5.0	1.4	11.2
Virginia:										
Softwoods	20.8	15.9	4.9	18.6	15.7	2.9	0.3	0.2	0.1	1.9
Hard hardwoods	56.8	38.2	18.6	43.7	34.2	9.5	5.2	4.0	1.2	7.8
Soft hardwoods	25.4	17.8	7.6	20.0	16.4	3.6	1.7	1.4	0.3	3.7
Total	103.0	71.9	31.1	82.3	66.3	16.0	7.2	5.6	1.6	13.4
Total softwoods	28.9	22.5	6.4	25.7	22.0	3.7	0.6	0.5	0.1	2.7
Total hard hardwoods	31.8	21.6	10.2	23.4	18.5	4.9	4.0	3.1	0.9	4.1
Total soft hardwoods	18.6	13.0	5.6	14.0	11.5	2.5	1.8	1.5	0.3	2.7
Total South	79.3	57.1	22.2	63.1	52.0	11.1	6.4	5.1	1.3	9.5

[a] Includes total sapling weight.

Table 6. Average Per Acre Green Weight of Aboveground Tree Biomass (Excluding Foliage) on Commercial Timberland in the South, by State and Species Group

Southern region by state and species group	Biomass			Growing stock			Cull			Saplings
	Total	Stem	Crown[a]	Total	Stem	Crown	Total	Stem	Crown	Total
	- - - - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	Tons - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -	- - - - - - - -
Alabama:										
Softwoods	24.5	18.9	5.6	21.8	18.5	3.3	0.5	0.4	0.1	2.2
Hard hardwoods	21.9	14.7	7.2	16.4	12.8	3.6	2.4	1.9	0.5	3.0
Soft hardwoods	13.5	9.3	4.2	10.5	8.5	2.0	1.0	0.8	0.2	2.0
Total	59.9	42.9	17.0	48.7	39.8	8.9	3.9	3.1	0.8	7.2
Arkansas:										
Softwoods	29.6	23.3	6.3	26.4	22.9	3.5	0.5	0.4	0.1	2.7
Hard hardwoods	36.1	24.6	11.5	27.2	21.5	5.7	3.9	3.0	0.9	5.0
Soft hardwoods	10.6	7.5	3.1	8.1	6.7	1.4	1.0	0.8	0.2	1.4
Total	76.3	55.4	20.9	61.7	51.1	10.6	5.4	4.2	1.2	9.1
East Oklahoma:										
Softwoods	15.0	10.7	4.3	13.3	10.4	2.9	0.4	0.3	0.1	1.4
Hard hardwoods	26.4	17.5	8.9	14.4	11.0	3.4	8.4	6.4	2.0	3.6
Soft hardwoods	4.4	3.1	1.3	2.7	2.2	0.5	1.1	0.9	0.2	0.6
Total	45.8	31.3	14.5	30.4	23.6	6.8	9.9	7.6	2.3	5.6
East Texas:										
Softwoods	35.4	27.8	7.6	31.0	26.8	4.2	1.2	1.0	0.2	3.2
Hard hardwoods	23.1	15.8	7.3	14.5	11.5	3.0	5.5	4.3	1.2	3.2
Soft hardwoods	10.4	7.3	3.1	7.0	5.8	1.2	1.9	1.5	0.4	1.5
Total	68.9	50.9	18.0	52.5	44.1	8.4	8.6	6.8	1.8	7.9
Florida:										
Softwoods	31.9	24.7	7.2	28.5	24.3	4.2	0.5	0.4	0.1	2.9
Hard hardwoods	14.7	10.1	4.6	8.7	7.0	1.7	4.0	3.1	0.9	2.0
Soft hardwoods	14.6	10.3	4.3	10.8	9.0	1.8	1.7	1.4	0.3	2.1
Total	61.2	45.1	16.1	48.0	40.3	7.7	6.2	4.9	1.3	7.0
Georgia:										
Softwoods	33.4	26.0	7.4	30.1	25.8	4.3	0.3	0.2	0.1	3.0
Hard hardwoods	23.7	16.2	7.5	18.1	14.4	3.7	2.4	1.8	0.6	3.3
Soft hardwoods	19.6	13.8	5.8	15.3	12.6	2.7	1.5	1.2	0.3	2.8
Total	76.7	56.0	20.7	63.5	52.8	10.7	4.2	3.2	1.0	9.1
Louisiana:										
Softwoods	34.4	26.8	7.6	30.6	26.2	4.4	0.7	0.5	0.2	3.1
Hard hardwoods	23.8	16.1	7.7	17.0	13.4	3.6	3.5	2.7	0.8	3.3
Soft hardwoods	19.3	13.5	5.8	13.9	11.4	2.5	2.6	2.1	0.5	2.8
Total	77.5	56.4	21.1	61.5	51.0	10.5	6.8	5.3	1.5	9.2

(Continued)

BIOMASS ENERGY INVENTORY AND MAPPING SYSTEM

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Abstract

A four-stage biomass energy inventory and mapping system was conducted for the entire State of Ohio. The product is a set of maps and an inventory of the State of Ohio. The set of maps and an inventory of the State's energy biomass resource are to a one kilometer grid square basis on the Universal Transverse Mercator (UTM) system. Each square kilometer is identified and mapped showing total British Thermal Unit (BTU) energy availability. Land cover percentages and BTU values are provided for each of nine biomass strata types for each one kilometer grid square.

LANDSAT satellite data was used as the primary stratifier. The second stage sampling was the photointerpretation of randomly selected one kilometer grid squares that exactly corresponded to the LANDSAT one kilometer grid square classification orientation. Field sampling comprised the third stage of the energy biomass inventory system and was combined with the fourth stage sample of laboratory biomass energy analysis using a Bomb calorimeter and was then used to assign BTU values to the photointerpretation and to adjust the LANDSAT classification.

The sampling error for the whole system was 3.91%.

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5. Energy biomass was then derived on a one square kilometer basis using the following parameters.

One square kilometer is 247.1 acres. Using the equation developed by Kasile, 1984, total weight per acre of hardwood five inches and larger, diameter freast height, trees is:

Total weight= -315 + 2673.1 (basal area per acre)

Then using 8100 British Thermal units (BTU) per oven dry pounds of wood and 70 percent moisture content (dry weight basis) the average BTU's per pound were calculated to be 4666 (green weight basis, 70°F). The average weight per acre in dense hardwood forest for all trees 5 inches and larger D.B.H. was 124.7 tons. This converts to 1.1635 x 10^9 BTU's per acre and 287.5 x 10^9 BTU's is the maximum energy biomass available for one square kilometer for the purpose of this report. BTU's for the other three forest categories were computed similar to that of dense hardwood forest with 3126 BTU's per pound green weight basis for conifers.

Agricultural land was defined as that which is cultivated, i.e., corn, soybeans, wheat. The International Bio Energy Directory and Handbook, 1984 computes values of 7,000 BTU's per pound for straw and corn stover. BTU's per acre for agriculture were proportioned based on acres per crop and production per acre, statewide, for a weighted average of 6.5 x 10^5 BTU's per acre

Rangeland harvests (hay crops) were stated to be 1.5 tons per acre at 15 percent moisture content producing 2.1 x 10^5 BTU's per acre.

6. The area percentage and energy biomass on a one square kilometer basis were then computed by multiplying the LANDSAT acreage by the photointerpretation ratio for each category; then determining the percentage of acres in each adjusted photo classification category.

7. The maps present a pictorial representation of the percentage of BTU's in each one square kilometer U.T.M. cell relative to the 287.5 x 10^9 BTU maximum for the dense hardwood forest category. Figure 1 depictes energy biomass relative to fully stocked dense hardwood forest. The "darker" the particular one kilometer block, the more energy biomass available in that one kilometer cell. Accessibility and location of the energy biomass is provided by the U.T.M. coordinate system.

Statistical Analysis

Sampling errors were computed for the ratio of photointerpretation area divided by LANDSAT area for each classification category using the 820 photointerpretation/ LANDSAT correlated one square kilometer cells. The average sampling error of photointerpretation, weighted by total area in each classification category is 0.09%. The weighted average field sampling error, weighted by the BTU's of energy in that classification category was: 3.91%. The weighted combined sampling error is then:

Background

The assessment of biomass for the production of energy is the first step in the development of a biomass energy production process. This assessment must contain two key features: (1) the amount of each type of biomass and its energy equivalent and (2) the location of this biomass on a mapping system that shows the transportation infrastructure. This project is the first in the Great Lakes region to meet both of these criteria.

Project

A system of biomass mapping and inventory of energy biomass using remotely sensed data was developed. The system demonstrates the methodology by providing a complete energy biomass inventory of the State of Ohio on a Universal Transverse Mercator (UTM) format to a one-kilometer grid square basis.

Maps to a scale 1:250,000 and 1:62,500 displaying the relative energy biomass on a one square kilometer basis were produced. For 1:1,000,000 scale, the relative energy biomass was displayed on a 100 square kilometer basis. Highway overlays were provided for each of these scale maps to provide access routes to the energy biomass.

Methodology

The specific steps taken to develop the biomass energy resource assessment are listed below:

1. A LANDSAT analysis of the entire State of Ohio was secured. The LANDSAT computer tape provided Level 1 classification of 23.5 x 10^6 picture elements (size: 1.1 acres each) that included most of the state of Ohio and adjoining boundaries. The Level 1 classification categories are: urban, agriculture, rangeland, forest, water, barren and unidentified.

2. A random selection of 820 one square kilometer cells out of 101,491 within the State of Ohio boundaries were photointerpreted on 1:24,000 scale stereo photo quadrangles. Photointerpretation used the same classification categories as did the LANDSAT, however the forest category was subclassified into: dense hardwood (50 to 100% crown cover); sparse hardwood (less than 50% crown cover); conifer forest (more than 80% conifer crown cover); and mixed conifer/hardwood forest.

3. A statistical analysis was conducted to correlate the LANDSAT category classifications with those conducted by photointerpretation. Statewide ratios of photointerpretation divided by LANDSAT classification were computed.

4. Ground samples were then installed in 114 randomly selected photointerpretation categories with probability proportional to statewide total energy biomass of each category with a minimum of 5 field samples in each category.

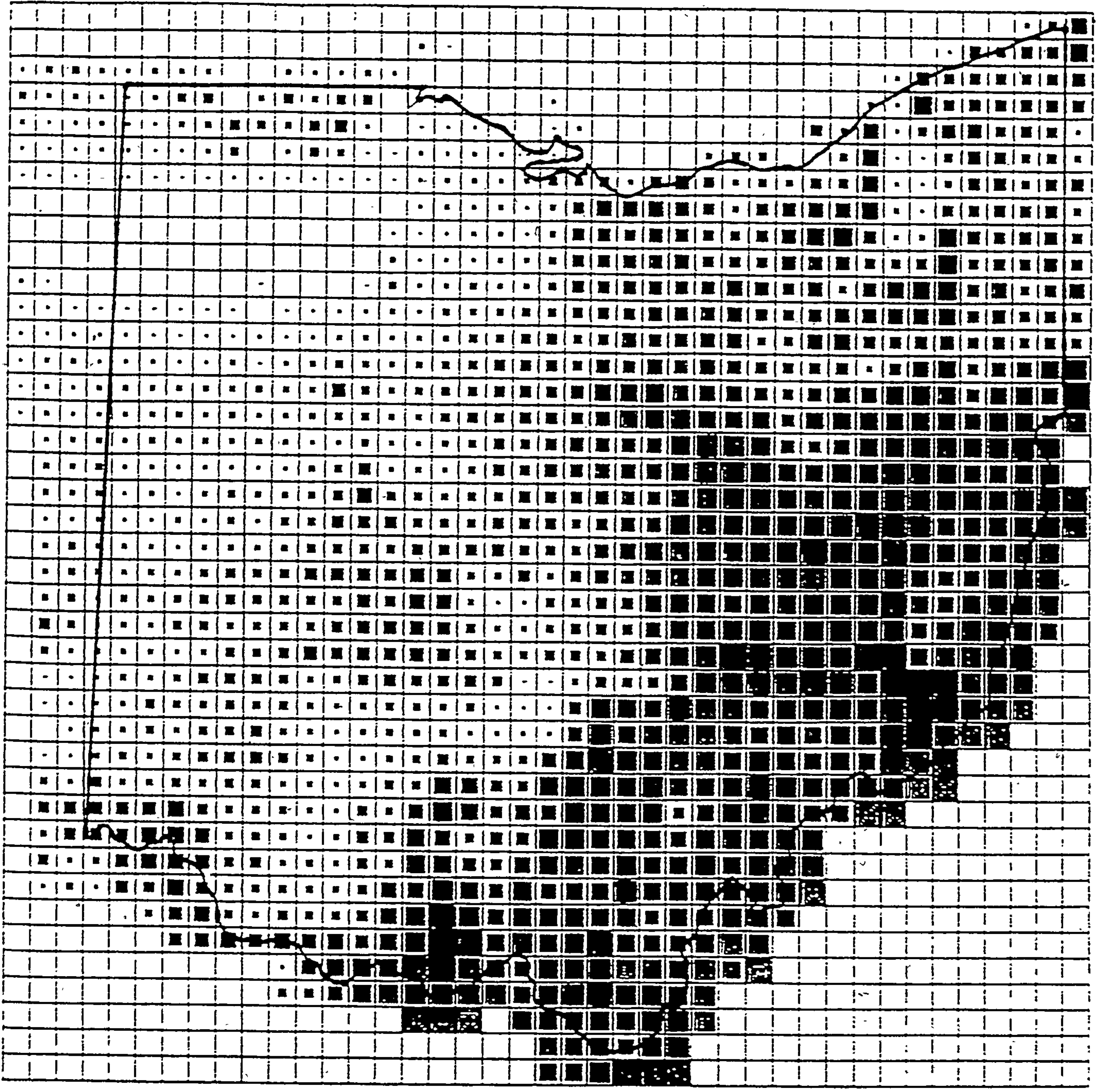

Figure 1 - Related Density - Biomass Energy

Sampling error, combined = $(0.09\%)^2 + (3.91\%)^2 = 3.91\%$

Planning for Biomass Energy Use

To use the product of the energy biomass mapping and inventory system one would locate U.T.M. cells on the biomass energy map on the basis of their darkness. Cells, or groups of cells, with large amounts of energy biomass will appear dark on the map. Using the transportation overlay, access to these high energy cells could be determined. To determine the actual amount of energy biomass in BTU's and how those BTU's are distributed by energy type one would look in Figure 2 for the proper coordinates and then read the land cover percents and the BTU's by cover type.

If a whole-tree chipper operation were used to supply a fuelwood boiler operation, the one kilometer cell shown on the fourth line from the bottom of Figure 2 shows that 83.2 percent of the area for that one square kilometer is covered by dense hardwoods; 7.2 percent of the area is covered by sparse hardwoods, 4.7 percent of the area is covered by mixed conifers/hardwoods; and 1.6 percent is covered by conifers. The BTU's available from these four cover types are: 23899 x 10^7; 975 x 10^7; 1023 x 10^7; and 451 x 10^7 respectively.

The small sampling error associated with this methodology to estimate energy from biomass over large areas provides a high degree of reliability in the U.T.M. energy values. Before any strategy of biomass energy development can be implemented, a detailed inventory is necessary. The tables and maps provided by this report provide that necessary detail to include amounts and types of energy biomass, and the routes to access and transport the material. Such information is the first step in providing private enterprise with the knowledge to institute an energy biomass utilization system.

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UTM		PERCENTAGE									BTUS X 10,000,000						
COORDINATES		DENSE	SPARSE			CULTI	RANGE				DENSE	SPARSE			CULTI	RANGE	
NORTH	EAST	HARD	HARD	MIXED	CONFR	VATED	LAND	URBAN	BARRN	WATER	HARD	HARD	MIXED	CONFR	VATED	LAND.	TOTAL
4414500	361500	14.3	1.2	0.8	0.3	68.5	14.9	0.0	0.0	0.0	4105	167	176	77	110	77	4712
4414500	362500	55.2	4.8	3.1	1.0	22.0	13.9	0.0	0.0	0.0	15855	647	679	299	35	72	17587
4414500	363500	35.7	3.1	2.0	0.7	49.2	9.3	0.0	0.0	0.0	10274	419	440	194	79	48	11454
4414500	364500	0.0	0.0	0.0	0.0	84.9	6.8	8.3	0.0	0.0	0	0	0	0	136	35	171
4414500	365500	39.9	3.5	2.2	0.7	53.6	0.0	0.0	0.0	0.0	11474	468	491	216	86	0	12735
4414500	366500	0.0	0.0	0.0	0.0	96.5	3.5	0.0	0.0	0.0	0	0	0	0	155	18	173
4414500	367500	32.4	2.8	1.8	0.6	61.0	1.3	0.0	0.0	0.0	9319	380	399	176	98	7	10379
4414500	368500	33.2	2.9	1.9	0.6	61.4	0.0	0.0	0.0	0.0	9542	389	408	180	99	0	10618
4414500	369500	52.7	4.6	3.0	1.0	36.3	2.4	0.0	0.0	0.0	15159	618	649	286	58	13	16783
4414500	370500	44.6	3.9	2.5	0.8	41.7	6.5	0.0	0.0	0.0	12819	523	549	242	67	34	14234
4414500	371500	2.0	0.2	0.1	0.0	80.6	13.4	3.6	0.0	0.0	584	24	25	11	129	70	843
4414500	372500	4.0	0.3	0.2	0.1	85.2	10.1	0.0	0.0	0.0	1161	47	50	22	137	52	1469
4414500	373500	8.0	0.7	0.4	0.1	90.1	0.6	0.0	0.0	0.0	2292	93	98	43	145	3	2674
4414500	374500	8.9	0.8	0.5	0.2	82.3	7.3	0.0	0.0	0.0	2563	105	110	48	132	38	2996
4414500	375500	34.2	3.0	1.9	0.6	52.2	8.1	0.0	0.0	0.0	9820	401	420	185	84	42	10952
4414500	376500	30.1	2.6	1.7	0.6	56.3	8.8	0.0	0.0	0.0	8644	353	370	163	90	46	9666
4414500	377500	7.6	0.7	0.4	0.1	82.1	9.1	0.0	0.0	0.0	2180	89	93	41	132	47	2582
4414500	378500	36.8	3.2	2.1	0.7	57.2	0.0	0.0	0.0	0.0	10580	432	453	200	92	0	11757
4414500	379500	51.3	4.4	2.9	1.0	36.6	0.5	3.2	0.0	0.0	14758	602	632	278	59	3	16332
4414500	380500	20.6	1.8	1.2	0.4	71.0	4.5	0.6	0.0	0.0	5919	241	253	112	114	23	6662
4414500	381500	27.4	2.4	1.5	0.5	66.0	2.2	0.0	0.0	0.0	7886	322	337	149	106	11	8811
4414500	382500	29.7	2.6	1.7	0.6	63.4	2.2	0.0	0.0	0.0	8531	348	365	161	102	11	9518
4414500	383500	51.9	4.5	2.9	1.0	37.8	1.9	0.0	0.0	0.0	14910	608	638	281	61	10	16508
4414500	384500	54.4	4.7	3.1	1.0	35.4	1.5	0.0	0.0	0.0	15630	637	669	295	57	8	17296
4414500	385500	53.3	4.6	3.0	1.0	37.1	0.9	0.0	0.0	0.0	15333	625	656	289	60	5	16968
4414500	386500	33.9	2.9	1.9	0.6	55.9	3.1	1.6	0.0	0.0	9748	398	417	184	90	16	10853
4414500	387500	29.7	2.6	1.7	0.6	61.0	4.5	0.0	0.0	0.0	8536	348	365	161	98	23	9531
4414500	388500	26.8	2.3	1.5	0.5	63.9	4.2	0.7	0.0	0.0	7700	314	330	145	103	22	8614
4414500	389500	41.4	3.6	2.3	0.8	50.3	1.6	0.0	0.0	0.0	11904	486	509	225	81	8	13213
4414500	390500	7.5	0.7	0.4	0.1	69.8	3.7	6.8	10.9	0.0	2166	88	93	41	112	19	2519
4414500	391500	28.3	2.4	1.6	0.5	64.6	2.5	0.0	0.0	0.0	8132	332	348	153	104	13	9082
4414500	392500	55.0	4.8	3.1	1.0	36.1	0.0	0.0	0.0	0.0	15816	645	677	298	58	0	17494
4414500	393500	31.2	2.7	1.7	0.6	54.7	6.6	2.5	0.0	0.0	8953	365	383	169	88	34	9992
4414500	394500	53.3	4.6	3.0	1.0	31.2	6.8	0.0	0.0	0.0	15328	625	656	289	50	35	16983
4414500	395500	40.5	3.5	2.3	0.8	51.1	1.8	0.0	0.0	0.0	11651	475	499	220	82	10	12937
4414500	396500	62.0	5.4	3.5	1.2	26.5	1.5	0.0	0.0	0.0	17814	727	762	336	43	8	19690
4414500	397500	55.8	4.8	3.1	1.0	31.2	4.0	0.0	0.0	0.0	16039	654	686	303	50	21	17753
4414500	398500	31.9	2.8	1.8	0.6	50.5	11.2	1.2	0.0	0.0	9175	374	393	173	81	58	10254
4414500	399500	17.0	1.5	1.0	0.3	68.8	11.4	0.0	0.0	0.0	4898	200	210	92	110	59	5569
4414500	400500	39.8	3.4	2.2	0.7	47.8	5.9	0.0	0.0	0.0	11445	467	490	216	77	31	12726
4414500	401500	73.7	6.4	4.1	1.4	13.4	1.0	0.0	0.0	0.0	21183	864	907	400	21	5	23380
4414500	402500	80.8	7.0	4.5	1.5	6.2	0.0	0.0	0.0	0.0	23210	947	993	438	10	0	25598
4414500	403500	63.5	5.5	3.6	1.2	25.3	1.0	0.0	0.0	0.0	18256	745	781	344	41	5	20172
4414500	404500	47.1	4.1	2.6	0.9	39.9	5.4	0.0	0.0	0.0	13539	552	579	255	64	28	15017
4414500	405500	25.1	2.2	1.4	0.5	58.3	7.7	3.1	0.0	1.7	7201	294	308	136	94	40	8073
4414500	406500	30.9	2.7	1.7	0.6	58.1	3.2	2.9	0.0	0.0	8868	362	380	167	93	16	9886
4414500	407500	24.4	2.1	1.4	0.5	23.6	7.5	20.9	17.2	2.4	7010	286	300	132	38	39	7805
4414500	408500	38.4	3.3	2.2	0.7	35.6	10.8	5.4	0.0	3.5	11038	450	472	208	57	56	12281
4414500	409500	22.5	1.9	1.3	0.4	53.0	4.9	14.9	1.0	0.0	6463	264	277	122	85	26	7237
4414500	410500	27.7	2.4	1.6	0.5	47.7	12.8	7.4	0.0	0.0	7948	324	340	150	77	66	8905
4414500	411500	48.0	4.2	2.7	0.9	34.4	9.9	0.0	0.0	0.0	13793	563	590	260	55	51	15312
4414500	412500	70.5	6.1	4.0	1.3	15.6	2.6	0.0	0.0	0.0	20258	826	867	382	25	13	22371
4414500	413500	71.2	6.2	4.0	1.3	10.4	0.8	5.3	0.8	0.0	20470	835	876	386	17	4	22588
4414500	414500	72.1	6.2	4.0	1.4	10.1	0.8	3.0	2.3	0.0	20729	845	887	391	16	4	22872
4414500	415500	61.8	5.4	3.5	1.2	13.1	2.7	5.1	0.0	7.2	17761	724	760	335	21	14	19615
4414500	416500	18.2	1.6	1.0	0.3	38.7	14.6	8.5	0.0	17.1	5225	213	224	99	62	76	5899
4414500	417500	45.9	4.0	2.6	0.9	37.4	4.6	3.2	0.0	1.5	13196	538	565	249	60	24	14632
4414500	418500	69.7	6.0	3.9	1.3	12.1	3.2	1.8	2.0	0.0	20044	817	858	378	19	16	22132
4414500	419500	78.4	6.8	4.4	1.5	8.3	0.7	0.0	0.0	0.0	22523	919	964	425	13	3	24847
4414500	420500	64.6	5.6	3.6	1.2	18.8	4.8	1.4	0.0	0.0	18572	757	795	350	30	25	20529
4414500	421500	20.0	1.7	1.1	0.4	54.7	14.8	7.3	0.0	0.0	5740	234	246	108	88	77	6493
4414500	422500	57.5	5.0	3.2	1.1	23.7	6.2	3.4	0.0	0.0	16514	674	707	312	38	32	18277
4414500	423500	83.2	7.2	4.7	1.6	2.8	0.7	0.0	0.0	0.0	23899	975	1023	451	4	3	26355
4414500	424500	77.0	6.7	4.3	1.4	8.9	1.7	0.0	0.0	0.0	22133	903	947	418	14	9	24424
4414500	425500	41.4	3.6	2.3	0.8	36.2	15.8	0.0	0.0	0.0	11890	485	509	224	58	82	13248
4415500	318500	0.0	0.0	0.0	0.0	92.0	8.0	0.0	0.0	0.0	0	0	0	0	148	42	190

Figure 2 - Area Percentage of Energy Biomass

BIOMASS RESOURCES IN CALIFORNIA

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Abstract

The biomass resources in California which have potential for energy conversion were assessed and characterized through the project funded by the California Energy Commission and the U.S. Department of Energy's Western Regional Biomass Energy Program (WRBEP). The results indicate that there is an abundance of biomass resources as yet untouched by the industry due to technical, economic, and environmental problems, and other barriers. These biomass resources include residues from field and seed crops, fruit and nut crops, vegetable crops, and nursery crops; food processing wastes; forest slash; energy crops; lumber mill waste; urban wood waste; urban yard waste; livestock manure; and chaparral. The estimated total potential of these biomass resources is approximately 47 million bone dry tons (BDT), which is equivalent to 780 billion MJ (740 trillion Btu). About 7 million BDT (132 billion MJ or 124 trillion Btu) of biomass residue was used for generating electricity by 66 direct combustion facilities with gross capacity of about 800 MW. This tonnage accounts for only about 15% of the total biomass resource potential identified in this study. The barriers interfering with the biomass utilization both in the on-site harvesting, collection, storage, handling, transportation, and conversion to energy are identified. The question whether these barriers present significant impact to biomass "availability" and "sustainability" remains to be answered.

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Total Resource Potential

The California Energy Commission in collaboration with the U.S. Department of Energy's Western Regional Biomass Energy Program (WRBEP) has conducted a study to evaluate the status of biomass energy development in California [1, 2]. Twelve major sources of biomass fuel were selected for assessment in this study, namely: (1) field and seed crops, (2) fruit and nut crops, (3) vegetable crops, (4) nursery crops, (5) food processing waste, (6) forest slash, (7) lumber mill waste, (8) urban wood waste, (9) yard waste, (10) livestock manure, (11) energy crops, and (12) chaparral. These biomass fuels can be utilized using either of the three biomass-to-energy conversion technologies in use today: direct combustion, gasification, and anaerobic digestion. The choice of technology is often dictated by the type of residue.

The total potential of biomass resources in California is approximately 47 million bone dry tons (BDT) (Table 1), which is equivalent to 783 billion MJ (740 trillion Btu). Livestock manure is the most abundant resource, accounting for over a quarter of the total biomass potential (Table 1). Chaparral and field and seed crop residue together contribute over thirty percent of the total biomass resources potential. Less abundant are lumber mill waste, forest slash, and urban yard wastes. Fruit and nut crops, food processing waste, urban wood wastes, vegetable crops, energy crops, and nursery crops contribute the least amount of biomass.

The San Joaquin Valley Air Basin has the highest residue production (12.1 million BDT), slightly over one quarter of the total resource potential. Most of the residue produced in this region comes from livestock manure (4.2 million BDT), field and seed crops (3.5 million BDT), and fruit and nut crops (1.2 million BDT). The Sacramento Valley Air Basin is the second highest producer of biomass, contributing about 7 million BDT. And by county basis, Fresno County has the highest biomass residue production (2.9 million BDT).

Amount of Biomass Currently Used for Energy Purposes

In 1992, California had a total electric power capacity of over 56,700 MW. About 19 percent of this power was generated by in-state renewable resources (hydro, geothermal, solar, wind, and biomass). The remaining 81 percent was generated by fossil fuels, nuclear power, and imports from out of state. Biomass energy conversion technologies currently produce about 1.5 percent of California's total electricity capacity. Direct combustion alone accounted for approximately 800 MW, which is about 75 percent of the total capacity supplied by biomass conversion systems.

Approximately 7 million BDT (124 trillion Btu) of biomass residue was used for generating electricity by 66 direct combustion facilities. This tonnage accounts for only about 15 percent of the total biomass resource potential identified in this report. The biomass resources that are presently being used for energy production include lumber mill waste, livestock manure, urban wood waste, forest slash, food processing waste, fruit and nut crop residue, and field and seed crop residue. Wood waste is the primary fuel source in the biomass combustion industry. It accounted for about 73 percent of the total biomass fuel consumption in 1990. Wood wastes are used in 61 of the 66 direct combustion facilities. Forty nine (74 percent) of these plants use wood waste exclusively.

No energy production was reported utilizing chaparral, urban yard waste, energy crops, nursery crops or vegetable crops. About half of the biomass residue for energy production came from lumber mill waste (3.43 million BDT). Urban wood waste and forest slash contributed approximately 0.81 million BDT and 1.52 million BDT respectively to energy production. A few direct combustion facilities (4 power plants) used residue from field and seed crops (0.24 million BDT) and food processing waste (0.49 million BDT). Only two direct combustion facilities actually used livestock manure (0.22 million BDT) for electricity generation.

Biomass Resources in California (BDT, MJ and BTU)

Table 1.

Fuel Type	A			B			C			D = A - B - C		
	Total Potential			Biomass Facilities Uses			Other Uses *			Gross Potential=Total - All uses		
	million BDT	billion MJ	trillion BTU	million BDT	billion MJ	trillion BTU	million BDT	billion MJ	trillion BTU	million BDT	billion MJ	trillion BTU
Chaparral	7.65	129.00	123.00	0.00	0.00	0.00	0.00	0.00	0.00	7.65	129.00	123.00
Livestock Manure	11.90	182.00	173.00	0.22	3.34	3.17	3.65	55.81	53.05	8.03	122.85	116.77
Urban Yard Waste	3.05	42.30	40.10	0.00	0.00	0.00	0.003	0.04	0.04	3.05	42.26	40.06
Urban Wood Waste	1.62	30.10	28.50	0.81	14.97	14.17	0.24	4.52	4.28	0.57	10.62	10.05
Lumber Mill Waste	5.47	106.00	100.00	3.43	66.48	62.72	1.93	37.41	35.29	0.11	2.11	1.99
Energy Crops	0.51	8.97	8.50	0.00	0.00	0.00	0.51	8.97	8.50	0.00	0.00	0.00
Forest Slash	5.23	99.60	91.60	1.52	28.84	26.52	0.00	0.00	0.00	3.72	70.76	65.08
Food Processing Waste	1.74	30.80	29.20	0.49	8.62	8.17	0.71	12.50	11.85	0.55	9.68	9.18
Nursery Crops	0.02	0.41	0.39	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.41	0.39
Vegetable Crops	0.92	14.90	14.10	0.00	0.00	0.00	0.00	0.00	0.00	0.92	14.90	14.10
Fruit & Nut Crops	1.88	33.50	31.70	0.33	5.89	5.57	0.00	0.00	0.00	1.55	27.61	26.13
Field & Seed Crops	6.62	105.00	99.70	0.24	3.76	3.57	0.38	5.95	5.65	6.01	95.29	90.48
Total	46.62	783	740	7.02	132	124	7.42	125	119	32.18	525	497
Percent	100%			15%			16%			69%		

- * 3.65 million BDT of livestock manure was sold for fertilizer.
- * 3 thousand BDT of urban yard waste was recycled.
- * 244 thousand BDT of urban wood waste was recycled.
- * 1.93 million BDT of lumber mill waste was used for particle board and plywood production.
- * 37% of energy crops was used as firewood and 63% was unspecified.
- * 0.71 million BDT of high moisture content food processing waste (pomace etc.) was used for animal feeding.
- * 375 thousand BDT of field and seed crop residue (rice and wheat straw) was used for animal feeding.

Amount of Biomass Currently Used for Non-Energy Commercial Purposes

Approximately eight million BDT of biomass residue is being used for non-energy commercial purposes, an amount equivalent to 124 trillion Btu. This accounts for about 16 percent of the total biomass resource potential (Table 1). Alternate uses for biomass products are as follows: livestock manure, which accounts for the highest percentage, is used as a fertilizer or for soil amendment; lumber mill waste is used for plywood production; field and seed crop residue, primarily wheat and rice straw, is used for animal feed and animal bedding; about 0.71 million BDT of the high moisture food processing wastes was also used for animal feed. Urban wood waste and urban yard waste are both recycled for various purposes. Approximately 37 percent of the 0.51 million BDT of energy crops was used as firewood for domestic consumption, while the other 63 percent was used for other purposes, such as wind breaks and for the preservation of wildlife species. Most residual field and seed crop materials, like bean straw, corn stalks, and wheat and rice straw, are left on the harvesting fields and are plowed back down into the soil for the next planting season. This organic material is essential in crop rotation systems as a soil conditioner, improving the air and water holding capacity of the soil and reducing wind and water erosion. It also improves the soil texture, serves as a field mulch, and improves soil tilth. In addition, approximately 2.08 million BDT of field and seed crop residue was burned to prevent the spread of plant disease and to help remove the residual materials before the next planting season.

Gross Biomass Resource Potential

Gross biomass resource potential is defined in this report as the total biomass resource potential minus the amount of biomass currently being used for energy and the amount of biomass used for non-energy commercial purposes. Calculating across biomass resource categories, there is an estimated 32 million BDT gross biomass resource potential (equivalent to 497 trillion Btu). This means that approximately 69 percent of the total biomass resource potential is not currently being used. Livestock manure, chaparral, field and seed crop residue, forest slash, and urban yard waste account for 92 percent of the gross biomass resource potential.

Barriers

Taking advantage of the gross biomass resource potential depends on acknowledging and addressing a number of serious barriers. These barriers can be categorized into four types: technical, environmental, economic, and institutional. They interfere with biomass resource utilization both in the on-site harvesting, collection, and handling stage, as well as during the process of transportation and conversion of biomass to energy.

Technical Barriers

All of the difficulties experienced in combustion can be related to biomass fuel characteristics, specifically low bulk density and high moisture content. Field and seed crop residue, fruit and nut crop residue, and other biomass residues vary widely in their energy content, in their inert components, chemical constituents, and physical properties. This requires careful mixing or fuel blending to match the requirements of fuel types to individual combustion technologies. There is a lack of specific data on the dry yields and the soil, climate, water, and nutrient needs of energy crops. Because of fixed growing schedules, most agricultural residue is available only during short periods of time during the year. Consequently, the supply of agricultural residue for biomass fuel is not steady year round. Slagging was one of the major concerns of the biomass combustion facilities, especially for the plants combusting agricultural and animal wastes. Slagging deposits can drastically reduce heat transfer lowering the boiler efficiency, and can produce severe maintenance problems. Another problem which is not well understood is the problem of boiler fouling and corrosion caused by reactions of alkali metals from the fuel ash. This issue poses a significant impact on the availability of biomass. Over 50% of the fluidized bed facilities surveyed indicated having problems with erosion in the fluidized bed due to the highly abrasive nature of the bed material. In fluidized bed combustion, erosion will impact, to some extent, almost all components that come into contact with the bed material. Corrosion is another problem that was reported primarily by fluidized bed facilities. Similar to slagging, corrosion is related more to fuel type than reactor design. Erosion and corrosion of the refractory was also a major problem.

Environmental Barriers

Removing field residue can cause soil degradation, soil erosion, and soil compaction. Additional research on the effect of biomass fuel cultivation on soil conditions is necessary. Studies of nutrient cycling should also be considered. Wildlife habitats will be affected if forest slash or field crop residue is removed from its original site. A majority of the environmental barriers that effect availability of wood wastes as biomass fuels deal directly with the repercussions of timber harvest. Timber resources in California are finite, and availability problems will eventually occur whenever the cutting of timber outstrips its growth rate. One factor directly affecting the percentage of forested land available for harvest is the exclusion of old growth (primary) forest from being harvested due to the habitat destruction incurred by logging. An environmental concern which has not been adequately researched and affects the availability of wood waste is the amount of forest slash that can be harvested without undue soil erosion, nutrient loss, and loss of small animal habitat, particularly that of the spotted owl. The outlook on collecting agricultural residues as opposed to in-field burning is positive from an air pollution controls perspective, but when residues are removed from the field, their vital nutrients and capacity to prevent soil erosion and compaction are removed as well. Ash from biomass combustion facilities have three main physical properties that create environmental problems to its disposal: the high pH value of the ash, the concentrations of heavy metals found in the ash, and the very fine crystalline silicon particulates found in fly ash.

Economic Barriers

The high cost of harvesting, raking, baling, collecting, processing, and transporting many biomass fuels severely limits the availability of these resources for energy production. Capital costs for biomass combustion facilities are very high, typically ranging from \$1500/kW to \$2500/kW. In contrast, capital costs for a modern state-of-the-art combined cycle range from \$600/kW to \$800/kW. The California Public Utilities Commission (CPUC) adopted Interim Standard Offer 4 (ISO4) in Decision 83-09-054 on 13 October 1983. The ISO4 contracts provide the option for some qualifying facilities to obtain fixed energy prices for up to 10 years after which energy prices revert to the short-run avoided cost (SRAC) of the purchasing utility. The SRAC is intended to represent the cost a utility avoids by purchasing energy from a QF. The SRAC, which is calculated primarily based on fuel prices, is expected to be far below the fixed, forecasted energy prices specified in the ISO4 contracts at the end of the fixed priced period. As a result, QFs may experience substantial revenue reductions at that time. The end of the fixed price period will probably have a significant impact on biomass projects primarily because fuel costs have increased dramatically in recent years [4]. There are many competing markets for biomass fuels which will decrease the availability of these fuels and drive prices even higher. For example, both the particle board and pulp industries utilize wood chips and wastes to fabricate their products. If, as expected, both of these industries continue to grow, the availability of wood wastes for biomass combustion will decrease, especially since wood waste for combustion commands a lower price than wood residues allocated for pulp or composite wood applications.

FINNISH BIOENERGY RESEARCH

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Abstract

Finland is one of the leading countries in the use of biofuels. The share of wood derived fuels of the total primary energy requirement was about 14 % (ca. 4 million toe) and peat about 5 % (1.4 million toe). The possibilities for increasing the use of biofuels in Finland are significant. There is theoretically about 10 million m^3/a (about 2 million toe/a) of harvestable wood. Areas suitable for fuel peat production (0.5 million ha) could produce ca. 420 million toe of peat. At present rates of use, the peat reserves are adequate for centuries. During the next few years 0.5 - 1 million hectares of fields withdrawn from farming could be used for biofuel production. The production potential of this field area is estimated to be about 0.2 - 0.5 million toe. In addition, the use of wastes in energy production could be increased.

The aim of the new Bioenergy Research Programme is to increase the use of economically profitable and environmentally sound bioenergy by improving the competitiveness of present peat and wood fuels. New economically competitive biofuels, new equipment and methods for production, handling and using of biofuels will also be developed. The main research areas are production of wood fuels, peat production, use of bioenergy and conversion of biomass. The main goals of the Bioenergy Research Programme are:

- To develop new production methods for wood fuels in order to decrease the production costs to the level of imported fuels. The total potential of the wood fuel use should be at least 1 million toe/a.
- To increase the competitiveness of peat fuels by decreasing the production costs by 20 %, and also reduce environmental load.
- To develop and demonstrate at least 3 - 4 new equipment or methods for handling and use of biofuels. The equipment and/or methods should provide economically competitive and environmentally sound energy production.

The most important area of research on *wood fuel production* is the development of various methods, machines and systems, in order to produce economically competitive fuel. Integrated harvesting appears to have the most promising potential. The central research focuses in *peat production* are the better utilisation of peat available in a bog and the development of peat production methods and machines. The work aims at decreasing production costs and also environmental load. The increase of bioenergy in the space heating of small houses and farms, as well as in heat and power production are the central areas in the *use of bioenergy*. The research into the *conversion of biomass* concentrates on the production of biomass-based liquid fuels.

Institutional Barriers

Lack of incentives to producers (farmers) and users (biomass facilities) of biomass fuels, including tax incentives, rebates, etc., contribute to the slow development of biomass as an alternate energy source. For instance, there are currently no tax credits available for direct combustion facilities and other biomass-to-energy conversion facilities. California has many non-attainment air districts making the siting of a biomass facility in these areas very difficult. Several facilities in these areas have experienced difficulty in obtaining offset fuels. Stiffer permitting regulations in non-attainment districts typically raise the power plants capital, operational and maintenance costs.

Resource Availability

The demand for biomass fuels for electricity production has increased from about 100,000 BDT per year in 1981 to about 7,000,000 BDT per year in 1990. PG&E has projected that the demand may reach nearly 8,000,000 BDT per year in 1993 [3]. Meeting this need depends on an accurate assessment of the availability of biomass fuel given existing barriers and competing uses. Several criteria for estimating the availability of biomass resources are identified, which are reported in the Biomass Resource Assessment Report [1].

Conclusion

Meeting the increased demand and sustainability of biomass fuels for electricity production is dependent on accurate assessment and availability of potential biomass fuels. The estimated total potential of these biomass resources is approximately 47 million bone dry tons (BDT), which is equivalent to 780 billion MJ (740 trillion Btu). About 7 million BDT (124 trillion Btu) of biomass residue was used for generating electricity by 66 direct combustion facilities. This tonnage accounts for only about 15% of the total biomass resource potential identified in this study. Wood waste is the primary fuel source in the biomass industry. Four direct combustion facilities are using agricultural residues and two direct combustion facilities are using livestock manure for electricity generation. About 8 million BDT of biomass residue is being used for non-energy purposes such as soil amendment or fertilizer, animal bedding and feed, firewood, wind breaks, and for preservation of wildlife species. The gross biomass resource potential was estimated to be 32 million BDT. Several barriers to the utilization of these residues to energy conversion were identified. The question whether these barriers present significant impact on the "availability" and "sustainability" of biomass resources remains to be answered.

The biomass industry's future depends upon these issues: 1) the renegotiation of the Standard Offer #4 contract's capacity and energy payments in 1995 and beyond; 2) the development of reliable fuel sources; 3) the ability to produce higher thermal efficiency biomass energy conversion technologies than are presently available in order to compete against fuel fossil technologies, and 4) sustainable and "available" biomass fuel.

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1 Introduction

The Finnish Ministry of Trade and Industry (MTI) started eight new energy technology research programmes for the next six years in the beginning of 1993. One of these new programmes is the Bioenergy Research Programme. The Research Programme concentrates on production of biofuels, small-scale use and conversion of biomass into liquid fuels. Bioenergy is researched not only in this programme. Also in research programmes for Energy and Environment Technology, Combustion and Gasification and Energy and Environment in Transportation bioenergy has a minor role.

2 Biomass resources and bioenergy use

The latest inventories of Finnish forests showed a significant increase in the overall growth. At present the estimated annual growth of stem wood is about 80 million m^3/a, corresponding to about 126 million m^3/a of total biomass (stem, branches, top wood, leaves and needles, stumps and roots). The use of wood has not increased in proportion to the forest growth. The annual rate of stem wood cuttings has been 50 - 60 million m^3/a during the 1980's, while the increased growth of stem wood would allow the use of 70 - 80 million m^3/a. For this reason there is a lot of unused wood available. It is estimated that at least 10 million m^3/a (1.8 million toe/a or 20 TWh/a) could be harvested for energy use.

In Finland the peat resources are also significant. According to GTK (the Geological Survey of Finland), there are about 500 000 ha of bogs suitable for fuel peat production. The energy content of these bogs is about 420 million toe (4700 TWh). The use of fuel peat in 1990 corresponded to about 14 TWh and the role of fuel peat in energy production is estimated to increase to over 20 TWh by the year 2000. The peat resources will last for centuries at the present level of use.

It is estimated that about 0.5 - 1 million ha of Finnish agricultural land will be made redundant from traditional farming during the next few years. These areas could be used for biomass production. The energy potential available from the fields is estimated to be 0.2 - 0.5 million toe/a (2 - 5 TWh/a). From some fields it is possible to produce fuel peat as well. The utilisation of solid wastes and sludges has not been significant in Finland. The energy content of unused wastes is estimated to be about 0.9 - 1.3 million toe/a (10 - 15 TWh/a). This is formed by municipal, industrial and agricultural waste.

The share of wood fuels in Finland's energy production is significant. About 4 million toe/a (45 TWh/a) of total energy requirement is produced with wood and wood derived fuels. Roughly one half of this amount is waste liquors from pulp industry and the other half mainly waste wood from the industry and firewood. The total share of wood derived fuels in energy production in Finland is about 14 %.

The role of fuel peat has increased rapidly in energy production in Finland during the last two decades. At the moment the use of fuel peat forms about 5 % of the total energy production, corresponding to about 1.4 million toe (15 TWh). About 90 % of the used fuel peat is milled peat. Fuel peat is used mainly in municipal heat and power production, in industry and in power production in condensing power plant.

The share of liquid-form biomass products, MSW and waste water sludges in energy production in Finland is relatively small, corresponding to less than 0.1 million toe/a.

3 Goals of the research programme

The research on wood fuel production was rather insignificant during the late 1980's and early 1990's. Most of the research work has been carried out at METLA (Finnish Forest Research Institute), TTS (Work Efficiency Institute), METSATEHO (R&D unit for timber procurement and production at the Finnish Forest Industries Federation), the University of Joensuu and VTT (Technical Research Centre of Finland). In addition, industrial enterprises have taken part in this work.

METLA has concentrated on the research of wood production and harvesting. TTS has examined the harvesting and use of small-sized wood for fuel, especially on farms. METSATEHO is concerned with research on industrial harvesting and harvesting machinery. Fast growing energy forests are studied at the University of Joensuu, while the treatment of wood raw-material and machinery in integrated fuel and raw material production are researched at VTT.

In Finland, during the last few years, fuel peat production has been studied in two large energy research programmes. The work has mainly been funded by Ministry of Trade and Industry. These programmes were concerned with the peat production based on solar drying and artificial dewatering of peat. Also the purification of run-off water from peat production sites has been researched. Several companies involved with peat and energy production have taken part in the research and funding of these programmes. In addition to companies, research has been done at VTT and the University of Oulu.

The research on the use of biofuels has included both biomass conversion into liquid fuels, gasification and combustion. The conversion of biomass has concentrated on black liquor and soap. Gasification and combustion research has been concentrated on providing basic knowledge on the gasification and combustion phenomena and development of new power plant processes (mainly based on pressurized gasification and combustion). The use of biofuels has mainly been researched by the Abo Akademi, VTT, boiler manufacturers and fuel users in two research programmes.

The aim of the new Bioenergy Research Programme is to increase the use of economically profitable and environmentally sound bioenergy by improving the competitiveness of present peat and wood fuels. New economically competitive biofuels, new equipment and methods for production, handling and use of biofuels will also be developed.

The main goals of the Bioenergy Research Programme are:

- To develop new production methods for wood fuels in order to decrease the production costs to the level of imported fuels. The total potential of the wood fuel use should be at least 1 million toe/a.

- To increase the competitiveness of peat fuels by decreasing the production costs by 20 %, and also reduce environmental load.

- To develop and demonstrate at least 3 - 4 new equipment or methods for handling and use of biofuels. The equipment and/or methods should provide economically competitive and environmentally sound energy production.

- To demonstrate at least 3 - 4 large-scale biofuel end-use technologies. Each of these should have a potential of 0.2 - 0.3 mill. toe/a till the year 2000.

- To produce basic research results on the conversion of biomass, evaluation of quality, usability, environmental effects of use and the total economy of different products. The aim of the biomass conversion research is to create 2 - 3 new methods to be further developed within industry.

4 Main research areas

4.1 Main research areas and estimated funding

The main research areas of the Bioenergy Research Programme are production of wood fuels, peat production, use of bioenergy and conversion of biomass.

Public funding for the research programme during 1993 - 1998 is suggested to be FIM 138 million. The estimated funding from industry is FIM 72 million. The total funding of the Bioenergy Research Programme would then be total FIM 210 million.

4.2 Production of wood fuels

The most important research area is the production technology, which can be divided into integrated and separate production methods of wood raw-material and wood fuel. There are several advantages of integrated harvesting. The output from the harvested area is significantly higher when compared with present methods. In small-diameter cutting areas the output could even be doubled. With whole tree harvesting the productivity of the forest increases and the unit costs decrease. The utilisation of wood raw material could be improved in terms of both quality and quantity.

The most important task in *integrated harvesting* is to separate the fuel fraction (bark, leaves, needles etc.) and industrial wood fraction. These separation methods can be divided into whole tree chip -methods and whole tree bundle delimbing and debarking -methods. The possible research and development projects in the area of integrated harvesting are:

- development of harvesting of undelimbed or partially delimbed tree,
- separation of whole tree chips into industrial raw material and fuel and
- development of whole tree bundle delimbing and debarking methods.

In *separate wood fuel production*, wood is harvested only for energy use. Harvesting is mainly targeted at the harvesting residues and forests, which are not harvestable for industry. The possible projects in separate wood fuel production are:

- production of wood fuel from the harvesting residues,
- harvesting techniques of small-diameter trees which are not suitable for industrial processing and
- wood fuel production techniques on farms.

In addition to the fuel production techniques, the research is targeted at the planning and controlling methods of fuel production, the inventory of energy wood resources, development of the silviculture and thinning models and integrated production of fuel peat and wood fuel.

4.3 Peat production

The central research areas in *peat production* are production from shallow bogs and the development of peat production methods and machines. Development work in this area aims at decreasing the production costs and environmental loads around the peat production sites.

Decreasing the peat production costs is achieved primarily by increasing the capacity of each machine in the peat production chain. The following parts of the production chain will undergo further research and development work:

- shortening the preparation time of a bog,
- underdraining of the peat production site,
- utilising all the available peat in a bog,
- developing a simple and fire-secure production chain,
- utilising modern production planning and control techniques,
- use of automatic machines,
- utilisation of post-farming and shallow peat areas and
- decreasing the transportation costs of peat.

Further goals are to develop new peat products, post-production use of bog in energy production, utilisation of the surface peat layer and to increase integrated peat and wood fuel production.

The environmental effects of peat production are primarily decreased by developing more environmentally sound peat production and cleaning techniques, by increasing underdraining in peat production areas and by optimizing the fraction size of drying milled peat. Dust emissions of peat production is given special attention in the case of vacuum harvesting of peat. Formation of greenhouse gas -emissions of peat production will also be studied. Reduction of environmental load is researched also in the new Energy and Environmental Technology Research Programme.

4.4 Use of bioenergy

The long-term goal of the research in *bioenergy use* is the increase in biofuel use in heat and power production and for space heating of houses and farms. In addition, the decrease of emissions from small-scale burning will be examined. The technical problems arising from an increase in the use of wood fuels and fuel peat are solved and efficient, economical and environmentally sound small-scale energy production techniques are developed. In order to reach these goals, handling and combustion techniques and methods will be developed. The most important projects are:

- the handling and drying of biofuels for new power plant processes,
- the use of biofuels in district heating plants and small-scale power plants and
- improvement of the small-scale combustion techniques and decreasing of the emissions.

The research in combustion technology will be concentrated on the small-scale (< 20 MW_{th}) applications. The research on the larger scale technologies, e.g. power plants using pressurised combustion and gasification is part of the new Combustion and Gasification Research Programme.

4.5 Biomass conversion

The *biomass conversion* research concentrates on the production of environmentally sound biomass-based liquid fuels. The research is directed especially towards the production of fuel oil, liquid fuel for small-scale power production, traffic fuel and fuel additives. The most important research and development projects are:

- liquid fuel production from the by-products of the pulp industry (black liquor, lignin, soap, tall oil) and
- the production of liquid fuel from wood or peat with flash-pyrolysis.

The research for production of biofuels for traffic is done in close co-operation with the new Research Programme on Energy and Environment in Transportation. The research topics are derived from the traffic energy and environmental point of view.

5 Applicability of research results

It is possible to maintain a competitive wood fuel by developing the *production of wood fuels* in Finland. This also has an effect on the Finnish national economy. In 1991 the total primary energy requirement in Finland was about 30 million toe. A level of 1 million toe could be achieved with new wood fuel production methods. This amount would represent about 3 % of the present energy requirement in Finland.

By developing wood fuel production it is possible to increase the economic utilisation of small-sized first thinning trees and also solve the silvicultural problems of first thinning forests. The increase in wood fuel utilisation also decreases the CO_2-emissions. Replacing e.g. 1 million toe/a coal with wood fuels decreases the CO_2-emissions by about 3.8 million t/a. During 1990 fossil fuel CO_2-emissions into the atmosphere were about 53 million tons in Finland.

The peat production research directly benefits industrial peat production. The machinery developed in ongoing research programmes have not yet been fully utilized. Applying the research results in practice will happen in the early years of this research programme. These results, as well as new results from the research and development programmes will also secure the effectiveness and competitiveness of peat production in the future and, in addition respond to the environmental regulations set for peat production.

VTT has estimated, that the use of bioenergy could be increased by 3 million toe till the year 2010, i.e. to the level of 8.5 million toe. At the same time, the power production could be increased by ca. 2000 MW_e with biofuels. Till the year 2000, the figures could be 1.5 million toe and ca. 1000 MW_e respectively. The increase in power production would consist of small-scale power production (160 MW_e), peat-fired condensing power production (300 MW_e), municipal combined heat and power production (160 MW_e) and pulp and paper industry combined heat and power production (330 MW_e).

AN EVALUATION OF THE REGIONAL SUPPLY OF BIOMASS AT THREE MIDWESTERN SITES

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Abstract

Research has been conducted on both the agronomy and the conversion of biomass. However, few studies have been initiated that combine the knowledge of growing biomass with site specific resource availability information. An economic appraisal of how much biomass might be grown in a specific area for a given price has only just been initiated. This paper examines the economics of introducing biomass production to three midwest representative areas centered on the following counties, Orange County, Indiana; Olmsted County, Minnesota; and Cass County, North Dakota. Using a regional linear programming model, estimates of economic feasibility as well as environmental impacts are made.

At a price of $53 per metric ton the biomass supplied to the plant gate is equal to 183;251 metric tons. At $62 per metric ton the biomass supply has increased to almost 1 million metric tons. The model predicts a maximum price of $88 per metric ton and at this price, 2,748,476 metric tons of biomass are produced.

Introduction

Increased interest in the development and utilization of alternative energy sources has shown that biofuels can be a feasible substitute for fossil fuels. Research indicates that a national energy program dedicated to the production of fuel from lignocellulosic crops could have major impacts on traditional energy sources in the United States. With proper development and with open and constant markets, energy from biomass could supply up to 10 percent of the nation's energy consumption (Biofuels and Municipal Waste Technology Division). Furthermore, biofuels have additional benefits not found in traditional fuel sources. These benefits include that: biomass represents a renewable energy source; biomass lessens our nation's reliance on fossil fuels; biomass fuel use is relatively benign to the environment; and biomass represents an alternative crop for farm regions facing low crop prices.

While substantial research has been conducted on the adaptability of biomass grown as a commercial energy crop, and on the process of converting biofuel crops into energy, little work has been completed analyzing the economic and physical impacts of biofuel production in an agriculturally based area. Stable biomass supplies would require substantial land use shifts from traditional to energy crops. Hectarage currently devoted to traditional crops will be replaced by biomass feedstocks if biomass production proves to be economically more attractive. Depending upon crop mixes, such shifts could have direct environmental impacts as levels of leaching, precipitation run-off, fertilizer and pesticide usage, and soil erosion change. Changes in farm income, food prices and government farm program participation may also occur. This study attempts to address some of these issues by analyzing the impacts arising from a biomass conversion facility located in each of three midwest regions.

The objective of this study is to determine the feasibility of supplying agriculturally-produced switchgrass to a potential biomass conversion facility located in Cass County North Dakota. The analysis includes estimitation of quantities of biomass supplied, changes in traditional crop sector activities, and environmental impacts. The supply of biomass is a function of its price, land resources available and costs of transportation. Environmental impacts are a function of price and hence of supply, changes in cropping practices and any change in erosion parameters.

In the Cass County region alone, there exist more than 6 million hectares (15 million acres) of cropland on more than 18 thousand farms. Currently, small grains dominate, however most of the region's farmland has the potential to produce biomass such as switchgrass, a grass native to much of the midwest. Given adequate institutional support, farmers may select switchgrass as an alternative crop enterprise.

In each region, a county has been identified to serve as the region center and as a potential site for the conversion plant location. Counties surrounding the processing plant have been aggregated into three hauling subareas based upon distance from this regional center. Transportation costs of biomass feedstocks are assumed to be a significant portion of production cost, therefore, within a region, subareas have been created to distinguish separate hauling distances. Counties within a 48 kilometer (30 mile) radius of the plant site are defined as being included in Hauling Region 1. Counties within a 48-96 kilometer (30-60 mile) radius are in Hauling Region 2, and Hauling Region 3 includes all other counties within a 145 kilometer (90 mile) radius.

One potential plant site for biomass conversion is located in Cass County North Dakota. The Cass County region is comprised of twenty-six counties located in eastern North Dakota, western Minnesota and northeastern South Dakota. Farms in eastern North Dakota and western Minnesota are located in the Red River Valley; an agriculturally significant region known for small grain and row-crop production.

Olmsted County Minnesota is the second conversion plant site. This region includes 42 counties in southeastern Minnesota, southwestern Wisconsin and northeastern Iowa. Farms traditionally grow row-crops, primarily corn and soybeans, with some oat and hay production. The final plant site is located in Orange County Indiana. This region includes 58 counties in southern Indiana, northwestern Kentucky and southeastern Illinois. Like the two previous regions, it has been subdivided into three subareas by hauling distance. Space limitations prevent a detailed analysis of each region; thus, only the Cass County region is examined further in this paper.

Soil and Crop Information

Information for the determination of soils and their characteristics is taken from the 1982 National Resources Inventory (NRI). The NRI is the federal government's primary information source for assessing the condition of the nation's water, soil and related resources (USDA, SCS). Acres in the region are summed by Major Land Resource Area (MLRA) and by Land Quality Group (LQG). Each LQG represents a particular Land Capability Class and Land Capability Subclass. Within that summation the dominant soil is determined based on number of hectares. One dominant soil is chosen to represent each particular LQG within an MLRA.

Crop yield and erosion estimates for each MLRA, LQG and rotation are simulatedud using the *Erosion Productivity Impact Calculator* (EPIC) (USDA, ARS), a plant growth and erosion simulator. The EPIC program requires weather generation parameters, and soil and tillage data for it to simulate soil erosion, plant growth and related processes over time. Weather generation data from Bismarck, North Dakota is used on all runs of EPIC. Representative soils for each land group in the model are selected using NRI data. Tillage and production practices, including levels of input use for the selected crop rotations are determined from the crop budgets developed for Cass County.

Representative crops for the region are selected based upon the 1987 Census of Agriculture (USDC). The Census of Agriculture provides numerous county and state estimates of agriculturally related, land use categories. For the purposes of this study, hectares in each crop are summed by MLRA, expressed as a percentage of harvested cropland, and sorted by hectares in descending order. Once crops are selected as representative of the region and MLRA, a set of rules from English provides the criteria for establishing which crops are required in rotations. Adoption of these rules provides assurance that crop production, as estimated by the Census of Agriculture, is reflected accurately in each MLRA.

After the crop rotations are selected, the 1982 NRI provides a list of actual rotations being grown by MLRA with rotations in hectares in descending order. By combining crop data from the Census of Agriculture, with rotations actually grown from the NRI, a set of rotations for the region are developed meeting these rotation rules. Each MLRA in the Cass County region produces a unique set of crop rotations. A total of 51 different rotations containing various combinations of traditional crops grown in the region are selected for the model. For the Cass County region the predominate crops include wheat, barley, sunflowers, corn grain and hay.

Budget Development

The development of budgets for the Cass County Region requires the selection of management practices, inputs, prices, costs and quantities for each specific crop. North Dakota State University (NDSU) Extension Service publications are used to develop this data. Specific costs are estimated through use of the *Budget Planner Version 2.0* developed by North Carolina State University and distributed by the University of California, Davis (Klonsky).

Machinery Component

The equipment data is taken directly from a list produced by the NDSU Extension Service (Swenson and Aakre). The implements are consistent with those in use on a 600-800 hectare (1,500-2,000 acre) farm growing a combination of small grains, hay and row-crops in the Red River Valley of southeastern North Dakota. Purchase price, annual use, years of life, trade-in value and hectares per hour are provided for each machine and placed directly in *Budget Planner.* All equipment is assumed to be purchased new in 1992 and depreciated accordingly. This extension bulletin also includes a listing of common tillage practices for the area when growing small grains. Row-crop and hay management practices are assumed to utilize common, conventional tillage techniques.

Inputs

Fertilizer recommendations are derived from Dahnke and Fanning and assume a market yield as the yield goal and soils containing "medium" amounts of primary nutrients. Herbicide and insecticide application rates are from Meister. All fuel prices, seed prices and quantities, market yields and fertilizer prices are from Swenson and Aakre. Machine and non-machine labor costs are assumed to be $8 and $10 per hour respectively. Twine is purchased per kilogram and the number of required kilograms per hectare depends on the crop and year. Both long and short term interest rates are assumed to be 6 percent. Current cropland rent per acre is $39.53 (Swenson and Aakre).

Fixed Costs

Cash fixed costs are allocated to individual crops in *Budget Planner* based upon the relative hectares of that crop. Annual telephone expenses are assumed to be $440 per telephone, and office expenses are $1,500 per year. Equipment insurance rates of $4 per $1,000 of equipment, and property tax rates of $5 per $1,000 of assets, are assumed. Equipment repair costs are calculated by *Budget Planner*. Noncash fixed costs, include buildings and other depreciable assets, have a total value of $75,500. Their combined salvage value is $5,600, with an average useful life of 26 years and total annual repairs of $800.

Methodology

A linear programming model is used to estimate biomass supplies and changes in current cropping practices. The model maximizes net revenue subject to various resource constraints. Prices for biomass production are changed in an incremental fashion, thereby producing an estimated biomass supply curve.

Space limitations prevent a detailed description of the mathematical model used in this study, however, a complete model description is available from the authors.

The objective function is subject to several constraints including land, labor, fertilizer and energy. The land constraints require that production activities not exceed the total amount of land available or the amount of land having conversion potential. The fertilizer constraint requires that the amount of fertilizer not exceed that which is purchased plus the amount available in the region from livestock wastes. Energy and labor are also constrained, limiting the objective function potential.

Supply of Biomass

Developing a supply curve for biomass requires estimating the quantities supplied at various prices (Figure 1). Biomass price changes in this analysis ran from $44 to $88 per metric ton ($40 to $80 per ton) delivered biomass in $2.00 increments. Biomass does not appear at the plant gate until a price of $53 per metric ton ($48 per ton) is reached. At this price, biomass supply is equal to 183,251 metric tons (202,000 tons). At a price of $62 per metric ton ($56 per ton) the biomass supplied is in excess of 900,000 metric tons (1 million tons). At $70 per metric ton ($64 per ton) the biomass supply equals 1,995,806 metric tons (2,200,000 tons). By the maximum of $88 per metric ton ($80 per ton), estimated biomass supplies are 2,748,476 metric tons (3 million tons) at the plant gate.

When no biomass is produced, the region produces 1,173,280 metric tons (46,190,000 bushels) of corn for grain, 1,248,921 metric tons (45,890,000 bushels) of wheat, 647,729 metric tons (29,750,000 bushels) of malting barley, 406,872 metric tons (14,950,000 bushels) of soybeans, 16,534 metric tons

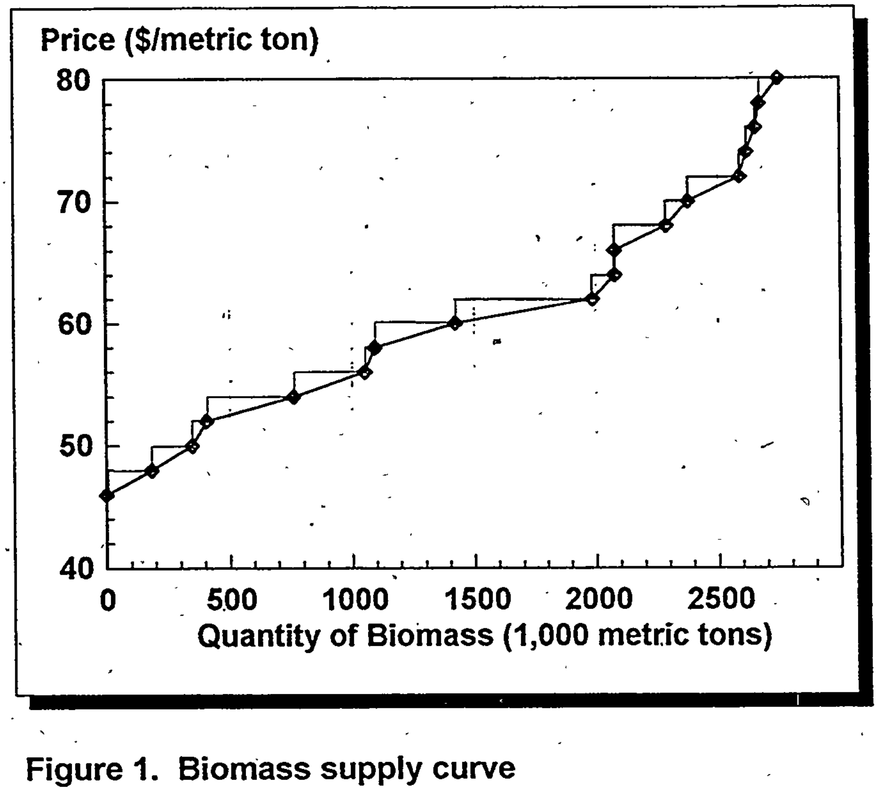

Figure 1. Biomass supply curve

(1,139,158 bushels) of oats, 27,408 metric tons (604,254 hundredweight) of sunflowers and 41,213 metric tons (45,430 tons) of legume hay. In this solution, no corn silage or non-legume hay is produced. For all crops produced, over 50 million kilograms (110 million pounds) of nitrogen, 9.5 million kilograms (21 million pounds) of phosphorus, and 20 million kilograms (44 million pounds) of potassium are applied.

At a price of $56 per ton, quantity of wheat has fallen to 1,045,348 metric tons (38,410,000 bushels), both corn and barley are at 736,634 and 631,400 metric tons (29,000,000 bushels) respectively, oat production has dropped to 12,157 metric tons (837,595 bushels), and legume hay has decreased to 37,817 metric tons (41,687 tons). Both soybean and sunflower production has remained unchanged. At this biomass price, 106,545 hectares (263,280 acres) of cropland have shifted into biomass production. Fertilizer quantities have also fallen; nitrogen has decreased to 39.5 million kilograms (87 million pounds), phosphorus is used at a rate of 8 million kilograms (18 million pounds) and potassium is 17 million kilograms (37 million pounds).

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ENERGY CONVERSION OF ANIMAL MANURES: FEASIBILITY ANALYSIS FOR THIRTEEN WESTERN STATES

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Abstract

The growth and concentration of the livestock industry has led to environmental disposal problems for large quantities of manure at feedlots, dairies, poultry production plants, animal holding areas and pasturelands. Consequently, waste management systems that facilitate energy recovery are becoming increasingly attractive since they address pollution problems and allow for energy generation from manure resources. This paper presents a manure resource assessment for the 13 U.S. Department of Energy, Western Regional Biomass Energy Program states, describes and evaluates available energy conversion technologies, identifies environmental and regulatory factors associated with manure collection, storage and disposal, and identifies common disposal practices specific to animal types and areas within the WRBEP region. The paper also presents a pro forma economic analysis for selected manure-to-energy conversion technologies. The annual energy potential of various manures within the WRBEP region is equivalent to approximately 111 x 10^{13} Btu. Anaerobic digestion systems, both lagoon and plug flow, offer positive economic returns in a broad range of utility service territories.

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Introduction

This paper presents the results of one project conducted under the auspices of the U.S..Department of Energy, Western Regional Biomass Energy Program (WRBEP). WRBEP is a leading organization in the identification, development and commercialization of various biomass resources and technologies in the thirteen WRBEP states, which are as follows: Arizona, California, Colorado, Kansas, Nebraska, Nevada, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, Utah and Wyoming. Figure 1 provides a map showing the WRBEP territory.

The growth and concentration of the livestock industry has led to the generation of large quantities of manure at feedlots, dairies, poultry production plants, animal holding areas and pasturelands. If not properly managed, livestock waste can cause significant harm to both water and air quality. Throughout the nation, increasing regulatory pressure has been imposed to reduce water contamination and methane emissions associated with large livestock operations. Consequently, waste management systems that facilitate energy recovery are becoming increasingly attractive since they address pollution problems and allow for energy generation from manure resources.

The purpose of this paper is to:

- present a manure resource assessment for the 13 WRBEP states;
- describe and evaluate available energy conversion technologies;
- provide an economic analysis for energy conversion of manures;
- identify environmental and regulatory factors associated with manure collection, storage and disposal, and identify common disposal practices specific to animal types and areas within the WRBEP region; and
- Outline future efforts.

Resource Assessment

The animals inventoried for the resource assessment include feedlot cattle, dairy cows, swine (breeder and market), and poultry (layers, broilers and turkeys). In calculating the energy potential of manure produced per animal type, the following factors were taken into consideration: volatile solids produced per day, biogas energy content, waste management system loss, and energy conversion efficiency. Table 1 lists the assumptions used for each animal type.

The energy potential of manure resources per ton varies significantly from animal to animal. Therefore, total animal numbers are not always as significant as manure volume per animal type and the biogas content per ton. Table 2 shows the volatile solids, collectible solids and energy potential for manure per 1,000 head of each animal type for one year.

Calculations and data provided in this paper indicate an energy potential of about 111 trillion Btu (22 million barrels, in oil equivalent) produced annually in the WRBEP region. The energy potential composite figure may not pinpoint the true economic potential, but illustrates the magnitude of the manure resource. Table 3 shows the ranking of the 13 WRBEP states in terms of the energy potential of manure resources.

Table 1. Assumptions for Calculating Manure Energy Potential

Assumptions	Feedlot Cattle	Dairy Cows	Market Hogs	Breeding Sows	All Swine	Poultry Layers	Poultry Broilers	Turkeys
Volatile Solids (VS) (lb/TAM*/day)[1,2]	5.7	11.2	1.1	1.76	1.2	0.048	0.032	0.13
Biogas Production (ft^3/lb VS destroyed)	9.6	14	8	8	8	8.6	8.6	8.6
Biogas Energy Content (Btu/ft^3)	600	600	650	650	650	600	600	600
Typical Waste Mgmt System Handling Loss [3]	25%	10%	10%	10%	10%	10%	10%	40%
Digester Efficiency[3]	50%	35%	50%	50%	50%	60%	60%	60%

* TAM refers to typical animal mass

[1] Barker

[2] ASAE 1990

[3] Wilcox 1993

Table 2. Manure Energy Potential Per Year for 1,000 Animals

Animal	Volatile Solids (tons/year)	Collectible Solids (tons/year)	Potential Energy (MMBtu/year)
Dairy Cows	2,044	1,840	10,817
Feedlot Cattle	1,040	780	4,494
Swine Breeders	321	257	1,336
All Swine	217	173	902
Swine Market	201	161	835
Poultry Turkeys	24	14	88
Poultry Layers	9	8	49
Poultry Broilers	6	5	33

* MMBtu refers to millions of Btu

In terms of animal populations, the states of California, Nebraska, Texas, Kansas and South Dakota rank high within the WRBEP area in most individual animal categories. California is number one among WRBEP states for dairy cow, turkey and layer production and number two for broiler production. Nebraska is the top WRBEP state for feedlot cattle and swine. Texas ranks first in broilers and second in feedlot cattle, layers and dairy cattle. South Dakota ranks second in swine and third in dairy cows, poultry layers and broilers. Colorado is in the top half of WRBEP states for feedlot cattle, swine and turkeys. Oklahoma ranks third in poultry broilers. Arizona, Wyoming, Utah, North-Dakota, Nevada and New Mexico rank low in terms of animal populations for most individual animal categories examined in this paper..

Table 3. Summary of WRBEP States Annual Manure Resource Energy Potential

State	Volatile Solids (tons/yr.)	Collectible Solids (tons/yr.)	Potential Energy (MMBtu/yr.)
Nebraska	7,137,861	5,548,689	31,432,811
Texas	5,288,556	4,396,126	26,203,432
California	4,163,179	3,530,725	20,841,160
Kansas	2,417,181	1,897,990	10,785,830
Oklahoma	1,271,552	1,133,594	6,906,154
South Dakota	995,384	839,111	4,700,018
Colorado	583,720	475,077	2,730,882
Arizona	436,080	361,104	2,088,017
New Mexico	337,599	283,399	1,653,411
Utah	334,025	264,537	1,568,116
North Dakota	308,414	270,541	1,544,703
Nevada	91,378	75,216	435,899
Wyoming	78,877	63,180	364,245
Total	**23,443,806**	**19,139,289**	**111,254,678**

Federal and State Regulations to Control Pollution from Livestock Waste

The principal pollutants from livestock waste are ammonia, excess nutrients and pathogens, along with biochemical oxygen demand (BOD). The major pollution problems associated with livestock waste are methane emissions from anaerobic digestion, surface water and groundwater contamination, and air pollution due to the formation of odor, dust, volatile organic acids and ammonia. Current federal and state regulations governing manure disposal target two areas: water quality and air quality.

Federal Regulations

Water Quality

The first comprehensive federal effort to improve water quality was the implementation of the Clean Water Act in the early 1970s. The initial focus of the CWA was regulating "point sources" of pollution. Livestock point sources consist of man-made structures such as feed pens, confinement buildings, slurry tanks, pipes or culverts, holding ponds or lagoons, irrigation systems, and dead animal disposal facilities (Sweeten 1991). Livestock point sources are directly regulated by the U.S. Environmental Protection Agency, or by state agencies on behalf of the U.S. EPA.

Any concentrated animal feeding operation (CAFO) that discharges pollutants into U.S. waters must obtain a National Pollutant Discharge Elimination System (NPDES) permit (CWA, Section 402). The basic requirements of the NPDES require "no discharge" from CAFOs into U.S. waterways. For an animal feeding operation to be considered a CAFO, the following criteria must be met (Weinberg 1991):

1. Animals are stabled or confined and fed for 45 days or more in a twelve month period;
2. Vegetation is not sustained on any portion of the lot or facility;
3. The feedlot must have *either*:
    A. 1,000 animal units (AUs) (Beef cow = 1 AU; dairy cow = 1.4 AU; swine = 0.4 AU) and discharge pollutants, or,
    B. between 301 and 1,000 AUs, if pollutants are discharged into:
        i. navigable waters through a man-made conveyance; or,
        ii. into navigable waters that originate outside of, but come into contact with the area used by the operation;
4. Pollutants are discharged in absence of a 25-year frequency, 24-hour duration rain storm.

Smaller facilities (less than 300 AUs) may be designated as CAFOs on a case-by-case basis if they present a significant risk to water quality. Most small facilities, however, are classified as non-point sources of pollution. Section 319 of the Clean Water Act creates a program to control non-point sources, including range and pastureland, feeding and watering sites, small-scale confinement facilities and manure disposal areas. Section 319 requires each state to submit both an assessment of state waters not expected to meet water quality standards because of non-point source pollution and a management program for controlling non-point source pollution. Most federal efforts to control agricultural non-point sources have emphasized a voluntary, non-regulatory approach based on the implementation of best management practices (BMPs) instead of regulation-driven treatment plans.

Air Quality

Methane can be produced through the fermentation of organic matter in the digestive tracts of animals and is one of the "greenhouse gases" that contribute to global warming. The federal government does not have any formal rules or regulations aimed at reducing methane emissions in the United States. However, the U.S. EPA, Global Change Division, is currently in the process of assessing the feasibility of capturing methane for conversion to on-farm electricity (Roos 1993).

State Regulations

Throughout the WRBEP region, the responsibility for developing and enforcing manure disposal regulations usually rests with state water quality control divisions. At a minimum, all of the states in the WRBEP region adhere to the U.S. EPA regulations governing discharges from 1,000 AU or greater animal feeding operations. Many states, including Arizona, California, Colorado, Nebraska, and Texas have more stringent regulations than those required by the federal government, and several allow local authorities to enact regulations even stricter that those imposed by the state.

Livestock Waste Storage and Disposal Methods

Manure can be collected in either a liquid, semi-solid slurry or solid form depending on the animal and operation type. Table 4 provides a brief description of 10 manure management systems utilized in the WRBEP area.

Table 4. Manure Management System Descriptions

System	Description
Pasture and Range	Manure from free-range animal grazing is allowed to lie where it falls, and is not handled in any formal manner.
Daily Spread	Manure is collected in any form on a daily basis and field spread.
Solid Storage	Manure is collected daily or biweekly as a solid or semi-solid and stored for several months before it is applied to fields.
Deep Pit Solid Stacks	Manure (from caged layers and occasionally broilers) falls into deep, well-ventilated pits. The dried manure is removed periodically and field spread.
Drylot (paddock)	Manure is allowed to accumulate in unpaved, open or semi-covered feedlots. The dried manure is removed and disposed of, usually as a soil amendment.
Litter	Poultry is often raised on beds of litter (wood shavings, straw, etc.). Manure is deposited directly into the litter, and the litter is removed periodically.
Pit Storage	Swine are sometimes raised in buildings with slatted floors and storage pits below. Manure stays in pit storage from 3 to 6 months.
Liquid/Slurry Storage	Liquid or slurry manure is stored in outside pits, tanks or lagoons. A typical lagoon has adequate space to retain 3 to 6 months waste.
Anaerobic Lagoon	A lagoon is often designed to treat waste and reduce odor, pathogens and BOD. The lagoon water can be recycled for field application.
Anaerobic Digester	Liquid or slurry manure is placed in a digester to undergo controlled decomposition and produce and recover methane for energy purposes.

Energy Conversion Technologies for Animal Manures

Various technologies are available for the conversion of animal manures to energy, including direct combustion, gasification and anaerobic digestion systems. In general, the preferred technology for on-farm energy conversion is anaerobic digestion because of its simplicity, compatibility with common manure management technologies, and relatively low initial capital costs. This paper focuses on anaerobic digestion, although certain gasification technologies may offer competitive advantages in the future. Further, there is one large-scale combustion system in operation in California that illustrates the feasibility of the combustion technology (NEOS 1990).

Anaerobic Digester Technology

An anaerobic digester is essentially a vessel containing bacteria that decompose organic matter and produce biogas in the absence of oxygen. The anaerobic digestion process occurs in three stages: hydrolytic, acid forming, and methanogentic. During the first stage bacteria break complex organic materials into simple sugars. In the second stage, anaerobic and facultative heterotrophic bacteria break down the simple sugars into simple organic acids. In the final stage, bacteria known as methanogens utilize simple organic acids in two decomposition pathways to produce methane. The first reaction splits acetic acid into methane and carbon dioxide while the second reaction combines hydrogen and carbon dioxide into methane and water

The simplest anaerobic digester is the ambient anaerobic lagoon. Manure in an adequately sized lagoon will progress naturally through all three stages. Five other unit processes - plug flow, complete mix, packed reactor, upflow sludge blanket and sequencing batch reactor - control environmental conditions in the digester to optimize methane production. Table 5 illustrates the levels of process complexity (i.e. the number of mechanical components) and operational complexity (i.e. the amount of maintenance and labor required for the production process) for the six digesters. The table also shows relative initial and operating costs. It is not surprising that the costs follow the process and operational complexity patterns.

Table 5. Digester Characteristics

Digester Process	Process Complexity	Operational Complexity	Capital Costs	Operating Costs
Ambient Temperature Covered Lagoon	Low	Low	Low	Low
Plug Flow	Low	Low	Low	Low
Complete Mix	Medium	Medium	Medium	Medium
Packed Reactor	Medium	Medium	Medium	Medium
Upflow Sludge Blanket	High	High	High	High
Sequencing Batch Reactor	High	High	High	High

Economic Analysis

The economic analyses presented in this paper illustrate a range of technologies and animal operations in distinct niche markets. The intent is to depict the breadth of the manure energy conversion facilities. Table 6 shows the location, technology, capacity (kW), and manure types for each of the five economic models.

Table 6. Manure-to-Energy Facility Sites

Location	Technology	Capacity (kW)	Manure Types
South Dakota	Plug Flow Digester	35	Dairy cows
Nebraska	Complete-Mix Digester	101	Swine, market
Texas	Covered Lagoon Digester	41	Dairy cows
California	Covered Lagoon Digester	81	Dairy cows
California	Direct Combustion	20,000	Dairy cows, feedlot cattle

Income Statements

Pro forma income statements were developed to model the feasibility of each of the five manure-powered energy projects. Basic economic and technical assumptions for anaerobic digesters were formed to allow variations in location, economic conditions, and technology. The assumptions are based on prior research and available data best suited for the technology and location of the facility and are summarized in Table 7.

The economic analysis focuses on dairy and swine operations because of the prevalent manure management technologies and the energy content of the animal manures. Dairy and swine manure have high moisture contents, making them idea for anaerobic digesters, which require manure in liquid or slurry form. Many swine and dairy operations already employ flushing systems which transport manure as a slurry and are compatible with digester systems.

Table 8 summarizes the significant financial analyses from each of the income statements. Three of the five scenarios modeled for this effort illustrate significant positive economic returns to the farm operation. Some dairy operations employing plug flow and covered lagoon digesters (South Dakota and California) appear to be attractive investments. A swine operation in Nebraska using a complete-mix digester is also projected to be economically feasible.

Table 7. Summary of Assumptions for Five Manure-Fueled Power Plants

Assumption*	South Dakota Plug Flow	Nebraska Complete-Mix	Texas Covered Lagoon	California Covered Lagoon	California Combustor
Animal population	300 cows	10,000 hogs	500 cows	1,000 cows	N/A
Generating capacity	35 kW	101 kW	41 kW	81 kW	20 MW
Installed cost	$144,047	$284,753	$128,082	$201,466	$60,000,000
Fixed O & M costs (per kWh/yr)	$13.20	$13.20	$13.20	$13.20	$11.25
Equipment salvage value	$7,350	$24,975	$8,610	$17,000	$12,000,000
Equipment Life (years)	10	10	10	10	10
Electricity purchase price (per kWh)	$0.075	$0.067	$0.036	$0.050	N/A
Electricity selling price (per kWh)	$0.045	$0.040	N/A	N/A	$0.035
Electricity production (kWh/yr)	216,047	624,137	252,055	504,111	115,632,000
Total on-farm energy consumption (kWh/yr)	180,000	430,000	267,500	600,000	N/A

For complete references, see "Energy Conversion of Animal Manures: Feasibility Analysis for Thirteen Western States (NEOS Corporation 1993)

Additional assumptions that held for all five systems are: Tax rate (20%), inflation rate (5%), discount rate (9%), loan interest rate (9.25%) and down payment on loan (33.3%).

Table 8. Summary of Financial Analyses for Manure-Fueled Power Plants

	South Dakota Plug Flow	Nebraska Complete-Mix	Texas Covered Lagoon	California Covered Lagoon	California Combustor
Net Present Value (NPV)	$43,000	$14,000	($9,000)	$49,000	($33,000,000)
Levelized Cost ($/kWh)	$0.1126	$0.0693	$0.0847	$0.0767	$0.0847

The South Dakota plug flow digester had the highest installed cost on a per-kW-basis. It was also the smallest of the power plants. This means that for its power generating ability it has the highest debt load and has to generate more electricity over the long-run or generate electricity more cheaply than alternative sources.

The Nebraska complete-mix digester has the highest capital cost of any of the anaerobic digestion technologies. The farm is assumed to be a farrow-to-finish swine farm. Swine manure is very low in total solids. Because of this, the only types of digester that could be used are a mixed digester, such as the complete-mix, and a covered lagoon digester. However, a lagoon cannot be easily heated and the temperatures in Nebraska are too cold during the winter to sustain digestion. Thus, the only alternative is the mixed-tank digester.

The Texas lagoon digester is not judged economically attractive for the given assumptions. Despite the low capital and operating costs, this digester is not competitive with grid-connected electricity's low price. However, small increases in manure collection efficiency, from 55% to 65%, would lead to a positive net present value (NPV).

Financially, the California digester performs the best of all four digesters. Its NPV is equal to $48,772 and its levelized cost is $0.0767/kWh. This project, like the Texas digester, would perform even better financially if the manure collection efficiency were to increase. The major difference between the Texas and California covered lagoon digesters is size. The California power plant is 98% larger than the Texas plant. Despite this, its installed cost is only 58% higher.

Using the currently available energy purchase prices for qualifying facilities (QFs), the California manure-burning power plant is not economically feasible. Its NPV is -$33,000,000 and the levelized cost is $0.0847/kWh. The best conditions for improving the financial performance of this facility, or one like it, would be a major increase in QF energy purchase prices. This project may also become feasible if the manure disposal costs rise. The power plant operators may then be able charge for manure removal if there is great enough demand for a cheaper disposal alternative.

Economic Sensitivity Analysis

Sensitivity analyses were performed to measure the effects of altering one or more of the assumptions incorporated in the income statements. The effects on the NPV and levelized cost caused by altering the discount rate, down payment, inflation rate, interest rate, and installed cost are analyzed by changing one factor at a time. Multiple-factor sensitivity analyses were performed to measure the effects of the most likely combination of variations in assumptions.

Altering the discount rate, which represents the time value of money or the opportunity cost of capital, affected both the NPV and levelized cost figures. Decreasing the discount rate increases the present value of future cash flows resulting in a higher NPV and a higher levelized cost for all scenarios.

Varying the size of the down payment changes the amount of capital borrowed. Increasing the down payment *decreases* the NPV. The levelized cost decreases with an increase in down payment because the operating costs are decreased (i.e., annual finance charges are reduced). The converse holds true for all three cases.

Only the operating income portions of the pro forma income statements are affected by the inflation rate. Therefore, increasing the inflation rate increases the apparent revenues and costs. The levelized cost increases as the inflation rate increases simply because the costs increase. NPV increases for the same reason.

The interest rate affects the operating costs by changing the amount of interest paid on the loan. Increasing the interest rate increases operating costs which lowers the project's NPV and increases its levelized cost.

The effect of changing the installed cost of a project on NPV and levelized cost is the same as that of the interest rate. Increasing the installed cost of a project increases the operating costs through increased interest payments and larger down payment which decreases NPV and increases the levelized cost.

In general, the greater the absolute magnitude of the NPV, the less sensitive it is to changes in a factor. For example, the California manure-burning power plant has the greatest NPV when taken as an absolute value. It is the least sensitive of the five power plants to all factors. Conversely, the Texas lagoon digester has the smallest NPV and it is the most sensitive of the power plants to changes in factors. NPV is most sensitive to the installed cost of the project. Even the NPV of the California manure-burning power plant changed ±16.6 by a ±10% change in installed cost. And this power plant was the least sensitive to installed cost of the five power plants.

In the multi-factor sensitivity analyses, performed since it is unlikely that one assumption would vary independently of all others, the assumption with the most influence on the financial strength of the digesters was the installed cost of the power plant. When the effects of varying the assumptions were combined, installed cost had more influence than the other assumptions. For the direct combustion power plant the price paid by the utility for the electricity produced was most significant. The price of electricity did not have the same influence on the digesters because their largest source of revenue was the savings created by displacing grid-supplied electricity.

Economic Analysis Conclusions

Three of the four digester power plants would be feasible, based on their positive NPVs, with the given assumptions. The only digester judged not feasible was the covered lagoon digester in Texas. However, its NPV of -$8,857 is not so low that it could not be improved. In the sensitivity analysis of the Texas power plant, two assumptions, the interest rate and installed cost, proved to have the most influence on NPV. The California manure-burning power plant was not feasible and needs to sell its electricity for almost 100% more than present rates in California to be feasible.

Conclusions

Several major conclusions stem from the analyses in this paper. First, substantial manure resources exist in the WRBEP area. Calculations and data provided in this paper indicate an energy potential of about 111 trillion Btu produced on an annual basis. Although much of this resource may be considered unrecoverable for a variety of reasons, there is ample opportunity to capture energy on a regional scale with modest contributions to the energy balance. Similar to other biomass resources and technologies, niche market opportunities are apparent.

Some animal operations and some states have greater potential for energy conversion than others. Manures that are more appropriate for energy conversion tend to be associated with dairy and swine operations. Manure management systems typical of dairy and swine operations, often liquid- or slurry-based, facilitate the ease of manure movement. Large agriculture-based economies in California, Texas and Nebraska, WRBEP's top three states in terms of manure energy potential, sustain substantial animal populations that contribute to their energy conversion potential. Warmer states within WRBEP, including Texas, New Mexico, Arizona, and California, may have the greatest potential for energy conversion of manures because of the ability to use low-cost lagoon technologies.

Federal and state environmental regulations fostering "best management practices" are major forces influencing the adoption of manure management practices that merge well with energy conversion options. To the extent that regulatory agencies, working in concert with state extension personnel, are able to implement the regulations, greater adoption of energy conversion technologies at the farm level will occur. The regulatory agencies will be challenged to promulgate the regulations. The economic benefits to the farmer associated with the on-farm promotion/enforcement process should be emphasized to facilitate regulatory compliance.

Economic benefits to the farmer appear to be real. Energy conversion technologies such as anaerobic digestion, and to a limited extent, gasification, are more mature than when first promoted in the late 1970s. Lagoon digesters show positive economic results in the warmer WRBEP areas, and plug flow and complete-mix digesters appear to have economic advantages in the colder climates. Although it is critical to emphasize the site-specific nature of the economic analyses, it is clear that opportunities for energy conversion of manure resources exist for animal operations in a broad geographic range within WRBEP.

Future Efforts

Future efforts with WRBEP may be categorized within the technology transfer and technology development areas. It is clear that there are opportunities for livestock operations to utilize energy conversion technologies for manure resources. The WRBEP mission to promote the adoption of economically advantageous technologies should lead to a series of workshops to facilitate the flow of information to farm operators. Coordination of the workshops on a sub-regional basis with state extension personnel will help ensure that the proper audience is reached. The technologies and economic approach used in this study may serve as reasonable templates upon which to base the workshops.

Technology adoption at the farm level will be hampered by the dearth of "real world" data. Many of the energy conversion inputs to the economic model in this paper are based on small data sets. Energy production rates as a function of technology, animal diet and climate are poorly documented, leading to considerable uncertainty for the farm operator. WRBEP has the opportunity to increase data availability by focusing on data collection activities for existing digester operations within the region. Further, WRBEP anaerobic digester PON II recipients should be required to carefully document their activities and collect complete data. Such data collection will be useful in providing the necessary information to farm operators upon which to base their business decisions.

The site-specific nature of determining the economic and practical feasibility of energy conversion of manure resources lends itself to the utilization of a geographic information system (GIS). WRBEP has the opportunity to implement a GIS to complement and coordinate data collection and analysis efforts and improve technology transfer activity efficiency. GIS is increasingly being incorporated into research and data storage efforts to facilitate information retrieval on an area-specific or data element-specific level. A county-level GIS analytical effort, coupled with close cooperation of state extension personnel, will help to identify appropriate targets for energy conversion projects.

Acknowledgments

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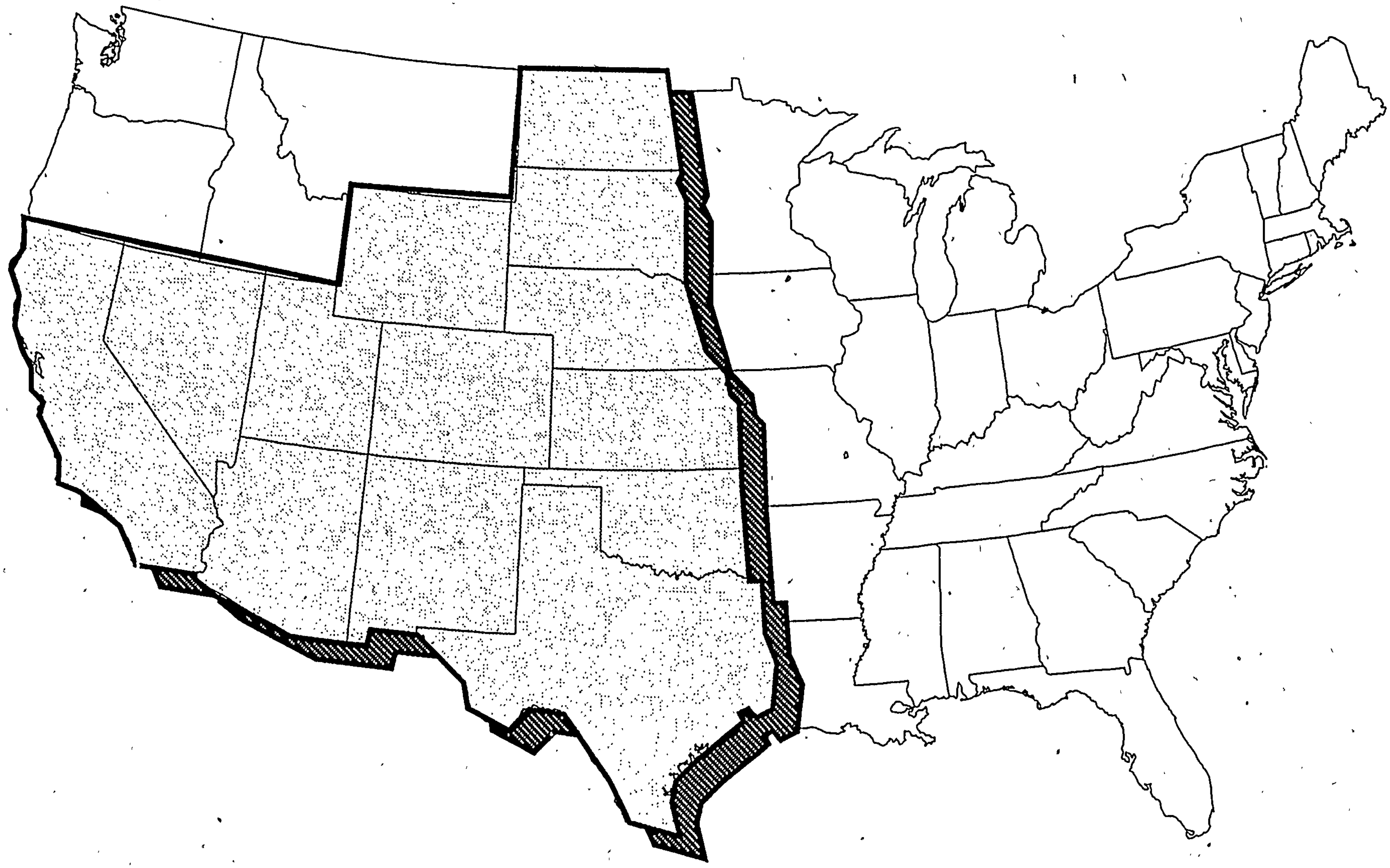

Figure 1. Map of WRBEP Territory

COTTON GIN TRASH IN THE WESTERN UNITED STATES: RESOURCE INVENTORY AND ENERGY CONVERSION CHARACTERIZATION

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Abstract

The disposal of wastes associated with the processing of cotton is posing increasing problems for cotton gin operators in the western United States. Traditional disposal methods, such as open-air incineration and landfilling are no longer adequate due to increasing environmental concerns. This paper evaluates the technical, economic and environmental feasibility for cotton gin trash to serve as an energy resource. Cotton gin trash has been quantified, by county, in the five cotton-growing states of the western United States. The energy conversion technology that appears to offer the most promise is gasification. An economic evaluation model has been developed that will allow gin operators to analyze their own situation to determine the profitability of converting gin trash to energy.

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Introduction

Cotton is among the leading cash crops in the United States. At the farm level alone, the production of each year's crop involves the purchase of more than $4 billion worth of supplies and services. Altogether, business revenue stimulated by cotton is estimated at some $50 billion - the greatest of any U.S. crop (National Cotton Council 1992). Five states (Arizona, California, New Mexico, Oklahoma, and Texas) within the U.S. Department of Energy's Western Regional Biomass Energy Program (WRBEP) territory produce significant quantities of cotton. In these five states, the cotton industry employs more than 100,000 people and generates more than $8.5 billion in revenue (National Cotton Council 1991).

Generally, two mechanical methods are used to harvest cotton - spindle-harvest and stripper-harvest. Gins that process stripper-harvested cotton generally generate larger quantities of cotton gin trash (CGT) than do gins that process spindle-harvested cotton. A commonly accepted value for wastes from stripper-harvested cotton is 609 bone-dry pounds of CGT per bale of cotton ginned, versus the spindle method which yields 109 bone-dry pounds/bale (Thomasson 1990). Table 1 shows the predominant harvest method used in each of the WRBEP cotton states.

Table 1. Cotton Harvesting Methods in the WRBEP Region (Numbers indicate the percent of cotton harvested by each method)

	Cotton Harvesting Method		
State	Spindle	Stripper	Other (Scraped)
Arizona	96	0	4
California	100	0	0
New Mexico	60	40	0
Oklahoma	16	84	0
Texas	28	72	0

(Source: Glade et al. 1993)

A major problem facing the cotton ginning industry is the search for environmentally and economically acceptable methods for disposal of gin trash. Although this problem has been researched extensively, the majority of CGT is still not being utilized in an economically effective manner, and disposal is a costly issue for many ginners and cotton producers (Thomasson 1990). Common disposal methods include spreading on land, composting, feeding to livestock and landfilling. An alternative disposal method is to convert the CGT to energy through gasification.

Common Cotton Gin Trash Disposal Practices in the Western U.S.

A telephone survey was conducted to determine current CGT disposal practices. State cotton ginners' associations were contacted to identify important characteristics of the cotton industry for each cotton-producing state in the WRBEP region. Representative cotton ginners and cotton seed oil crushers in each cotton-producing county were contacted and asked to provide information regarding waste disposal practices. State and federal regulations regarding cotton gin trash disposal were also assessed (Cohen and Lansford 1992).

Although there is at present no single most desirable method of CGT disposal, there is a great opportunity for entrepreneurs who wish to pursue more profitable uses for CGT (Thomasson 1990). The problem faced in CGT disposal is two fold. Ginners must not only collect and store CGT, but also dispose of it, and both operations must be performed without excessive air pollution. Storage of CGT throughout the ginning season is undesirable because of potential fire hazards and because most gins do not have enough storage facilities. There are many ways to dispose of CGT, including field application, composting, use as livestock feed, conversion to energy, and disposal in landfills.

About 85% of the gins surveyed spread CGT on farmland. Feeding CGT to livestock was the second most used disposal practice (41%), followed by composting (11.5%) and landfilling (.33%). None of the gins surveyed reported incinerating CGT, and many gins used more than one CGT disposal practice. Figure 1 shows this breakdown (Cohen and Lansford 1992).

Federal and State Regulatory Issues

Federal regulations concerning CGT disposal are obscure, as most federal regulations found for this study were not specifically set up for CGT, but rather focused on air pollution, solid waste disposal, and on the presence of chemicals that may have been sprayed on or are naturally occurring in cotton. For example, aflatoxins are naturally occurring mycotoxins produced by molds that may be found in cotton gin trash and other animal feeds.

The Clean Air Act was amended in 1990 to provide a more effective program to improve the quality of the nation's air. Sections 107-110 of the act address air quality control regions, air quality criteria and control techniques, national ambient air quality standards, and implementation plans. While there is nothing specific to CGT disposal, these sections set forth laws stating that every state must adopt some type of air quality control program, and set forth guidelines as to what must be included in these programs.

Public Law 94-580 (1976), the Solid Waste Disposal Act, provides technical and financial assistance for material and energy recovery from discarded materials, the safe disposal of discarded materials, and regulates the management of hazardous wastes. Sections 1001-1008 give the General Provisions under this act. Since nothing more applied to CGT it was assumed that disposing of CGT in approved landfills is not prohibited by the federal government.

Section 40 of the Code of Federal Regulations (CFR) addresses environmental protection. Part 50 of this section specifically addresses the national primary and secondary ambient air quality standards and part 50.6 sets the national level for particulates. CGT disposal would fall under this section due to the dust that it can generate. Section 40, Part 186 may relate to CGT disposal, because some CGT is used for animal feed. This section gives the Federal Regulations of Tolerances for Pesticides in Animal Feeds. Part 186.588 sets a standard of 6 parts per million of S, S, S, Tributyl phosphorotrithioate in cattle feed. This chemical is a common cotton defoliant that could be a component of CGT. Some of the trade names for this defoliant include Folex, Parathion (generic name), and D.E.F.

Section 21 of the CFR addresses food and drugs. The Food and Drug Administration regulates the amount of aflatoxins allowed in animal feed. Part 509 governs unavoidable contaminants in animal food and food-packaging material and includes aflatoxins. The level was set at 20 parts per billion in 1969, but in 1982 the FDA raised the level to 300 parts per billion in animal feed.

State regulations were determined by contacting state government air quality offices. All of the state offices have regulations concerning air quality that either follow or are more strict than the national guidelines. Oklahoma and Arizona have specific regulations concerning CGT. No regulations could be obtained that specifically addressed CGT for other states. None of the states had any restrictions on landfilling CGT.

Cotton Gin Trash Availability in the WRBEP Region

This section presents findings of a resource assessment of total CGT production, by county, for the five major cotton-producing states in the western United States. For comparative purposes, information on energy potential is also included. The amount of CGT generated in each county is based on the method of harvest (stripper vs. spindle) as well as the total amount of cotton *produced* in that county, not the total amount ginned. This methodology was chosen because the data for total cotton ginned, by county, are incomplete. Although it is likely that not all of the cotton grown in a given county is ginned in that same county, it is believed that the amount of cross-county cotton movement is minimal (Johnson 1993; Mayfield 1993). Thus, this approach offers the best way to estimate CGT availability by county.

This assessment utilizes U.S. Department of Agriculture, National Agricultural Statistics Service (USDA/NASS) data for average annual cotton production based on the years 1981 through 1991. Data for 1986 and 1983 were not included in these calculations due to lack of availability. To adjust for seasonal variations in cotton production, a ten year average (1981-1991) was used to estimate annual CGT generation. State-level annual production figures for the years 1967-1991 were analyzed to determine long-term trends in the industry. Table 2 provides a state summary of the county-level data.

Table 2: Cotton Gin Trash Production (1981-1991 average) and Number of Gins

State	ANNUAL COTTON GIN TRASH Average 1981-1991 (bone dry tons)	ACTIVE GINS	ESTIMATED ENERGY POTENTIAL (Million BTUs/YR)	ANNUAL BARRELS OF OIL EQUIVALENT
Arizona	60,967	90	816,953	140,370
California	155,454	138	2,083,089	357,919
New Mexico	5,411	26	72,507	12,458
Oklahoma	85,076	63	1,140,018	195,879
Texas	1,065,925	494	14,283,395	2,454,192
Total WRBEP Region	**1,372,833**	**812**	**18,395,963**	**3,160,818**
Rest of U.S	258,955	724	3,469,997	596,219
Total U.S	1,631,788	1536	21,865,960	3,757,038

Source: USDA NASS; Cotton Ginnings (Summary reports for the years 1981 through 1991)

As indicated in Table 2, there are approximately 1.6 million bone dry tons of cotton gin trash generated annually in the United States at 1,536 gins. The WRBEP region produces approximately 1.4 million tons, or more than 80 percent of the nation's total. Texas alone produces almost two thirds of U.S. CGT. Texas also has more cotton gins than any other state in the country, and as indicated, produces more than five times the CGT as the next closest state, California. Oklahoma and Arizona also produce significant quantities of CGT. Outside of the WRBEP region, Mississippi is the largest producer, generating approximately 90,000 bone dry tons per year. Figure 2 is a regional map of the western cotton producing states, showing the major cotton producing areas within each state.

Arizona

Two counties, Maricopa and Pinal, generate approximately 45,000 tons of CGT, or nearly 75% of Arizona's 60,967 annual tons of CGT. These two counties also contain 58 out of the 90 active cotton gins. Although cotton is harvested using the spindle method (which yields less CGT per bale than the stripper method), the sheer volume of cotton grown and ginned in Arizona leads to the generation of large quantities of CGT. The quantity of cotton ginned in Arizona in 1991 is approximately 60 percent higher than the quantity ginned in 1967. The number of active gins in Arizona has declined from a high of 120 in the late 1970s to a low of 85 in 1991. The increase in the overall quantity of cotton ginned coupled with the decrease in the number of gins means that the volume passing through each gin has steadily increased. It appears that several counties in Arizona may be candidates for pilot CGT to energy projects.

California

Most of California's CGT is generated in the San Joaquin Valley counties of Fresno, Kern, Kings, Tulare, Madera and Merced. These six counties generate nearly 150,000 tons of CGT, or 95 percent of California's annual total. The number of cotton bales ginned in California in 1991 is more than double the quantity ginned in 1967, while the number of active gins in California has declined steadily from a high of 270 in 1967 to today's figure of 126. The average number of bales per gin in 1991 was more than 20,000 bales per gin, as compared to approximately 4,000 bales per gin in 1967. Although the CGT generated in California is spread out over a very large geographic area, it appears that there could be opportunities for CGT energy conversion pilot-projects to be developed in any one of the counties mentioned above.

New Mexico

New Mexico produces very little cotton, hence there is very little CGT available in the state. Doña Ana county has the most CGT, with approximately 1,900 tons per year. Based on this information, it is likely that energy production from CGT is not a viable alternative in New Mexico. The average volume of cotton passing through each gin has steadily increased since 1967, but not nearly as much as in the other states in the WRBEP territory. It is likely that New Mexico will remain a small player as far as cotton production is concerned. Based on the information available, opportunities for energy generation from CGT in New Mexico appear to be minimal.

Oklahoma

Oklahoma's cotton producing counties are concentrated in the extreme southwest portion of the state. Most of the cotton in the region is stripper-harvested, which leads to large quantities of CGT being generated in several counties. The counties which have significant amounts of CGT are: Tillman, Jackson, Washita, Kiowa and Harmon. The 231,000 bales of cotton ginned in Oklahoma in 1991 represents only a slight increase over the 189,000 bales ginned in 1967. The number of active gins in Oklahoma has declined from a high of 139 in 1967 to a low of 61 in 1991. The average volume of cotton passing through each gin has steadily increased. This trend reinforces the evidence that CGT is being concentrated at fewer gins in

After more than fifteen years of research by various institutions, especially Texas A&M University, an economically feasible method has been found to convert CGT to energy through a fluidized bed gasification process. To prevent ash slagging, CGT must be converted to a gas in an oxygen-starved atmosphere at a temperature no more than 1450°F at any point in the system. The fluidized bed gasifier is the only gasifier that presently meets these requirements.

Hot Gas Cleanup

When CGT fuel is converted to gas for combustion, ash is entrained in the gas stream. Before oxygen is added to the gas for completion of the combustion process, the ash must be removed to prevent ash slagging. Preferably, the ash removal should take place at the temperature of the hot gas (1200°F to 1400°F) so that sensible heat is not lost during the process. The temperature at which the solids separation takes place can be lower, but it should be higher than 800°F to prevent tar condensation. Removing ash prior to combustion requires smaller solids separation equipment than would be necessary if the solids were removed following combustion, because the volume of gas is much greater following combustion. A smaller solids separation device is a significant advantage of gasification over direct combustion.

A Sample CGT Fueled Energy Conversion System

Figure 3 is a flow chart of a conventional biomass energy conversion system capable of producing electricity from CGT. A more advanced system, although not yet ready for commercial application, utilizes an integrated gasifier and gas turbine and has a much greater efficiency than the system depicted in Figure 3. When this system reaches full development, it will be smaller in size for its power output and more cost effective. In addition to electricity, it is possible to generate process steam and activated carbon (the char-ash) from both of these systems.

Char-ash as a Source of Activated Carbon

A little-used by-product of the CGT gasification process is char-ash. Char-ash, which contains significant carbon, can be separated from the gas stream at low temperatures by means of a cyclone system. For many years, researchers were unsure of how to dispose of this material. However, recent research carried out at Texas A&M University has indicated that the char-ash produced from CGT gasification is a "low quality" activated carbon (AC) with an iodine number of 242, versus a high quality commercial AC with an iodine number of 800 (Parnell et al. 1991). The AC from CGT is considered low quality because it contains more ash than commercial AC. However, research indicates that the CGT activated carbon is just as effective at removing heavy metals and COD from waste water as is commercial AC (Capareda 1990). CGT char-ash may have potential as a source of AC in the water treatment industry.

Activated carbon is used mostly for waste water treatment and drinking water purification. U.S. demand for activated carbon is projected to expand 4 percent a year through 1994 to 147,500 tons annually. Total western world consumption stood at 300,000 tons/year in 1988, with the United States and Japan accounting for 60 percent of the total (Blendon Information Services 1990).

Although municipal-scale treatment plants are still the major market, recently demand has grown for AC-based home water filters. Changes to the Safe Drinking Water Act will increase the number of synthetic organic chemicals and heavy metals that must be controlled in drinking water. The new regulations will also require the lowering of the maximum allowable concentrations of certain organic chemicals (trihalomethane (THM) for example) in drinking water. It has been demonstrated that activated carbon is very effective in removing THM and other organic compounds from drinking water (Lykins et al. 1988).

Oklahoma. Oklahoma appears to have several counties and gins where both gin volume and the amount of available CGT may warrant more detailed investigation of pilot energy production.

Texas

Texas produces more cotton and hence more gin trash than any state in the country. The 10-year average for CGT generation in Texas is more than 1 million tons per year. The high plains area of Texas has the greatest concentration of CGT in the entire United States. Texas has seen a steady increase in the amount of cotton ginned since 1967. In 1991, Texas cotton gins processed more than 4 million bales of cotton. The number of active gins in Texas has declined from a high of 1,200 in 1967 to a low of 472 in 1991. The average volume of cotton passing through each gin has increased nearly five fold since 1967. The top ten cotton producing counties in Texas are Gaines, Lubbock, Hale, Terry, Dawson, Hockley, Lynn, Lamb, Floyd and Crosby. These counties are clustered together, and all generate significant quantities of CGT. This region represents the area with the greatest opportunity for pilot CGT to energy conversion projects.

Energy Production From Cotton Gin Trash

As an energy feedstock, CGT has a major advantage over other biomass resources because CGT does not need to be collected and transported to a processing facility. CGT is already produced at a central facility, the gin, as a by-product of the cotton ginning industry. Converting CGT directly to energy is a seldom-used way to dispose of CGT, requiring special capital-intensive facilities. Because converting CGT to energy is costly, it is likely that only large ginning facilities will consider this an option.

A possible problem with converting CGT to energy is that many cotton gins operate seasonally, and waste is not produced year-round, leading to inefficient use of capital-intensive equipment and thus high fixed costs (Lansford et al. 1984) The newest ginning technology involves the construction of super gins that replace three or four older cotton gins, and use bale moderators to extend the ginning season. As this evolution in the ginning industry continues, the supply of CGT will be concentrated and made available for a longer period of time. The further concentration of gin trash will improve the likelihood that CGT can be used for energy production.

Experience has shown CGT to be a difficult resource to use for fuel because it causes severe slagging in direct combustion, regardless of the type of combustor used (LePori 1993). Direct combustion of CGT is therefore not recommended without further technological advances. Using CGT as a fuel source is most feasible with gasification, but it must be done using a carefully designed and controlled process. Gasification of CGT is a promising alternative for CGT disposal and has the potential to create a large and relatively stable CGT market.

Fluidized Bed Gasification of CGT

Gasification of CGT offers several advantages over direct combustion. Gasifiers can convert the energy content of a feedstock to hot combustible gases at 85 percent to 90 percent thermal efficiency (Thomasson 1990). Also, the fuel throughput per unit area is greater for gasification than for combustion. This means that smaller gasification units can process the same amount of fuel as larger combustion units. A final advantage is that the materials that cause slagging and clinking can be removed at low temperatures, which means that the gas can be cleaned up and then used at higher temperatures without significant loss of sensible heat (Parnell et. al. 1991).

The capital and operating costs of complying with the new THM standard could be significant for utilities serving more than 10,000 people (McGuire and Meadows 1988). Many water utilities are presently investigating the use of activated carbon for trace organic removals. Because commercial AC is so expensive (high quality commercial AC has a value of approximately $2,000 to $3,000 per ton) many smaller utilities may not be able to afford it. If a lower priced AC were commercially available, the potential market could be substantial. Since the sale of char-ash as an activated carbon is a promising possibility, it can be included as an output product (along with steam and electricity) in the economic analysis of the gasification system alternatives.

Economic Analysis

The economic analysis of CGT gasification is based on an existing cotton ginning facility with the capability of hauling additional CGT to the plant site. The analysis includes different economic and financial conditions faced at the facility. The basic assumptions underlying the model are shown in Table 3. Two scenarios are considered: a "Base Case" facility and a "High Efficiency" facility. The technology for the high-efficiency facility is still in the developmental stages and is not currently available for commercial applications. Economic sensitivity analyses were conducted to illustrate the effects of changes to input assumptions.

The "Base Case" Scenario: Conventional Steam Power Plant

In order to perform an economic analysis, a "typical" plant size and site was chosen as the base case. The facility depicted is a cogeneration plant, where the gasifier is used to fuel a conventional steam power plant. The capacity on this unit was chosen to be 2.0 MW with an installation cost of approximately $2.8 million. In addition to generating electricity for its own needs, the facility is capable of selling back electricity to the utility. The cost to allow for these sales is an additional $50,000 for interconnectors and switchgears. Table 3 summarizes the values used for evaluating the economic feasibility of the base case.

Based on the size of the generator and the combined efficiency of the boiler and steam turbine, the ginning facility would need access to a feedstock of approximately 38,000 tons of CGT per year. This quantity of gin trash would be generated at a gin that processes approximately 108,500 bales of cotton annually, assuming stripper-harvest. A gin of this size does not presently exist anywhere in the WRBEP region, so the facility would need access to the CGT of several gins. However, future consolidation of gins into "super gins" may make this a more likely scenario.

The plant project has a net present value (NPV) of negative $6,530,735 and a levelized cost of $0.0824/kWh. The levelized cost per kWh is greater than that which would be paid for purchasing the same amount of electricity ($0.050/kWh). Thus, the base case is an unfavorable situation in which the gin operator would most likely not be interested in pursuing a simple generation option.

Under the base case, the ginning facility would probably be required to haul additional CGT to the site. The costs of this hauling are not included in the analysis due to difficulty in determining the average distance traveled and a lack of information on costs ($/ton) for hauling CGT. However, including a cost for hauling CGT would cause the NPV to drop even lower. Furthermore, the base case scenario does not allow for the sales of either char-ash or excess steam.

Sensitivity Analysis

The sensitivity analysis measures the change in the NPV and the levelized cost caused by altering a single assumption. For this analysis, the altered assumptions will include:

- Char-ash Sales;
- Steam Value; and,
- Both Char-ash Sales and Steam Value

There are a total of three analyses performed by differing the aforementioned assumptions. First, the results are presented showing the economic impact on the NPV and levelized cost by including a value for the sales of char-ash, while holding all other assumptions constant. Second, the impact on NPV and levelized cost is shown by adding a value for the sales of excess steam, while holding all other inputs constant. Finally, an analysis showing the economic impact of allowing for char-ash and steam sales is presented. For the analysis, the char-ash is conservatively valued at 10% of the high grade AC price, or $200/ton. Steam production associated with the gasification/combustion process has a value for process use. In this analysis, the value is assumed to be $2.00/1,000 lb. of steam.

At $200/ton for char-ash, the NPV of the project becomes positive $7,343,914 and the levelized cost increases to $0.0882/kWh. The increase in the levelized cost, relative to the base case, occurs due to a higher taxable income, leading to substantially higher taxes. Char-ash sales offer CGT-fired gasification systems an opportunity for producing a non-energy revenue stream. Under the steam sales scenario, the NPV of the project becomes negative $4,372,304 and the levelized cost is $0.0824/kWh. The NPV has increased over the base case but is less than that of the char-ash sales scenario. The combination of both char-ash and steam sales offers the greatest NPV of three scenarios. The NPV for this scenario is $8,275,271 and the levelized cost increases to $0.0978/kWh. Once again, the levelized cost has increased due to higher taxable income.

The "High-Efficiency" Scenario: Integrated Gasifier/Gas Turbine Power Plant

An integrated gasifier/gas turbine power plant offers significant improvements in efficiency relative to conventional gasifier/steam turbine combinations. However, such an integrated unit is not commercially available, although several are being developed. This section will analyze the estimated economic performance of the high-efficiency unit.

The major difference between the high-efficiency unit and the base case unit is the generator efficiency assumption. The gas turbine unit has an assumed efficiency of 33%, whereas the combined boiler and turbine efficiency for the base case unit is assumed at 12%. In both cases, gasifier efficiency is assumed to be 75%. Because the gas turbine unit has a greater efficiency, it can process the same quantity of CGT as the base case, while producing substantially more power. Processing the same 38,000 tons of CGT assumed under the base case, the improved plant would produce approximately 5.5 MW of electricity. Once again, it is unlikely that this amount of CGT could be found at any one gin, so CGT would probably have to be brought in from several ginning sites. The last assumption to be changed for the high-efficiency unit is the installed cost. With the greater capacity and CGT supply requirements, it is assumed that it will cost $5.225 million for a 5.5 MW unit.

Based upon the new assumptions outlined above, the integrated gasifier/gas turbine unit has a NPV of negative $5,128,733 and a levelized cost of $0.0447/kWh. The levelized cost is less than the cost of purchased electricity, but with the negative NPV, it is not financially feasible to pursue this option.

Table 3: "Base Case" Economic Analysis Assumptions

*	Feedstock Requirements	108,500	Bales
*	**Method of Harvest**	**1**	**Enter 1 or 2**
	Stripper = 1		
	Spindle = 2		
#	Tons of CGT (1)	37,977	
#	Capacity	2,001	kW
*	Installed Cost	$2,800,000	
*	Costs		
	Fixed	$142.46	/kW/year
	Variable	39.99	mills/kWh
*	CGT Disposal Costs	$0.00	/bale ginned
*	Depreciation Method	ACRS	
*	Equipment Life	10	years
#	Equipment Salvage Value	$560,000	
*	Electricity Prices		
	Purchase		
	Energy	$0.050	/kWh
	Demand	$48.00	/kW/year
	Sell		
	Energy	$0.022	/kWh
	Demand	$28.00	/kW/year
#	Energy Production	14,020,185	kWh/year
*	Total Gin Energy Consumption	2,600,000	kWh/year
*	Available Waste Heat	6,500	Btu/kWh
*	Energy Use	65.0	kWh/Bale
#	Char-ash Produced	9,494	Tons
*	Char-ash Value	$0	/Ton
*	Steam Produced	20,000	lb/hour
*	Steam Value	$0	Klb
*	Interconnect/Switchgear	$50,000	
*	Tax Rate	50	%
*	Inflation Rate	5	%/year
*	Discount Rate	9	%
*	Electricity/Energy Escalati	1	%
*	Loan Interest Rate	9.25	%
*	Down Payment on Loan	33.3	%
*	Fuel Tax Credit	$5.35	/barrel of oil equivalent
*	Btu's per barrel-of-oil	5.80	million

Capacity Calculation Assumptions:

*	CGT Energy Content	7,000	Btu/lb.
*	Gasifier Efficiency	75	%
*	Boiler/Turbine Efficiency	12	%
*	Generator Heat Rate	37,922	Btu/kWh
*	Conversion Factor	3,413	Btu/kWh

Electricity Production Calculation Assumptions:

*	Availability Factor	80	%

*= Entered Values #= Calculated Values

The sensitivity analysis for the high-efficiency facility uses the same changes as used in the base case. As in the sensitivity analysis performed on the base case, each scenario is analyzed for its impact on the NPV of the unit as well as the levelized cost of production by the unit. By selling the char-ash for $200/ton, the resulting NPV of the integrated gasifier/gas turbine project becomes positive $7,910.676 and the levelized cost increases to $0.0491/kWh. With a large NPV and a levelized cost of electricity below the utility price, it would be more profitable for a gin to produce electricity and sell char-ash for AC.

When the steam value is increased to $2.00/1,000 lb., the NPV of the project becomes negative $2,970,302 and the levelized cost is 0.0447/kWh. The combination of both char-ash and steam sales offers the greatest NPV of the three scenarios but simultaneously shows the largest levelized cost. The NPV for this scenario is positive $8,979,837 and the levelized cost increases to 0.0522/kWh. With a levelized cost only slightly higher than the assumed purchase price of electricity and a large, positive NPV, this option is the most profitable of all the scenarios analyzed.

Summary of Economic Analysis

The assumptions altered in these analyses are not the only factors that are capable of being changed. The assumption.table (Table 3) and the corresponding income statements are written so as to allow for a closer approximation of regional economic conditions. "Entered" values can make it possible to duplicate current market conditions in any WRBEP state or utility service territory. Each scenario presented herein will have dramatically different results by using site-specific data, and accurate market value of char-ash and steam. Table 4 summarizes the results of the economic analysis.

Table 4: Summary of Economic Analysis

	CGT Gasification Scenario			
	Base Case		High Efficiency	
	NPV ($)	Levelized Cost ($/kWh)	NPV ($)	Levelized Cost ($/kWh)
Electricity Only	(6,530,735)	0.0824	(5,128,733)	0.0447
Electricity + Char-ash	7,343,914	0.0882	7,910,676	0.0491
Electricity + Steam	(4,372,304)	0.0824	(2,970,302)	0.0447
Electricity + Char-ash + Steam	8,275,271	0.0978	8,979,837	0.0522

Once commercially available, the integrated gasifier/gas turbine system offers the greatest opportunity for use of CGT. Due to the efficiency of the system, the levelized costs are comparable with utility energy prices and the positive NPV is attractive for entrepreneurs. Selling char-ash and valuing the steam along with the electricity production gives the greatest NPV of $8,979,837.

Conclusions

The majority of CGT generated in the western United States is not being utilized in an economically effective manner, and CGT disposal is a costly issue for many ginners and cotton producers. Although few regulations have been implemented that specifically address CGT, the cotton ginning industry is effected by a wide range of regulations, including those relating to the environment, health and safety, and transportation. As far as regulations are concerned, the primary issues facing ginners are the standards for particulate matter and the amended Clean Air Act. Although the Clean Air Act is meant primarily for urban areas, it will affect every industry, including agriculture. Gins in PM10 non-attainment areas and gins whose emissions contain arsenic, will face the biggest challenges. These gins will most likely be required to make costly investments in new control technologies.

Although widely practiced in the past, concerns over air quality and the enactment of stricter government regulations have made open-air burning a less acceptable method of disposal. A survey of gins in the WRBEP region indicates that the most common method of CGT disposal is field application. A significant number of gins feed CGT to livestock, and just a few use it for compost. CGT is seldom disposed of in landfills because the costs of transportation and tipping fees outweigh the costs of giving CGT away. As an energy feedstock, CGT has a major advantage over other biomass resources because CGT is already produced at a central facility, the gin, as a by-product of the cotton ginning industry. A possible constraint to using CGT as an energy feedstock is that many cotton gins operate seasonally, and waste is not produced year round.

The five cotton producing states in the WRBEP region produce nearly 1.4 million tons of CGT, or more than 80 percent of the CGT generated in the country. The greatest concentration of CGT can be found in a cluster of counties located in the high plains of Texas. These counties present the greatest opportunity for implementation of a pilot gasification/gas turbine project. Certain counties in California, Oklahoma and Arizona also produce significant quantities of CGT, with New Mexico being a much smaller player.

Trends within the cotton ginning industry were analyzed over the past 25 years. In each of the states within the WRBEP territory, the total amount of cotton ginned each year has increased steadily, while the overall number of gins in operation has decreased. This means that the volume of cotton being ginned (and hence CGT being produced) at individual gins has increased. These larger volume gins are called "super gins" because they replace three or four older cotton gins and use bale moderators to extend the ginning season. Super gins concentrate the supply of CGT and make it available for a longer period of time. Because converting CGT to energy requires significant capital expenditures, it is likely that only large ginning facilities, where significant quantities of CGT are already present, can consider cogeneration as an option.

A major problem associated with direct combustion of CGT for energy is the dirt, sand, salts and other contaminants always present in CGT. These contaminants melt easily at the high temperatures common to the combustion process, and produce slag and clinkers that can damage or reduce the efficiency of the conversion equipment. For this reason, it appears that the most promising technology for converting CGT to energy is fluidized bed gasification.

Fluidized bed gasification of CGT for energy production is technically feasible using currently available technology. However, the economic analyses indicate that converting CGT to energy will be most profitable if an integrated gasifier/gas turbine system is used. Attaching a value to the char-ash and steam significantly improves the economics of this system. A potential drawback of this arrangement is one of scale. The inputs used in the economic analysis assumed an input of 38,000 tons of CGT, which would correspond to an extremely large gin that processes approximately 108,500 bales of cotton per year. It is doubtful whether any gins of this size exist in the WRBEP territory. At the present time, conversion of CGT to energy does not appear to be a viable solution for most small to medium sized cotton gins. Other disposal methods (such as composting and spreading on land) are less capital intensive, have lower operating costs and are less time-consuming for the gin operator.

Several caveats apply to the above statements. First, several small-to-medium size gins may be able to combine their CGT, thus increasing the resource available for energy conversion. However, hauling costs and distances must be carefully analyzed and included in the economic model. Second, the assumptions made in the economic analysis are rather general in content. For example, the cost of electricity was assumed to be 5 cents per kWh. Raising or lowering this value, depending on an individual gin's particular situation, will change the economics of the project. Modification of other assumptions will have similar impact. Third, the market for CGT activated carbon is still unknown. Without significant technology transfer efforts and additional research, present users of activated carbon are unlikely to recognize that an alternative source may exist.

Future Actions

The resource inventory that was completed for this report was carried out at the county level. In order to determine where a pilot CGT-to-energy project might be implemented, it will be necessary to carry out a more detailed analysis of resource availability at the gin level. This effort could be carried out as a survey, and efforts should initially concentrate only on the top cotton producing counties of states such as Texas, Oklahoma and California. The use of a geographic information system (GIS) could facilitate this analysis.

There are three major reasons to carry out a more detailed resource assessment. First, it is necessary to determine the specific location of gins that produce enough CGT to fuel a gasifier. Second, in order to complete a more detailed economic analysis it is necessary to know site-specific data (such as present CGT disposal costs, cost of electricity, amount of CGT available, location of nearby gins, etc.) for individual gins. The third reason for doing a site specific assessment is to determine if any individual gin operators would be interested in participating in a pilot project.

Finally, a study should be conducted to determine the market potential for low value activated carbon. If the char-ash really does have a market value of $200/ton as activated carbon, the economics of CGT to energy projects could improve significantly. Included in this study could be an analysis of gasifying CGT solely to produce char ash. In other words, the gas could be flared and activated carbon would be the desired product.

Acknowledgments

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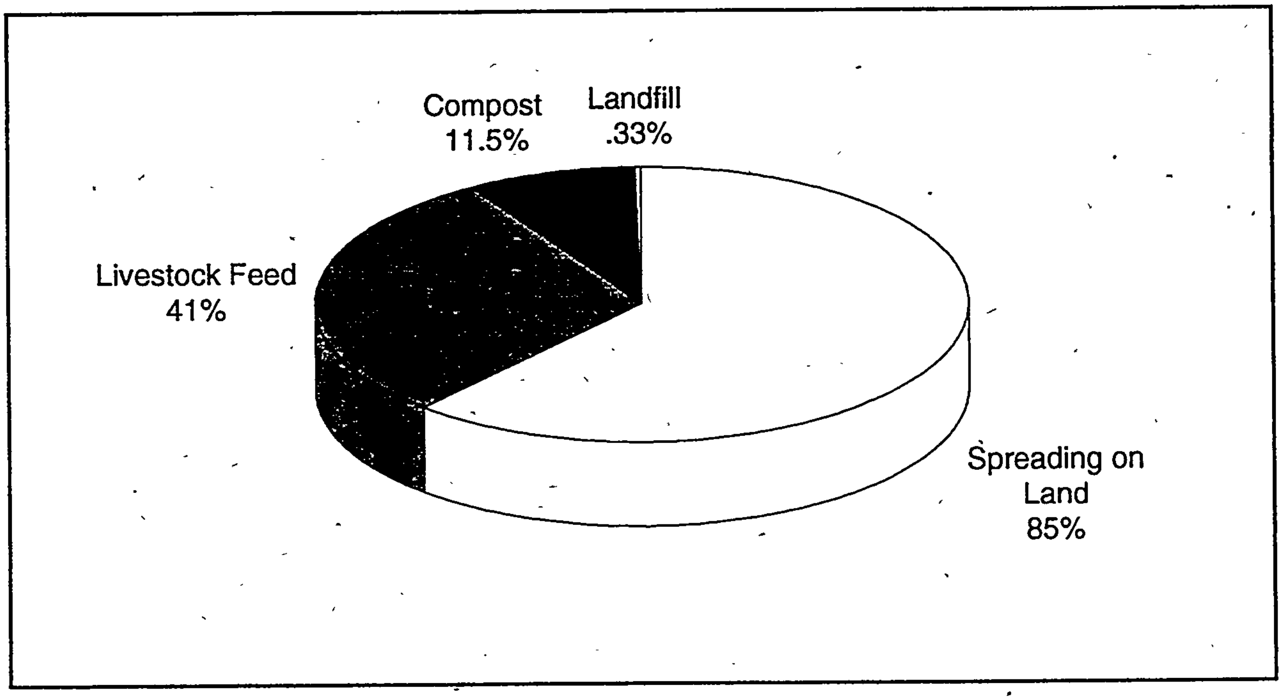

Figure 1.
CGT Disposal Methods in the WRBEP Territory
(Numbers add to more than 100% because some gins use more than one method)

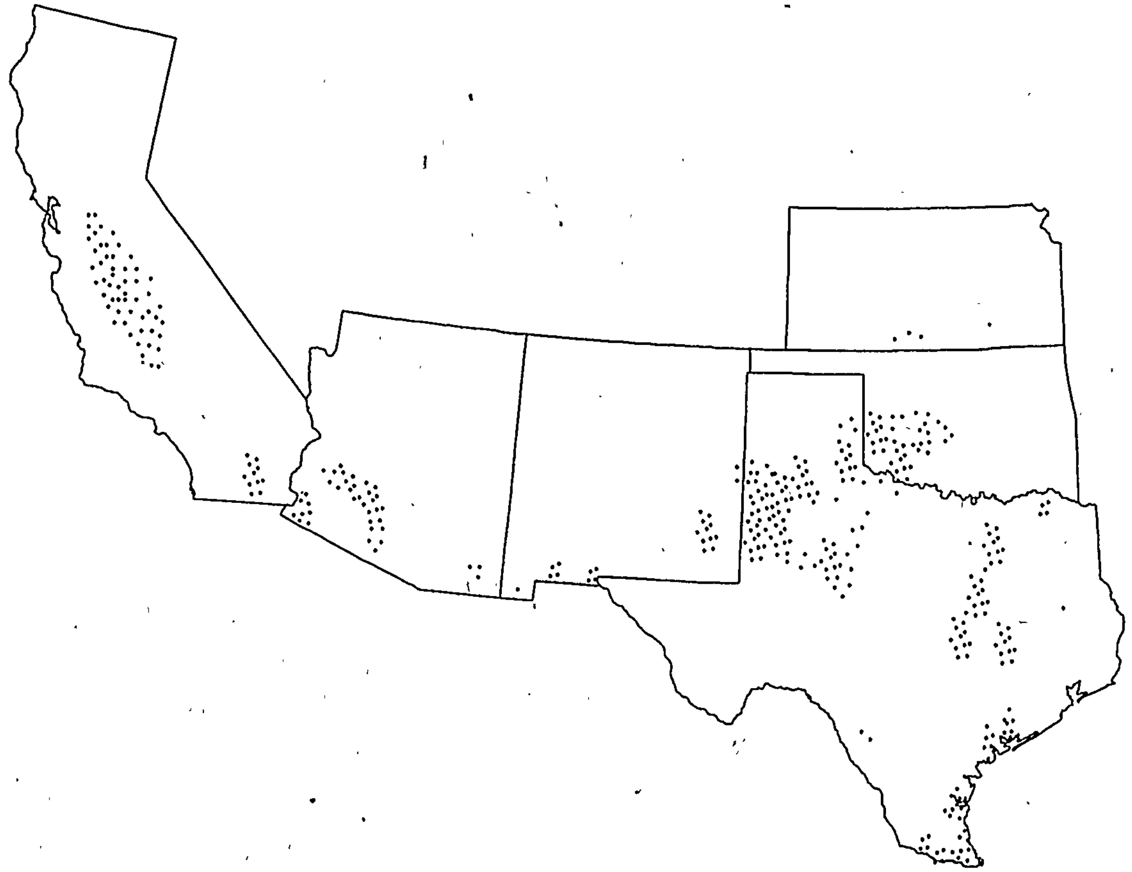

Figure 2
Cotton Producing Regions in the WRBEP Territory

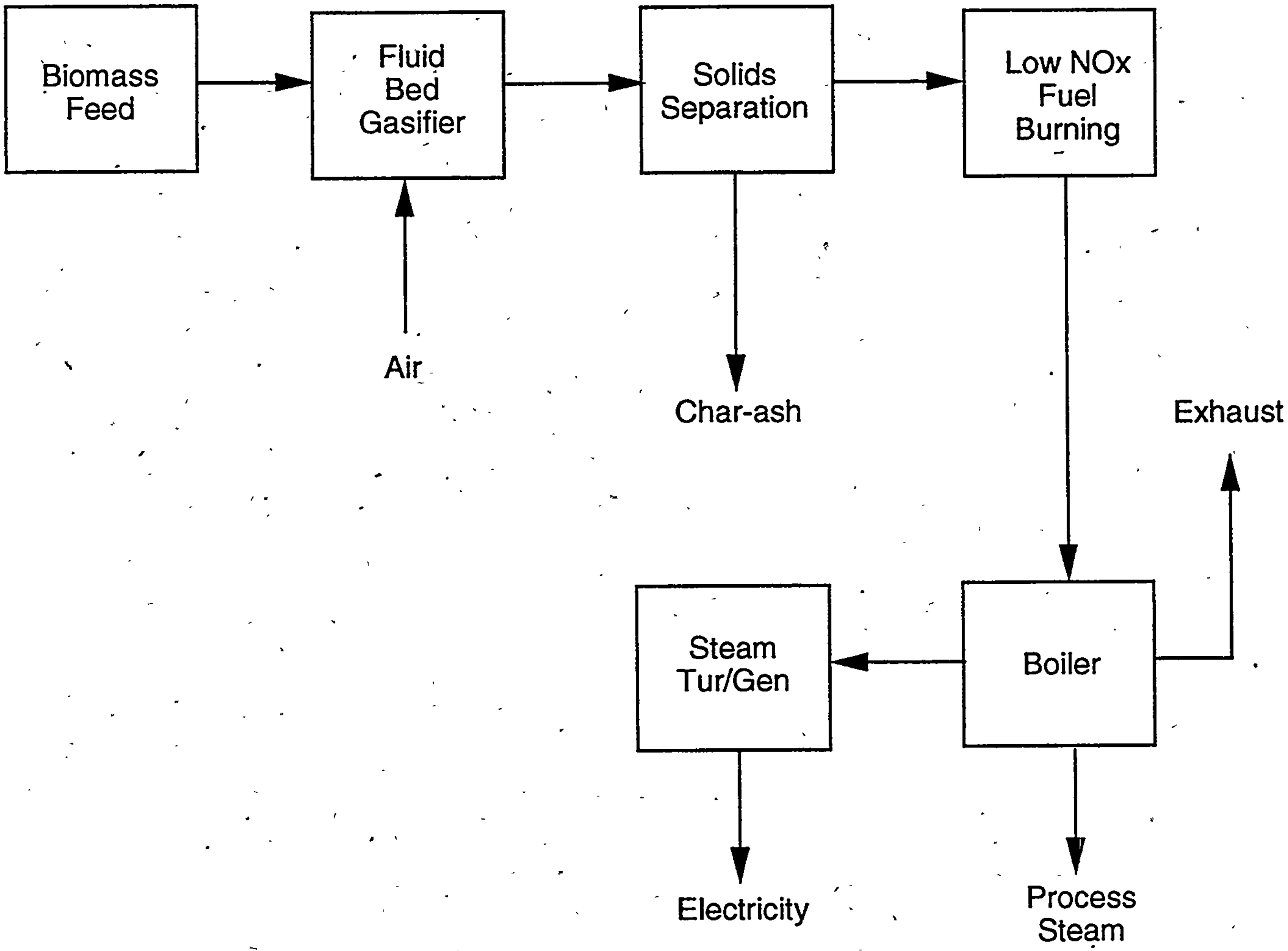

Figure 3
Basic Biomass Gasification System

SYSTEMS FOR HARVESTING AND HANDLING COTTON PLANT RESIDUE

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Abstract

In the warmer regions of the United States, cotton plant residue must be buried to prevent it from serving as an overwintering site for insect pests such as the pink bollworm. Most of the field operations used to bury the residue are high energy consumers and tend to degrade soil structure, thereby increasing the potential for erosion. The residue is of little value as a soil amendment and consequently is considered a negative value biomass. A commercial system to harvest cotton plant residue would be of both economic and environmental benefit to cotton producers.

Research has been underway at the University of Arizona since the spring of 1991 to develop a commercially viable system for harvesting cotton plant residue. Equipment durability, degree of densification, energy required, cleanliness of the harvested material, and ease of product handling and transport are some of the performance variables which have been measured.

Two systems have proven superior. In both, the plants are pulled from the ground using an implement developed specifically for the purpose. In one system, the stalks are baled using a large round baler, while in the other the stalks are chopped with a forage harvester, and then made into packages using a cotton module maker. Field capacities, energy requirements, package density and durability, and ease of handling with commercially available equipment have been measured for both systems. Selection of an optimum system for a specific operation depends upon end use of the product, and upon equipment availability.

Introduction

Cotton is Arizona's major crop, with more than 190,000 hectares (470,000 acres) planted annually, while total U.S. plantings exceed 4,400,000 hectares (11,000,000 acres). It has been estimated that the total amount of cotton crop residue produced in the United States exceeds 2.4 million tonnes (2.6 million tons) per year.

In Arizona, cotton plant residue must be buried to prevent it from serving as an overwintering site for insect pests such as the pink bollworm. Most of the field operations used to bury the residue are high energy consumers, and tend to degrade soil structure, thereby increasing the potential for erosion. The residue is of little value as a soil amendment, and consequently is considered a negative value biomass. A commercial system to harvest cotton plant residue would be of both economic and environmental benefit to cotton producers.

Project Description

The cotton stalk harvesting project commenced at the University of Arizona in the spring of 1991. Field evaluation of various implements began following the cotton harvest, and continued into January of 1992. During the summer of 1992, equipment modifications were completed, and additional equipment was obtained. Field evaluation began in November, and continued into February of 1993. To facilitate presentation, project activities have been divided into three categories of operations.

Uprooting and Windrowing

Three implements were evaluated to determine their effectiveness for pulling the plants from the soil and bringing them together into a windrow.

1. Uprooter-Shredder-Mulcher (USM). This two row Israeli implement undercut and then pulled the cotton stalks from the soil. After pulling, the stalks were conveyed by belts to a shear-bar cutter, where they were chopped and blown down a chute, which placed the material below the soil surface. For this project, the USM was modified. The chute was replaced with a forage harvester spout, so that the chopped material could be blown into a trailing wagon, rather than below the ground surface.
2. Cotton stalk puller. This implement was designed and fabricated for the project. The two row implement undercut the cotton stalks, then used a pair of counter rotating pneumatic tires, which were hydraulically powered, to pull each row of stalks from the ground. The pulling action of the tires, combined with the forward motion of the implement, caused the stalks to be thrown up and to the rear, where they were directed together by a pair of shields, to form a windrow on the soil surface.
3. Windrow inverter. This commercial implement was developed to invert forage windrows and place them adjacent to their original location, thereby hastening field drying. Since the operation of combining windrows was essentially that of moving one windrow to the side and placing it on top of another, it was thought that this implement could perform the task for cotton stalks, and hence it was included in the test program.

Densification

Of the various types of equipment considered functionally suitable for cotton stalk densification, only the two thought most promising were evaluated during the test program.

1. Large round balers. These implements, developed for forage harvesting, collect the crop and roll it into a cylindrical form. Twine, wrapped around the outside of the bale, holds bales together for handling. Large round balers are manufactured in two sizes. The smaller units produce bales measuring 1.2 m (4 ft) long and 1.2 m (4 ft) in diameter, while the larger ones produce bales 1.5 m (5 ft) long, and 1.8 m (6 ft) in diameter. Both sizes were evaluated during the trials to compare energy efficiencies.

2. Cotton module makers. These implements produce large, relatively dense packages of harvested seed cotton which can be easily transported. They typically produce modules measuring 2.1 m (7 ft) wide, by 2.2 m (7.5 ft) high, and up to 9.6 m (32 ft) in length. Modules made from two forms of chopped cotton stalks were evaluated during the course of the study. Several were made with the USM when set to a theoretical length of cut of 35 mm (1.40 in.). Another series was made from material chopped using a pull-type forage harvester set to a theoretical length of cut of 28 mm (1.125 in.). This material was collected from windrows which had been uprooted by the cotton stalk puller. In each case the chopped material was transported to the module maker using a high dump wagon, with compression (ie. densification) of the module obtained using the module maker's hydraulic system, powered from a tractor PTO.

Handling

Both large and small round bales were successfully loaded onto trailers and trucks using tractor-mounted front end loaders, and forklifts. These devices, which are also used for handling other baled materials, are commercially available. A truck-mounted cotton module mover was used to load and transport the modules. The modules generally retained their integrity through the loading, transport and unloading processes.

Results

Biomass yield

Biomass yields varied with harvest method. For the USM, an average yield of 6166 kg/ha (5501 lb/ac) was recorded in 1991, and 4013 kg/ha (3580 lb/ac) in 1992. The 1991 yields for baling averaged 4987 kg/ha (4449 lb/ac). These values are on an as-harvested basis. In 1992, yields for the balers and forage harvester averaged 3990 and 4125 kg/ha (3560 and 3680 lb/ac), respectively, at harvest. On a dry matter basis the 1992 values were 2354, 2368 and 2600 kg/ha (2100, 2113 and 2320 lb/ac), respectively, for the USM, balers and forage harvester.

Weights and Densities

All of the bales, and each load of chopped material, were weighed at harvest. In addition, some of the modules and bales were weighed following several weeks of field storage. This information, when combined with dimensional measurements of the various packages, was used to calculate average package density at harvest, and following storage. (Table 1) The greatest module density was recorded for those made using the forage harvester. In comparing the baler data, it can be seen that the smaller unit provided the greatest density.

Table 1. Average Weight and Density of Modules and Bales at Harvest, and When Hauled from the Field.

System	Weight (lb)				Density (lb/ft^3)			
	Harvest		Haul		Harvest		Haul	
	1991	1992	1991	1992	1991	1992	1991	1992
Modules								
USM	7863		7320		10.52		8.86	
Forage Harvester		11972		*		14.95		*
Bales								
Small	505	426	339	301	9.53	8.04	6.40	5.68
Large (2 rows)	1094	862	844	665	7.70	6.07	5.94	4.68
Large (4 rows)	801	832	608	604	5.64	5.86	4.28	4.25

* Still in Storage

Soil Contamination

Soil collected with the cotton stalks was measured to determine the amount of contamination in each system. The USM modules averaged 7.7 and 3.3 percent soil, respectively for 1991 and 1992, while the forage harvester modules averaged only 2.7 percent soil. The USM would be expected to retain more soil than the forage harvester since the plants are pulled, chopped and immediately placed in the module. Material collected with the forage harvester, is handled twice, with the second operation taking place when the soil on the roots is drier, and hence easily dislodged.

The bales contain significantly less soil than the modules. This is as expected, since the tumbling action inside the bale chamber knocks soil from the roots, allowing it to fall to the soil surface. The small bales averaged 0.48 percent over the two years, while the large bales averaged 0.68 percent soil contamination.

Energy Requirements and Field Capacities

Energy required for each of the harvesting operations was measured. The mean values compiled during the studies are presented in Table 2 along with operating speeds and field efficiencies, determined through a series of time studies. In all cases the values cited are considered to be those which are achievable under commercial conditions, and are not necessarily the highest or lowest figures recorded.

Table 2. Energy Requirements, Field Efficiencies and Capacities for the Various Harvesting Operations.

Method	# rows	Travel Velocity (mph)	Theor. Capac. (ac.hr)	Field Effic. (%)	Effect. Capac. (ac/hr)	Energy (hp-hr/ac)	Energy (hp-hr/t)
Puller	2	3.84	3.10	81	2.50	12.75	7.29
Windrow inverter	2	2.73	4.42	94	4.16	0.55	0.22
USM	2	3.84	3.10	81	2.51	23.29	15.28
Forage harvester	2	1.85	0.51			12.96	7.07
	6	1.89	4.57	80	3.65	4.83	5.34
Baler Small	2	2.06	1.66	86	1.43	9.18	4.78
Baler Large	2	1.43	1.15	80	0.92	12.51	7.03
Baler Large	4	1.49	2.40	81	1.95	10.37	5.46
Module maker	-					1.20	0.50

In comparing the USM to the forage harvester, energy required for pulling stalks must be added to cutting energy. The total energy for harvesting on an area basis is 47.4 and 33.4 kw-hr/ha (25.7 and 18.1 hp-hr/ac) for two and six rows, respectively. On a weight basis the values are 11.8 and 10.5 kw-hr/t (4.4 and 12.8 hp-hr/ton) respectively. These are both less than the USM.

The most energy efficient baling process, on either an area or weight basis, was found for the small baler collecting two rows. The least efficient operation was the large baler harvesting two rows.

The USM and the puller provided the greatest theoretical field capacity, of the two row operations. Considering that the USM provided a once over harvest, its competitive performance was further enhanced. For the other systems, two or more operations were required to harvest cotton stalks. That is, for example, stalks must first be pulled or cut, and then baled. Pulling, followed by baling, yielded a theoretical field capacity for the system of 0.34 and 0.23 ha/hr (0.83 and 0.58 ac/hr), for the small and large balers respectively, using a single tractor to power both the puller and baler. These values are considerably less than values for the USM.

Introduction

Energy Mines and Resources Canada, in conjunction with Agriculture Canada, are involved in an ongoing initiative to use agricultural by-products to produce energy. Cereal grain chaff has been identified as a suitable feed stock for ethanol production.

Cereal grain chaff is produced in large volumes on the Canadian prairies and cereal grain growing areas of the United States. For the crop years 1987 to 1991, Statistics Canada (1991) reported Canadian cereal grain production was 26,360,000 t (28,990,000 ton) of wheat and 12,600,000 t (13,860,000 ton) of barley. A survey of PAMI combine test data revealed that conservative ratios of chaff to grain are 0.41 for wheat and 0.20 for barley. A calculation using these values results in a total annual cereal grain chaff yield for Canada of 13,300,000 t (14,600,000) ton). The chaff, if uncollected, contains weed seeds which add to weed control problems, and may have an allelopathic effect on emerging crops which reduces yields. The existence of a heavy decomposing chaff mat also limits nitrogen availability to the new crop. Currently, cereal grain production is only marginally profitable due to low grain prices and any economic return available from chaff sales would be important to grain producers. Chaff collection equipment has been developed to collect the chaff into small field piles for later recovery and use as livestock feed. Craig et al. (1989) determined the cost of this process was \$2.35/t (2.14/ton). Coxworth and Redekop (1991) suggested a realistic chaff value for both ethanol and feedlot usage would be \$35 to \$40/t (\$32 to \$36/ton). This work demonstrated that the value of chaff for use in ethanol or livestock feed exceeds its cost of collection in the field by approximately \$33 to \$38/t (\$30 to \$36/ton). Provided that an efficient method of collecting the chaff from the field can be devised, significant economic returns should be available to yield field prices of about \$10/t (\$9/ton) which should be high enough to encourage farmers to collect the chaff in piles.. The Prairie Agricultural Machinery Institute (PAMI) was contracted by Energy Mines and Resources to carry out a series of projects designed to define and solve any problems with a chaff collection and long haul system.

The primary problem in chaff collection is its low bulk density of 40 to 80 kg/m^3 (3 to 5 lb/ft^3) in field conditions. Since transportation costs will form a high portion of the final value of chaff, a low cost hauling system, which optimizes payload (by increasing the bulk density), needs to be developed.

Results and Discussion

Initial work by Lischynski, et al., (1992) at PAMI indicated that field compaction was feasible to a resulting chaff density of 160 kg/m^3 (10 lb/ft^3) by pressure application of approximately 110 kPa (16 psi) or to a maximum of 220 kg/m^3 (13.7 lb/ft^3) at a pressure of 210 kPa (30.7 psi). Laboratory tests indicated that repeated cycles of pressure followed by relaxation would only increase the density by a further 10%. Tests using conventional garbage compression equipment confirmed that densities in the 130 to 170 kg/m^3 (8.25 to 10.25 lb/ft^3) range could be obtained. Laboratory work also investigated the forces needed to retain compressed chaff and the shear force required to remove it from the compression chamber. An economic analysis was conducted using the capital cost equation from Audseley and Boyce (1974) with a number of basic assumptions for equipment capital and operating costs for various chaff densities.

$$C_c = C * i * \left[\frac{1+r}{2} + \frac{1-r}{2n} \right] + \frac{1-r}{n}$$

Where C_c = annual capital cost, i is the interest rate, r is the ratio of resale value, n is the life of the equipment, and C is the original capital cost of the equipment.

Costs for all systems were based on the assumption of the use of one compactor. All systems were considered as driven by a farm tractor during loading and a trailer or highway tractor system for unloading. As hauling distance increased, the number of trailers were increased to keep the compactor or loader tractor working as steadily as possible. Annual repair costs were taken as a percentage of original capital cost. Loading time was assumed as one hour and it was assumed that all hauling would be done in 8 weeks per year. At 6 days per week and 12 hours per day, the working time would be 575 hours per year. Travel time was based on a travel speed of 80 km/h (50 mph). A chaff value of \$10/t (\$9/ton) in the field piles was used and a processing plant delivered price of \$35/t (\$38.60/ton) was considered as the upper limiting cost. Where possible, industry accepted rental rates for farm machinery were used (from the Farm Machinery Custom and Rental Rate Guide 1992) instead of the Audseley and Boyce equation.

Costs for a moderate chaff density of 170 kg/m^3 (10.6 lb/ft^3) are presented in Figure 1. At a hauling distance of 170 km (105 mi), the cost is \$19.74/t (\$17.93/ton). At 296 km (184 mi), the \$30.80/t (\$27.50/ton) cost may still be economical at higher chaff values.

Further work produced designs of two prototype chaff compression trucks, a rotary compactor type and a reciprocating compaction type, to meet the basic requirement of production of 160 kg/m^3 (10 lb/ft^3) compaction. When the designs were completed, the economic analysis was redone based on estimated costs to manufacture and operate the designed compression units.

Detailed tests were also conducted to determine the efficiency of densifying chaff through particle size reduction. Size reduction was attempted using standard farm machinery, including forage harvesters and hammermills. The forage harvester virtually had no effect on increasing the density, whereas the hammermill proved successfully but was power intensive. The hammermill used for the tests was a New Holland Model 357 grinder mixer and results are given in Table 1. Further work is required to confirm these values because of the difficulty in obtaining steady state flow conditions.

Table 1. Hammermill Test Results.

Screen Size		Chaff Density		Approximate Power	
mm	(in)	kg/m^3	(lb/ft^3)	kW·h/t	(hp·h/ton)
3	(1/8)	184	(11.48)	239	(291)
6	(1/4)	140	(8.75)	101	(123)
19	(3/4)	95	(5.95)	18	(22)
Raw Chaff		60	(3.72)	0	(0)
*Further work is required to confirm these values because of the difficulty in obtaining steady state flow conditions.					

The detailed cost comparison illustrated below was completed based on the size reduction results and the calculations from the prototype compactor design cost analysis. Table 2 and Table 3 illustrate the cost assumptions of chaff compaction and size reduction by hammermilling used in the economic analysis.

Table 2. Compaction Cost Assumptions.

Rotary Compactor	
Trailer Cost	$65,000
Loader Cost	$15,000
Tractor Size	89 kW (120 hp)
Tractor Cost	$35/h
Available Payload	11.7 t (12.9 ton)
Reciprocating Compactor	
Trailer Cost	$60,000
Compactor Cost	$22,000
Tractor Size	89 kW (120 hp)
Tractor Cost	$35/h
Available Payload	11.9 t (13.1 ton)
Interest Rate	10%
Resale Value	15%
Equipment Lifetime	10 yr
Repair Cost	2% of original cost
Highway Tractor Cost	$40/h

Table 3. Size Reduction Cost Assumptions.

Trailer Cost	$40,000
Tractor Size	134 kW (180 hp)
Tractor Cost	$53/h
Available Payload	12.7 t (14.0 ton)
Interest Rate	10%
Resale Value	15%
Equipment Lifetime	10 yrs
Repair Cost	2% of original cost
Highway Tractor Cost	$40/h

The results of the analysis are illustrated in Figure 2. At a chaff cost of $10/t ($9/ton) in the field and $35/t ($38.60/ton) at the plant, both rotary and reciprocating compacting systems are economical to a hauling distance of 140 km (87 mi) as hauling costs remain below $25/t ($39.60/ton). The size reduction system, as illustrated, is economical to a hauling distance of 166 km (103 mi). This analysis was based upon using standard highway transport trailers. When the analysis is changed to consider the use of specialty wood chip trailers with increased volumes, lower densities down to 128 kg/m3 (8 lb/ft3) can be hauled at similar cost.

Conclusions

These figures suggest that all three systems studied had economical potential. Even lower density values such as 128 kg/m^3 (8 lb/ft^3) will provide economical hauling of chaff to a centralized processing plant, providing specialized hauling trailers are used.

Of the three systems, size reduction was the most economical. This advantage to size reduction occurs primarily because heavy machinery is not required to contain this chaff. This reduces relative payload and results in lower transportation costs as less trailers are then required. Since size reduction is probably a mandatory component of plant processing, the savings realized by field size reduction would further increase the feasible hauling distance.

Other than direct cost advantages, the size reduction system is less complex than the compaction system. Existing low density haul trailers such as wood chip trucks could be used interchangeably and only adaptations of existing farm machinery need be developed. The trailers would also not have to be unhitched during loading as they could be top filled, so there are also convenience advantages.

As a result of these findings, work is now under way by PAMI to incorporate a size reduction function into the operation of existing chaff loading machinery. Laboratory tests are under way to optimize size reduction efficiency. A chopper type size reduction system and a fan shredder type size reduction system are being evaluated for potential. Moderate increases in density have been achieved with the chopper system, but more refinement is required to obtain the desired bulk density of 128 kg/m^3 (8 lb/ft^3). The perceived final outcome is to produce a combined, pile pick-up, size reduction, and truck loading unit which can be readily powered by existing farm tractors.

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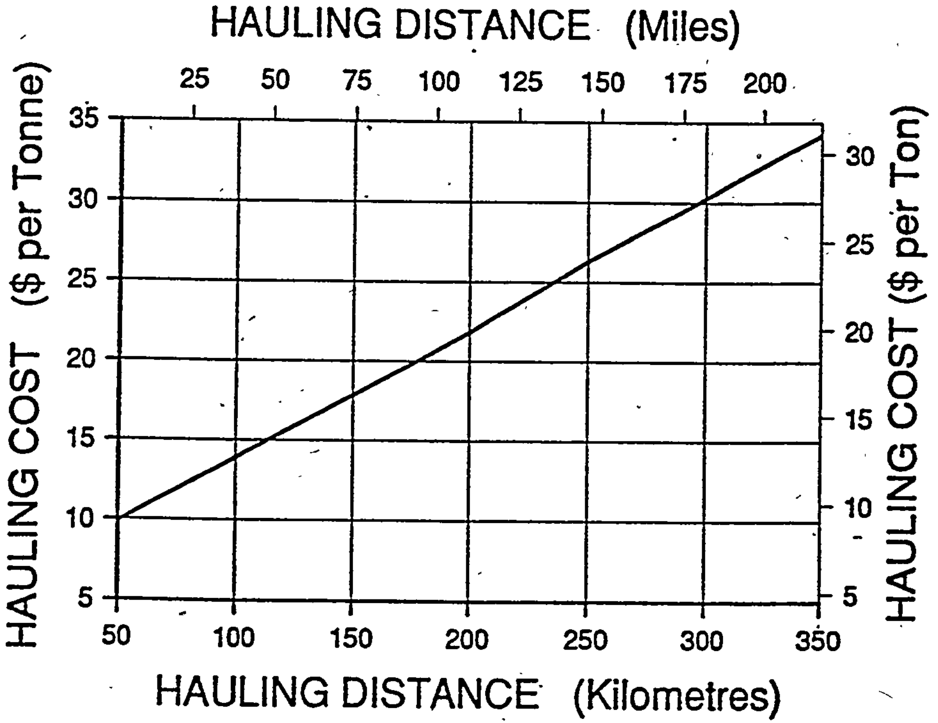

Figure 1. Estimates of long hauling chaff costs at chaff density of 170 kg/m^3 (10.6 lb/ft^3).

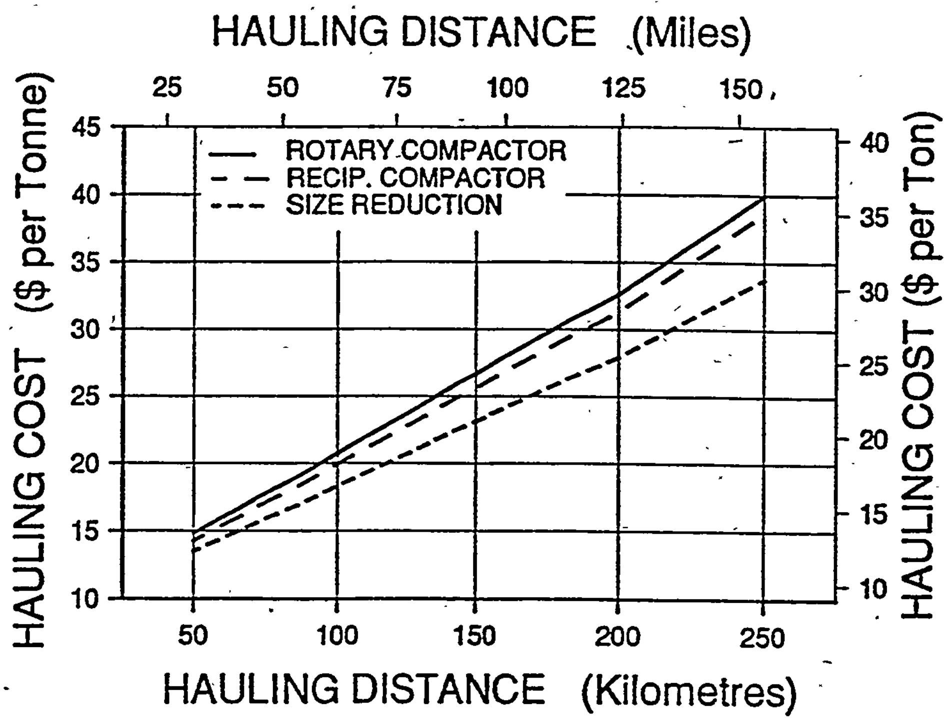

Figure 2. Cost of chaff hauling using compaction and size reduction at 160 kg/m^3 (10 lb/ft^3) density.

Managing Woodwaste: YIELD from RESIDUE

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ABSTRACT

Historically, the majority of sawmill waste has been burned or buried for the sole purpose of disposal. In most jurisdictions, environmental legislation will prohibit, or render uneconomic, these practices. Many reports have been prepared to describe the forest industry's residue and its environmental effect; although these help those looking for industry-wide or regional solutions, such as electricity generation, they have limited value for the mill manager, who has the on-hands responsibility for generation and disposal of the waste.

If the mill manager can evaluate waste streams and break them down into their usable components, he can find niche market solutions for portions of the plant residue and redirect waste to poor/no-return, rather than diposal-cost, end uses.

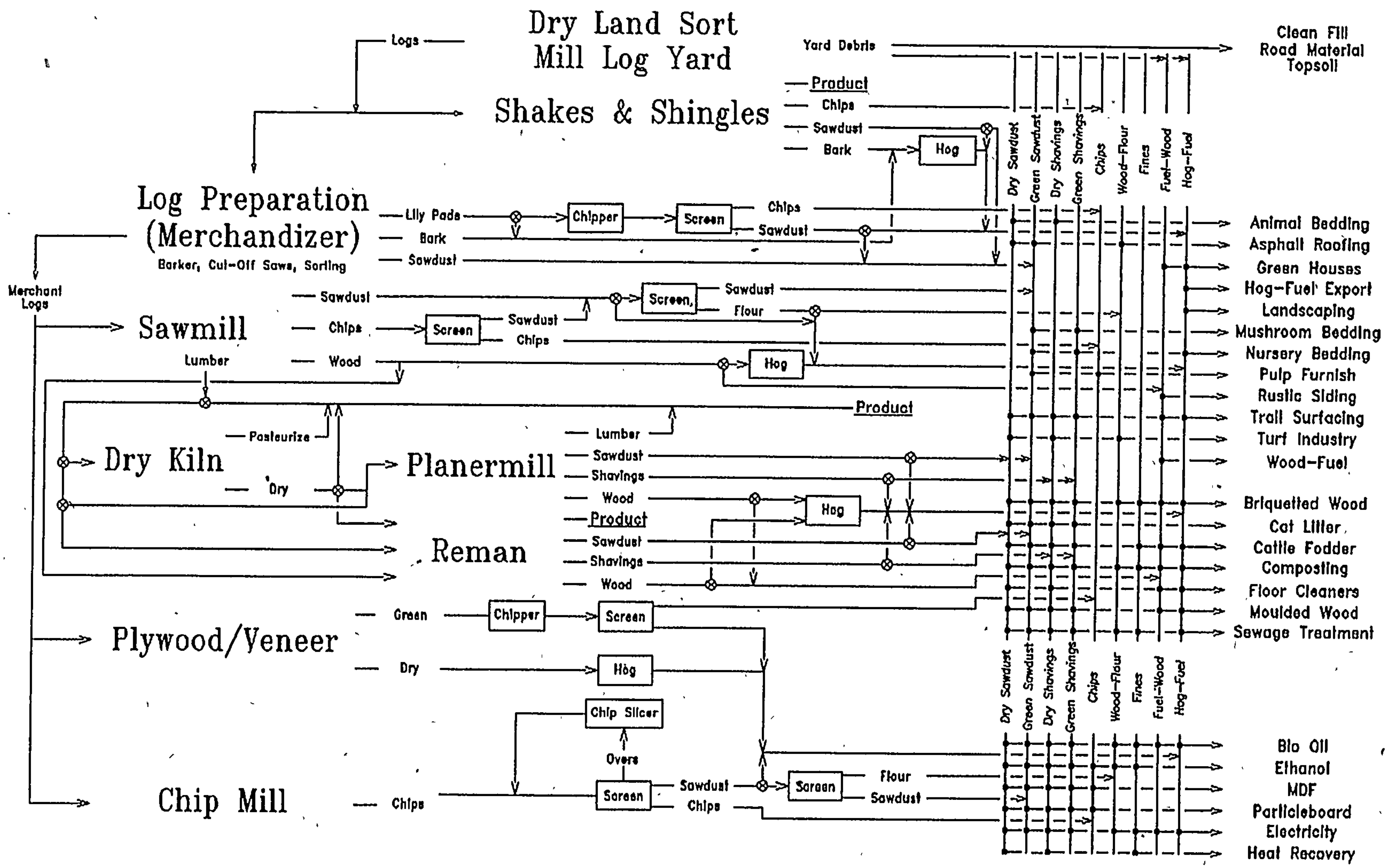
In the modern mill, residue is collected at the individual machine centre by waste conveyors that combine and mix sawdust, shavings, bark, etc. and send the result to the hog-fuel pile. The mill waste system should be analyzed to determine the measures that can improve the quality of residues and determine the volumes of any particular category before the mixing, mentioned above, occurs. After this analysis, the mill may find a niche market for a portion of its woodwaste.

The authors provide a set of useful, yet simple, mathematical tools that permit the mill manager to evaluate his waste and compare it with the *specifications (requirements)* of alternative value-based usage. Using these estimates of volume and the description provided of the qualities of the waste, as seen by these ***potential new customers***, the mill manager would decide if the possible opportunity warrants investigative effort.

A glossary of terms, defined as they relate to the Forest Industry, is included. The authors suggest that a common set of terms will assist any discussion to resolve woodwaste problems.

It is unlikely that a sweeping, all-encompassing hog-fuel solution, even if it exists and could be developed economically, is the best answer for all stake-holders.

The best solutions, from the point of view of biomass management and the continuing well-being of the individual mill, will probably come from those most knowledgeable about, and/or closest to, waste production. It is the mill's management and operating personnel who are best able to change residue from woodwaste, with its associated disposal cost, to a by-product that adds value to the bottom line.



Sawmill Residue is collected at the individual machine centre by waste conveyors that mix sawdust, shavings, bark, etc., in the hog-fuel pile. For many years, burning and burial were common means to manage this waste. The system should be analyzed to determine: the potential to improve the quality of the residues and an estimate of the volumes of any particular category before mixing occurs. Thus, management may find a niche market for some of the woodwaste.

Dry Kilns Wood is dried to lower shipping cost. Some B.C. Coastal mills may dry or pasteurize wood in order to destroy the Pinewood Nematode.

Reman The waste situation can be drastically improved by remanufacturing edgings, finger-jointing trim ends, etc.

Planermill Finishes lumber to market size. A lot of sawdust and shavings are produced with a smaller quantity of wood.

Plywood / Veneer Chips can be produced from green veneer trim, but not the dry veneer or waste panels, because of the low mc and the presence of glue residue.

Chip Mill The overs from chip mills are normally recycled to the mill for chipping. This practice seldom returns a usable chip; it increases the quantity of pins and fines and wastes energy. A chip slicer is recommended.

INTRODUCTION

Governments have in place, or are planning, legislation that does not permit burning with no benefit other than disposal. Many reports demonstrate the scope of the forest industry's annual residue and its environmental effect. The reports help those looking for industry-wide or regional solutions, such as electricity generation, but have limited value for the mill manager. It is not likely that an all-encompassing hog-fuel solution, if it exists, is the best answer for all stakeholders and could be economically developed.

This paper assists the mill manager to evaluate waste streams, to look for a niche market solution or a local use for portions of the plant residue. If individual mills can redirect more waste to an economic return, rather than a disposal-cost end use, the problem diminishes.

POTENTIAL WOODWASTE USES

Woodwaste or hog-fuel has a 'shelf life' varying from nine months to three years and is affected by such conditions as: species, wood:bark ratio, temperature, rainfall, wind, pile management and others.

Electricity Bark comprises about half the woodwaste described; but, when we review the potential residue usage options, it has slight demand except as a fuel. In British Columbia, 20% of the energy required by industry is supplied by incinerating woodwaste, mostly bark, in boilers to produce steam. The woodwaste in BC that has <u>not yet</u> found a beneficial usage would generate 750 aMW. To put this in perspective, this additional energy is 130% of the 1991 Canadian Entitlement, often called Downstream Benefits, under the Columbia River Treaty or 80% of the 1991 output from the Revelstoke hydroelectric plant.

To determine the size plant that is possible, use the formula, right. For a large plant, with high pressure and temperature steam, an efficiency (*eff*) of 30% would be appropriate. The Coefficient of Utilization (*CofU*) is the measure of the time the plant will be at full power and, for this calculation, 85% is reasonable.

$$watts=\frac{BDT\ of\ fuel \times \dfrac{BTU_{NET}}{lb} \times 2{,}204.6}{3{,}415 \times 8{,}760 \times CofU} \times eff$$

$$BTU_{NET} = High\ Heat\ of\ fuel - Latent\ Heat,\ H_2O$$

The minimum electricity selling price for these plants to be feasible is often higher than the value of electricity in most areas of Canada. Utilities in the USA, but not Canada, are required, by law, to buy new supplies of electricity developed in their area of service and offered for sale at their published, avoided cost price.

The low value assigned to electricity and the reluctance of Canadian utilities to encourage IPP, Independent Power Producer, development makes this an uncertain potential usage.

However, if transportation costs can be minimized by plant proximity to the fuel sources and another revenue stream (co-generation), an acceptable-to-the-investor plan can be devised.

Selected Wood Charactoristics: average values, provided for estimation only.

Species	Wood Density lb/ft³	Wood Density kg/m³	Wood High Heat BTU/lb	Wood High Heat MJ/kg	Wood mc^od %	Bark Density lb/ft³	Bark Density kg/m³	Bark High Heat BTU/lb	Bark High Heat MJ/kg	Bark mc^od %
Softwood										
Cedar, western red	20.53	329	9 700	22.57	62	21	336	8 700	20.24	63
Cypress, yellow	26.15	419	9 900	23.03	52	21	336			112
Douglas-fir	28.08	450	9 200	21.40	45	31	497	10 100	23.50	107
Fir, balsam	20.90	335	8 616	20.05	118			9 100	21.17	
Fir, (unspecified)	20.50	328	8 300	19.31	69	31	497	9 100	21.17	59
Hemlock, western	26.40	423	8 500	19.78	85	34	545	9 800	22.80	100
Larch western	28.08	450	8 530	19.84	49	31	497	9 220	21.45	72
Pine, jack	26.27	421	8 500	19.78	51	33	529	9 040	21.03	
Pine, lodgepole	25.52	409	8 600	20.01	50	33	529	10 760	25.03	85
Pine, ponderosa	24.21	388	9 100	21.17	76	31	497	9 616	22.37	50
Spruce, Sitka	21.65	347	8 100	18.84	43					84
Spruce, white	22.46	360	8 500	19.78	59	28	449	8 720	20.29	77
Hardwood										
Alder, red	23.28	373	8 000	18.61	101			8 410	19.57	77
Aspen, trembling	23.34	374	8 610	20.03	90			8 570	19.94	107
Birch, white	31.57	506	9 340	21.73	73			10 110	23.52	45
Cottonwood, black	21.10	338	8 800	20.47	175			9 000	20.94	104
Maple, broadleaf	29.08	466	8 400	19.54	71					102
Poplar, (unspecified)	21.04	337	8 615	20.04	135			8 810	20.50	

Units of Measure	COEFFICIENTS Sawdust m^3_{SWE}	Shavings (m^3_{SWE}) Dry	Shavings (m^3_{SWE}) Green	Bark BDT Whitewood	Bark BDT Cedar
GPU = 200 ft³	2.27	1.39	0.61	1.1	0.77
BDU = 2400 lb	2.72	2.72		1.1	
m³	0.40	0.245	0.108	0.20	0.135
ft³	0.10	0.007	0.003	0.006	0.004
Cunits SWE	2.83	2.83		1.36	0.95
yd³	0.31	0.188	0.082	0.15	0.10
Bone Dry Tonnes	2.50	2.5		1.0	

Conversion Coefficients for units of measure

Example: Given GPU, to find
a) (m_{SWE}),
multiply by 2.27 for sawdust
1.39 for shavings
0.61 for green shavings
b) BDT_{Bark},
multiply by 1.1 for Whitwoods

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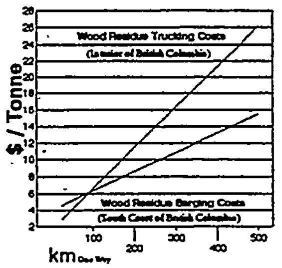
Publication SP-24R ISSN 0824-219, 1985.

Heat Recovery Another approach that has wide use in Canada is incineration in a burner with a steam or hot oil heat recovery boiler on the stack gases. The energy recovered can drive an electric turbine, be used to dry lumber in a kiln, heat the plant, etc. In this case, we recommend an *eff* of 20% and a *CofU* equal to 70%.



The air quality of the larger plant will be superior; but the smaller unit can be designed to conform to air standards proposed by Departments of the Environment and will be welcomed as a substantial improvement.

Capital costs are lower for this down-sized solution, regulatory approval will be substantially easier, and the Return on Investment will not be too much lower.

The main impediments to implementation and financial success for either of these residue usages are regulatory approval, distance from fuel to furnace, value of electricity and the lack of any benefit(s) that can be derived from the energy at the site. These could be the drying, briquetting of waste, dry kilns, area heating, and others. This topic is too site and circumstance specific to permit generalization; but, if unused woodwaste is concentrated in an area, good value would be obtained from a site-specific study.

As a rule, green and dry material are evaluated separately, though many mills will have them mixed. The conveyor curves (following page) help the manager estimate volume per hour for each type of residue.

The first set of the following uses requires little more than screening. Some, like briquetting, need special process equipment, and others, such as MDF, are separate industrial operations.

Animal Bedding Dry sawdust and shavings are preferred. Residuals cannot be contaminated with anti-stain or other chemicals, and Cedar is undesirable.

Asphalt Roofing Sander dust or flour can be used as filler for roofing or a plastic extender in moulded shapes.

Green Houses Some nursery operators who have converted to wood fuel, hog-fuel, pellet or briquette, report cost savings of 50% over fossil fuels.

Hog-Fuel Export The export of hog-fuel, like chips, usually requires a permit. The principle is that export is not allowed if the material is required domestically. If hog-fuel is processed by cubing or pelletizing, the permit for the export of needed-for-use, forest industry feed stock may not apply. This utilizes sawdust, shavings and bark. The mixture is hogged and dried then compressed by extrusion to increase its bulk density. Costs of processing, including natural gas for drying and freight, may make the product noncompetitive; however, if surplus, low-energy heat is available because of the variable needs of another process, or if generation cannot use the residue as it develops, this could be an attractive option.

Landscaping Hogged and screened bark with minor sawdust content is wanted for decorative topping. The preferred species is Douglas Fir.

Mushroom Bedding Coarse green hemlock, aspen and alder sawdust and shavings with nutrients can be employed for bedding mushrooms.

Nursery Bedding Hogged bark and sawdust can be used for soil extenders and topping for nursery plants and shrubs.

Pulp Furnish Opportunities to generate added volumes of chips and the sale of sawdust depend on the plant location. Attention should be given to the yield of existing sawmill waste chippers, affected by speed and maintenance, to ensures that the maximum volume goes to the chip pile rather than to waste as pins and fines.

Rustic Siding Small sawmills that do not have a barker may edge the slab to produce a rustic siding.

Trail Surfacing Hogged bark and sawdust can top off hiking trails or golf courses. This minimizes trail upkeep, weed growth and soil erosion. If it is a riding trail, cedar is not recommended (White Line Disease).

Turf Industry Sawdust, in a mat form, is seeded with grass. Potential exists as the absorbent, with sewage sludge, in hydro-seeding.

Wood-Fuel The use of wood as household fuel is being limited by many municipalities; yet, the needs of national and provincial parks may represent a local niche for a mill.

Briquetted Wood This is a proven technology that could be economic for the conversion of dry sawdust and shavings to a useful product. Institutions, such as hospitals, schools, etc., that use oil heat could use this as an alternative fuel. Briquettes resist water absorption and require much less space than the feedstock. This practice could supply plant or kiln heating and local institution clients.

Cat Litter Small pellets made from pure sawdust, essentially the same technology as pelletizing, have a market as an environmentally friendly cat litter.

Cattle Fodder Cud-chewing animals, such as cows and sheep, are able to digest cellulose because microorganisms in their rumens produce somewhat similar enzymes that hydrolyze cellulose to sugar. Studies have shown that steam alters <u>hardwoods</u>, such as aspen, so that much of the carbohydrate can be digested by sheep or cattle. This can be used, with a protein or nitrogen source, as a winter supplement .

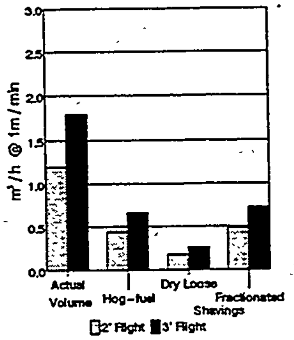
Composting Wood, green or dry, is mixed with sewage for nitrogen and set up in wind rows to compost to topsoil. A leachate control system is required. Hardwood is preferred.

Floor Cleaners Dry sawdust or shavings impregnated with anti-static cleaning and sanitizing agents is used for removing dust, oil and liquid spills on industrial floors and highways.

Moulded Wood Woodwaste (hogged) and combined with sawdust to prepare a mixture that is dried, mixed with resin and poured, into moulds. Various products for the auto and furniture industry can be produced;

RESIDUE CONVEYORS

Each graph can be used to calculate the solid wood equivalent (SWE) and volume of material handled.



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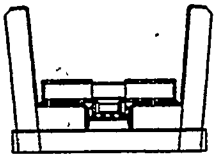
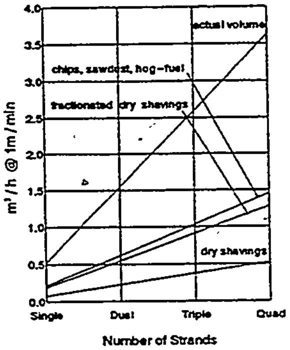
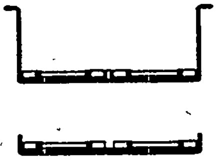


Application:
bark, trimends, log bucking ends, sawmill refuse.

Features:
low to medium maintenance, steep conveying angles, high initial cost.

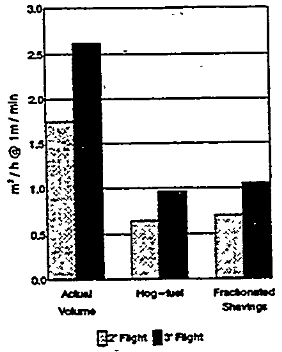


BOX LINK

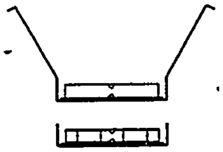


Application:
chips, sawdust, hog-fuel.

Features:
metering capability, medium maintenance, high capacity, steep conveying angles, some noise, high initial cost.

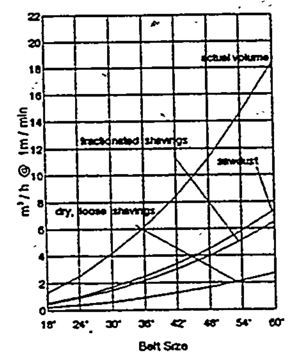


LONG LINK

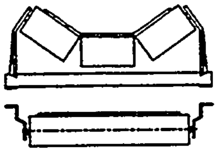


Application:
bark, trim ends, log bucking ends, sawmill refuse.

Features:
low to medium maintenance, steep conveying angles.



TROUGH BELT



Application:
chips, sawdust, hog-fuel.

Features:
high capacity, low HP, less product damage, quiet, steep conveying angles. Smooth, 25°, ribbed, 36°.

a British Columbia plant fabricates inner automobile door panels.

Sewage Treatment Kelowna, BC, treats 100,000 litres per day of sewage with hog-fuel. Sewage, at 6.5% solids, is held in lagoons formed by hog-fuel berms. High bark content is needed to contain the liquid. The berms are turned into the centre to mix with the sludge as water evaporates. Compost is trucked to form a fertile landfill. The process uses 25-40,000 m^3 of hog-fuel annually.

Bio Oil A new technology (the first commercial plant began operation in 1993) that will reduce green wood and bark to an oil that can fuel a diesel or be burned in a boiler. Other chemicals from the reaction and better use of the resultant carbon could make this a profit centre for the mill.

Ethanol An emerging technology that converts cellulose and hemicellulose of green wood to sugar and lignin. The sugars are fermented and distilled to produce alcohol. Ethanol, added to gasoline, is an extender and oxygenator. It is normally included in a ratio 10:90. The lignin slurry is a useful feedstock for glue or, dried, an excellent biomass fuel.

MDF Medium Density Fibreboard. Fine wood fibres are blended with urea-formaldehyde or phenol-formaldehyde resin, dried, formed into a mat and compressed in a hot press. Hardboard and particleboard technologies are combined.

Particleboard Shavings and sawdust are milled to particles and dried to 3% mc^{ow}, blended with glue to build mats that are pre-loaded into a press and compressed under heat and pressure.

CONCLUSION

If process energy costs are too high, analyze low-quality energy, e.g. condensate return, or heat recovery for drying and operation of the press at a time other than the demand peak. If woodwaste generates steam and/or electricity, consider 'storing' or 'selling' energy in the form of dried fuel, pellets, etc.

Thw mill' location often dictates the potential use of residuals because the transportation costs for bulky materials can become prohibitive.

GLOSSARY

These terms are defined as they relate to the Forest Industry. In some cases, the same term does not have the same meaning for everyone or is not limited to this definition. We suggest that the glossary will assist any discussion to resolve wastewood problems.

Biomass Oceanographers use it as a unit for the mass of living organisms, e.g. plankton, in a volume or area. Modern usage is any organic material, unrelated to an area or volume.

Bulk Density Theoretical ovendry weight divided by the volume of nonsolid wood, such as chips, sawdust, bark, etc.

Chips Fragile pieces of wood, 2-6 mm thick and 15-25 mm long, that are used as the primary feedstock in a pulp mill. Produced by chip-n-saw edgers, disc chippers, etc.

Edgings Residual from a saw edger, often eight or more feet long and quite thin.

Flour Fine material that passes through the screen as being too small (< 2mm) to be used as furnish for a pulp mill. This material comes from a chip-n-saw, saw edger, etc.

GPU or VMU Gravity Packed or Volumetric Unit. 200 ft³ of hog-fuel, chips or sawdust as compacted by gravity in a scow.

Higher Heat The heat value of wood or bark, ovendried, expressed in BTU/lb or MJ/kg. The values are by weight and do not vary greatly between species; however, when expressed by volume, denser species normally provide greater heat.

Hog-fuel Common use equates hog and hog-fuel; the term is widely used to identify any or all wood waste from sawmills. We propose to limit the term hog to the machine and hog-fuel to the material coming from the hog.

Lily Pad This is produced as the log enters the mill when flared or damaged butts, usually less than 24" thick, are trimmed from the log.

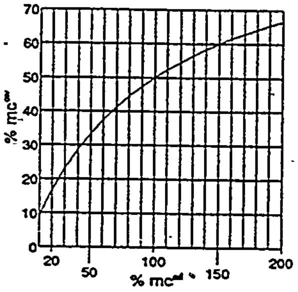
Moisture The forest industry has two methods:

Pulp and Paper Mills use the percentage (H_2O) in the original weight.

$$mc^{ow} = \frac{100 \times H_2O}{original}$$

Sawmillers prefer the percentage of H_2O to the ovendry weight.

$$mc^{od} = \frac{100 \times H_2O}{ovendry}$$



Ovendry Dried to a constant weight at 103°C ±2°C.

Overs The output from a chipper, chip-n-saw, etc., that is too large to be accepted by the screen as a chip. If these recycle to the chipper, they become fines and pins (waste).

Residuals The portion removed from the final lumber. This includes material that presently has value (chips), may have value (sawdust and shavings) or has a disposal cost (hog-fuel).

Sawdust Small particles of wood cut off by the saws. If the length of the fibre is sufficient(>2mm), this material, if green, could be used as pulp furnish. Both dry and green may be available but cannot be used interchangeably.

Shavings Lumber is planed after kiln drying and in some cases in its green form. Green shavings can be used as a pulp furnish.

Slabs Residual of an outside cut that squares the log to a cant. If the plant saws barked logs, all of this is wood.

SWE Solid Wood Equivalent. Used in relation to a m³ as a method of equating different forms of residue or product to the original species.

Trim Ends Pieces of wood, usually less than 24" long, and, if the mill has kilns, dry. Some green trim ends are made in the sawmill and possibly some dry wood from the planer.

Woodwaste Residue from the portion of the tree received by the processing facility that is neither recovered nor used in the process. Post facility waste is not included.

OVERVIEW OF FEEDSTOCK RESEARCH IN THE UNITED STATES, CANADA, AND BRAZIL

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Abstract

This paper provides an overview of the current biomass feedstock efforts in Brazil, Canada, and the United States. The report from Brazil provides an historical perspective of incentive programs, the charcoal and fuelwood energy programs, the alcohol program, and other biomass energy efforts. The efforts in Brazil, particularly with regard to the sugar cane to ethanol and the charcoal and fuelwood programs, dwarfs any other commercial biomass system in the Americas. In the author's view one of the bright spots in the future is the Biomass Integrated Gasification/Gas Turbine Electricity Project that received initial funding (6-year project) in 1992. In the sugar cane-based ethanol industry biotechnology research continues to develop higher yielding cane varieties and more efficient microorganisms to convert the sugar cane carbohydrates into alcohol.

Canada is a large country where diversified forms of biomass can be found. A number of important institutions and enterprises taking part in the economical development of the country are involved in research and development pertaining to biomass. A large segment of the population is working on various aspects of the biomass such as forestry, agricultural, industrial, urban, food processing, fisheries and peat bogs.

Biomass feedstock research in the United States is evolving to reflect Department of Energy priorities. Greater emphasis is placed on leveraging research with the private sector contributing a greater share of funds, for both research and demonstration projects. The feedstock program, managed by Oak Ridge National Laboratory, is focused on a limited number of model species with most of the research centered at a regional level using a multidisciplinary approach. Activities have been expanded beyond those traditionally associated with crop yield improvement to include a stronger emphasis on emerging environmental issues such as biodiversity, sustainability and habitat management. DOE also is a supporter of the National Biofuels Roundtable, which is developing principles for producing biomass energy in an economically viable and ecologically sound manner. Geographical Information Systems are also being developed as tools to quantify and characterize the potential supply of energy crops in various regions.

The United States Biofuels Feedstock Program

Introduction

The year 1993 has been an important and pivotal one for biomass feedstock development program of the United States Department of Energy (DOE). At the national policy level, we have seen major *changes* in energy system and environmental management priorities, in terms of both technology choice and of new paradigms of how the government should fund and manage research. **The evolving nature of the DOE biomass feedstock research and demonstration reflects these new priorities, as well as the new DOE working relationships with the private sector and with other federal agencies.** However, underlying the biomass feedstock program is also the *continuity* provided by more than fifteen years of field trial experience including species selection, breeding, and the development of superior breeding stock, as well as the optimization of cultural techniques. In this overview, we will focus initially on the new U.S. Federal energy and environmental research and demonstration priorities, as well as the new research and demonstration management paradigms that will be driving future demonstration and commercialization programs. We will also examine the major core thrusts of the current DOE biomass feedstock research program and then will talk about specific research activities that demonstrate how the new priorities and paradigms will work in practice.

New National Energy, Environmental, and Agricultural Priorities and their Implications for Biomass Feedstock Research

With passage of the 1990 Clean Air Act Amendments (CAAA) and 1992 National Energy Policy Act (NEPACT), the United States set itself on a course to reduce levels of urban air pollution (particularly ozone, carbon monoxide and air toxics), lower powerplant emissions of sulfur dioxide and other pollutants, stabilize emissions of global warming gases such as carbon dioxide, while simultaneously decreasing U.S. dependence on imported petroleum. The new Clinton Administration, and the new senior management team at the Department of Energy, have affirmed their commitment to these goals, and to a larger future role for biomass energy for both power generation and for the production of liquid transportation fuels. Domestic liquid and solid fuels derived from biomass are increasingly seen by senior U.S. energy planners as among the most promising options for meeting the stricter emissions regulations under the 1990 Clean Air Act Amendments. Biomass-derived fuels also have the added advantage of lowering the levels of import of fossil fuels without increasing global warming emissions. In fact, when derived from energy crops, such biomass-based fuels have no net carbon monoxide production since the growing plants absorb as much CO_2 as is produced during the combustion process(NREL, 1993). Biomass-based alcohols (ethanol and methanol) and ethers (such as ETBE and MTBE) can be used as neat fuels or as gasoline blending agents to lower vehicular emissions of CO and volatile hydrocarbons. Biomass-based combustion feedstocks can be used as the base fuel or co-fired with coal or other fossil fuels in utility boilers to sharply lower emissions of SO_2 and CO.

At the same time, the United States is trying to fundamentally transform its farm policies, reducing the level of farm price supports, diversify the farm economy by introducing new income sources, and eliminate farm practices that contribute to soil erosion and to the over-application of pesticides and herbicides. In this context, short-rotation wood energy crops and herbaceous energy crops are seen as valuable components in a sustainable management program designed to reduce soil erosion in marginal lands and provide additional farm income on set-aside or low quality rural lands.

Four Elements of the New Government Research Paradigm for the 1990s.

All these new energy and environmental priorities must be implemented within the context of shrinking federal budgets: research for its own sake or any form of business as usual are no longer possible. A new paradigm of research program management is developing in the federal government, reflecting new budgetary realities and a renewed emphasis on producing results that contribute to national policy goals. The new research model has four key imperatives:

1) **Concentrate the limited resources in those activities with high probability of success;**
2) **Leverage limited DOE funds;**
3) **Enlist the private sector as partners in scale-up and commercialization activities;** and
4) **Build broad coalitions to collaboratively address and solve potential environmental concerns from field activities and technology scale-ups before they occur.**

Narrow the Breadth of Research Activities

One of the characteristics of the new research model for the 1990s is that DOE will focus its financial and manpower resources on a small number of activities that have a high probability of commercial success, rather than on a broad range of activities or experiments that are selected because they are interesting science. We will increasingly be betting on prospective winners, and channeling most of the available funding to them. This is a process that we began in 1986, when we narrowed the range of promising feedstocks based on more than eight years of field trials. That process continues today. For example, the DOE biomass feedstock program is now concentrating most of its effort on understanding and optimizing one model herbaceous feedstock (switchgrass or *Panicum virgatum*) and one model short rotation woody crop (hybrid poplar or *Populus sp.*).

Leverage the Limited DOE Biomass Feedstock Program Funding

As is discussed below and shown in figure 3, the funding for the DOE biomass feedstock program has been declining in recent years. However, the proposed transition from laboratory experiments and small field tests to larger scale field demonstrations will require substantial new financial investments. DOE is planning to bridge the shortfall in resources by cooperating with other Federal agencies and potential biomass users (such as electric utilities and transportation fuel producers) in the design, management, and funding of research and demonstration activities. A key step in the creation of this cooperative structure was the signing in 1991 of a Memorandum of Understanding (MOU) on cooperation in biomass energy between the Department of Energy and U.S. Department of Agriculture (USDA). When the MOU was drawn up, it was expected by DOE that the USDA would assume a major role in funding future biomass feedstock research, as well as drawing on its nation-wide extension program for field trials and farmer/landowner education and support. Other important cooperative programs that are under development include the recently announced solicitation for Letters of Interest, which offers cost-sharing opportunities between DOE and various interested end-users to develop business plans for setting up dedicated biomass production systems linked to biomass conversion units that would use the biomass feedstock.

Involve the Private Sector on Cost-Shared Basis in Technology Scale-up and Commercialization

In recent years, the DOE Office of Transportation Technologies has been a pivotal player in a number of major cost-shared research and commercialization programs with American business firms. The Advanced Battery Consortium, which includes DOE, the three major U.S. automobile manufacturers, and a number of U.S. battery producers, was jointly funded by government and industry at a level of more than $50 million to accelerate the commercialization of light-weight, high energy density batteries for use in electric cars. Similarly, the DOE Biofuels Systems Division has signed Cooperative Research and Development Agreements or CRADAs with several major firms, including AMOCO, to co-fund the scale-up of the Simultaneous Saccharification and Fermentation Process or SSF technology developed by the National Renewable Energy Laboratory (NREL) for the conversion of cellulosic feedstocks to ethanol.

Inviting private sector participation in cost-shared development is one of the fastest mechanisms for determining whether or not a technology is really approaching commercialization. If industry sees the technology as being technically promising and economically feasible, they will normally be interested in participating in the pilot scale activities, and there are a number of good reasons to include potential future producers in this venture. First, they know the market place into which the product will be sold. Second, the private sector participation identifies early on the non-technical obstacles to commercialization, ranging from lack of financing to shortage of specialized equipment. With industry cooperation, solutions can be found while field trials and small-scale demonstrations are underway

Seek Collaborative Solutions to Potential Environmental Problems and Conflicts

For some time, major U.S. environmental organizations have been observing the U.S. biomass feedstock development program, intrigued by its potential to displace significant usage of fossil fuels for power generation and liquid fuel production, but concerned by possible ecological and environmental impacts of the creation of dedicated biomass plantations. At the initiative of the U.S. Audubon Society and the Electric Power Research Institute (EPRI); the U.S. DOE, several of its national laboratories, representatives of electric utilities, pulp and paper companies, and a number of environmental organizations have agreed to participate as members of the newly formed National Biomass Roundtable. The purpose of this consensus building organization is to establish ground rules and guidelines for large-scale biomass feedstock development that is acceptable to all parties, that protects biological diversity, and ensure environmentally sustainable systems.

The Current DOE Biofuels Feedstock Development Program

Strategic Goals

The DOE Biofuels Feedstock Development Program has a range of ambitious long-term strategic goals, as well as near-term programmatic operational goals. ***The first strategic goal is to develop the biomass base that would allow the United States to meet 15% of its primary energy demand from biomass.*** This amounts to more than 16.5 - 18 X 10^{15} BTUs or 16.5 - 18 quads. While very ambitious, this goal is derived from a careful analysis of the large resource of land in the United States that is or could become available for biomass production, as well as the biomass growth potential on those lands. As can be seen in figure 1, Oak Ridge National Laboratory has identified more than 393 million acres (159 million hectares) of land in the United States as being capable of growing energy crops without irrigation.

More than 75% of this land is located in the North-Central and South-Central sections of the country, with most of the remainder being along the Eastern Seaboard.

To make use of this large potential, the DOE biofuels feedstock development program will need to focus not only on the development of fast-growing species, but on related environmental, economic, harvesting, transportation, and storage issues that are **cost effective** and **environmentally sustainable** in the long-term.

Cost Goals

To be widely used, biomass energy crops must be cost-competitive with other fuels. Therefore, cost reduction has been one of the benchmarks by which we measure the success of our program. Through species selection and selective cross-breeding, we have already succeeded in reducing the cost/million BTUs from an average of more than $5.00/MBTUs in 1983 to $3.25/MBTUs today. As can be seen in figure 2, our projected cost/dry ton is a function of many innovations, although the most important factor is directly related to increasing the yield per acre. Researchers in the Pacific Northwest have recently achieved yields of 20-25 Mg/ha/yr, which have been sufficient to encourage the pulp and paper industry to install larger scale field trials with newly developed hybrid poplar plant material. Stettler et al, 1992).

To reach the wider base of utilization for energy production and be competitive with other feedstocks, we project that feedstock costs must be reduced to $2.00/MBTU (34 $/dry ton), primarily through yield increases and adaptation of improved clones to a variety of soil types and locations.

Major Elements of the DOE Feedstock Program

The DOE biomass feedstock program, which is managed by Oak Ridge National Laboratory, has six major components: **Crop Development, Environmental Research, Equipment Development, Systems Integration and Assessment, Commercialization, and Information Management.** This program draws upon the technical strengths and collaboration of a number of national laboratories, major universities, and cooperating state and federal agencies, as can be seen in table 1 (below).

In virtually every aspect of the current DOE Feedstock Research Program, we can find the new research paradigm outlined earlier. The crop development program focus has been narrowed to two model energy crops that appear most promising, one herbaceous and one woody, and leading researchers have encouraged to seek additional funding sources to leverage DOE contributions. In most parts of the program, the private sector is being involved, either through cost-shared applied research or through field trials. More emphasis is being placed on economic analysis, in order to find the combination of factors that will bring candidate feedstocks into the marketplace and will accelerate private sector co-funding of ongoing research.

Table 1: Major Elements of the DOE Biomass Feedstock Program

Program Component	Current Research Foci	Key Implementing Organizations/Contractors
Crop Development		
Model Herbaceous Energy Species	**Midwest Region** -- Productivity/ Breeding Research	USDA Agricultural Research Service; sites at Iowa State, Purdue, Nebraska, and Indiana
	Southern Region -- Breeding/Culture Trials/ Physiology/ Tissue Culture	Breeding -- Oklahoma State Culture Trials --Texas A&M; Auburn; VPI Physiology -- Oak Ridge Nat. Lab Tissue Culture -- U. of Tennessee
Model Short Rotation Woody Species	**NW Poplar Research Group** -- Molecular Genetics/ Genetic Improvement/ Genetic Mapping/ Pathology	University of Washington and Washington State; co-funding provided by USDA, NSF, Washington Technology Center, Boise Cascade, James River Corporation, Scott Paper, and Occidental Chemical Company
	North Central Poplar Research Cooperative -- genetic advancement of *populus deltoides*/ accelerated breeding and small distributed field trials	USFS/Rhinelander;USFS/Grand Rapids; U. of Minnesota; Iowa State; Aspen Cooperative
	Southeastern RFP	To Be Determined
Environmental Research		
Biodiversity	Midwest - bird and small animal populations	Oak Ridge National Laboratory/USDA Forestry Service, U of Minnesota, and National Audubon Society Possible co-funding being explored
Habitat Fragmentation	Role energy crops can play in reducing habitat loss	
Chemical Fate/ Water & Air Quality	nutrient/pesticide cycling/ erosion measurement/ greenhouse gas & carbon dynamics	
Equipment Development		
Feedstock Storage	Effects of storage conditions on quality of feedstocks	National Renewable Energy Laboratory, Oak Ridge National Laboratory, and others.

Economics Analysis and Integration		
Resource Assessment	Southeast Regional Cost/Supply Curves	Oak Ridge Nat. Lab/U. of Tennessee
	National Supply Curves	Oak Ridge Nat. Lab/U. of Tennessee
Geographic Info Systems (GIS) /Supply Curves	Land-Use change/ cost-supply dynamics at various sites	Oak Ridge Nat. Lab/Tennessee Valley Authority
Commercialization		
	Demonstration w/ Commercial Partners	Oak Ridge National Lab/TVA
	Outreach to potential commercial collaborators	Oak Ridge National Lab, USDA Extension Service, and respondents to Letter of-Intent
Information Management		
Energy Crops Forum	Data exchange among feedstock researchers	Oak Ridge National Lab and various biomass feedstock collaborators
Data Base	energy crop field data and literature	Oak Ridge National Lab

The DOE Feedstock Budget

There are practical reasons why the DOE Biofuels Feedstock Development Program has been seeking to leverage its funding and to encourage cost-shared activities with the private sector. The budget for feedstock research has been declining over the past several years (see Figure 3). At the same time, the number of interested parties has been increasing as well as the complexity of issues related to large-scale feedstock development. (U.S. Department of Energy, 1993).

Cost-Shared Activities

As was mentioned earlier, it was initially expected that the Memorandum of Understanding (MOU) on cooperation in biomass energy between the Department of Energy and U.S. Department of Agriculture (USDA) would lead to large-scale USDA funding of biomass energy feedstock research. While this has not yet happened, DOE has continued its collaborative efforts with USDA field units, particularly the U. S. Forest Service Experiment Stations in Rhinelander, Wisconsin, and Grand Rapids, Minnesota, and a smaller effort with the Agricultural Research Service's switchgrass breeder in Lincoln, Nebraska. In some cases DOE can play the role of a catalyst. By providing the base funding that helps create centers of excellence, such as the University of Washington/Washington State University (UW/WSU) Poplar Research Group, DOE encourages private firms to support particular aspects of the research in response to their own needs. It also ties the research community more closely to the needs of the ultimate users to their studies and provides immediate feedback on the utility of the work for the commercialization process.

Implementing the New National Priorities and Research Paradigms

To illustrate the new national energy/environment priorities, as well as the new federal research paradigm, I would like to briefly describe two major initiatives: The Northwest Poplar Research Group, and the recent Letter of Intent -- *Economic Development Through Biomass Systems Integration*, which will determine the technical, economic, and environmental viability of integrated biomass production and conversion systems.

The North-West Poplar Research Group

For the past fifteen years, the DOE Biofuels Feedstock Research Program has supported a consortia of scientists at the University of Washington and Washington State University to increase the production of woody biomass in *Populus trichocarpa* through the development of genetically improved cultivars that are suitable for an operational short-rotation cultural system in the Pacific Northwest. This program has used a multi-disciplinary approach to develop a new crop material and a matching cultural system to produce feedstock predictability and repeatability. Key elements in this program's success have been (1) the choice of species and the approach to its genetic improvement, (2) the careful assessment of how improved cultivars differ from unimproved stock, and (3) the successful transfer of the concept from the research scale to the operational scale. *Populus* has been an attractive choice because of its rapid growth, easy clonability and capacity to resprout. From its inception, this group of dedicated researchers has focused narrowly on developing the most promising species for their region, and as a result has contributed to the DOE selection of poplar as the model short rotation woody energy crop. Early hybridization experiments (crossing *Populus trichocarpa* with *Populus deltoides*) led to a remarkable doubling of biomass productivity in four-year rotations. Over time, the scope of the research has broadened, as has the range of skills involved. From two initial scientists, the group has grown to nearly 35, including twelve senior investigators as well as postdoctoral researchers, graduate student, technicians, and visiting scientists.

While there are many factors that contribute to the success of the UW/WSU Poplar program, it has been crucial that the team has been highly **inter-disciplinary** (currently involving senior investigators in eight different departments of the two universities), has served as a **resource and center of excellence for other researchers** (distributing new hybrid cultivars to interested researchers around the world), **has welcomed early private sector involvement**, and has been **open to suggestions/requests from local users** of the research. The program has also adapted to new demands and needs that have emerged, including the requirement to integrate biotechnology, pathology, environmental assessment and data collection into the core laboratory and field research program.

From a core DOE feedstock development budget that has generally ranged from $200-$300 thousand, the group's annual research budget has been leveraged to the range of $1.2-$1.6 million. The program has added grants from Washington State, US Forest Service, and National Institute of Environmental Health and Safety grants to the core funding, thus significantly leveraging the DOE Biofuels research program support. Equally important, they have also added more than $250,000 of industrial support, initially from paper and fiber companies but now including substantial amounts of funding for new areas of research, such as the use of poplar as an environmental remediation strategy. For all of these reasons, the Northwest Poplar Research Group can serve as a model for other such consortia and, indeed Science magazine recently singled it out in an editorial as "a challenging precedent for other areas" seeking Federal research support.

The DOE Solicitation for Letters of Interest

On May 10, 1993, DOE's National Renewable Energy Laboratory (NREL) announced a "Letter of Interest (LOI)" in the Commerce Business Daily to invite all interested parties to respond to this solicitation entitled *Economic Development Through Biomass Systems Integration.*

This solicitation supports DOE's efforts to assist in the commercialization of biomass energy systems and is requesting proponents of integrated biomass production and conversion systems to share the cost of feasibility studies. The LOI consists of two parts (A) Liquid Fuel Production and (B) Electricity Production. In a related event, EPRI has issued a "Host Utility Announcement" in which they will consider cost-sharing feasibility studies with EPRI members who respond to Part B of the LOI. For all responses DOE has required a minimum of 50% cost-sharing.

EPRI is also considering funding a series of cost-shared feedstock demonstration projects with DOE and possibly USDA. EPRI would like for these feedstock demonstration projects to grow enough feedstock to supply a 25 MW power plant. Ideally, there would be 7-9 of these projects located in geographic areas that have a high potential for bioenergy production. These demonstrations should give potential utility investors (as well as other interested parties) a good idea of the costs, environmental factors, and sustainability of dedicated feedstock systems including short rotation trees and herbaceous energy crops. By participating in this program, DOE will be able to leverage its resources to get a number of large energy crop pilot installations planted. Feedback from the participating utility partners that will in turn help guide future DOE feedstock research.

As was mentioned earlier, major co-funded efforts with key industry leaders, individual firms or trade associates have become increasing prominent in the energy and environmental sectors in the past few years, partly as a means for helping U.S. firms compete in increasingly complex world market, and partly as an effort to speed introduction of technologies that are central to national environmental and energy goals. In the case of biomass direct combustion, electric utilities have become increasingly interested in testing emerging technologies that provide cost-competitive energy production while not requiring new and expensive emissions clean-up technologies. Biomass, being naturally low in sulfur, is of particular interest to utilities struggling to meet new sulfur dioxide limits imposed by the 1990 Clean Air Act Amendments. This new attention to the importance of environmental issues, combined with the leveraging of federal energy funding, is characteristic of the new direction for biofuels research.

National Biofuels Roundtable

The last example of innovation in the evolving federal biofuels feedstock research program is the National Biofuels Roundtable. It represents a new cooperative approach to working with the environmental community and seeking compromise solutions to potential problems. The National Biofuels Roundtable was born out of an all-day meeting two years ago, convened and sponsored by the National Audubon Society and Princeton University to examine the extent to which biomass could be produced on a large-scale for energy purposes without creating environmental degradation, such as erosion, groundwater contamination, and the loss of biodiversity. This initial meeting has been the impetus to the formation of the National Biofuels Roundtable. This organization is sponsored by EPRI, the National Audubon Society, and DOE. It has brought together specialists from the environmental community such as the National Resources Defense Council, the World Resources Institute, and the Union of Concerned Scientists; DOE and its national laboratories; other Federal agencies such as the Forest Service, the Fish and Wildlife Service, the Tennessee Valley Authority, and the Soil Conservation Service; private paper and fiber companies active in short-rotation biomass production including the James River Corporation and Scott Paper Company;, and electric utilities including Minnesota Power that are interested in biomass power. The National Biofuels Roundtable is currently working on a number of consensus documents that are designed to provide guidelines for biomass energy development that can serve the dual purposes of promoting the use of biomass while assuring that the installations will be undertaken in an environmentally sound and sustainable fashion.

There are a number of aspects to the National Biofuels Roundtable that make it symbolic of the new direction of Federal energy and environmental policy. First, environmental considerations are now becoming a central part of the planning and execution of all activities, even the field testing of technologies or energy sources that are not yet fully commercial. Second, the definition of environmental concerns has broadened considerably in recent years, far beyond those that are mandated by the Clean Air Act, Clean Water Act, and other U.S. environmental legislation. Now concepts such as the preservation of biological diversity, are part of the planning cycle as well. Third, U.S. private sector firms, federal agencies, and environmental groups have learned that potential problems can often be solved by discussion and compromise rather than by confrontation and litigation. The result is a search for "win-win" solutions that can move the commercialization process forward, insure reasonable rates of returns for investors while assuring environmental protection and long-term sustainability.

Brazil

General Information and Economic Indicators

In 1965, the *per capita* energy consumption in Brazil was about 286 kg of oil equivalent, reaching 915 kg by 1990. In the 1965-80 period, the average annual growth of energy production was 8.6% with consumption growing at a similar rate of 7.9%. In the 1980-90 period production grew at an average rate of 9.9% compared to a much lower 4.9% consumption rate. The economic recession which plagued the country since the 1980s helped Brazil avoid the possibility of a severe energy crisis in early 1990s.

The two oil embargos of the 1970s forced the government to look for alternative sources of renewable energy. As the largest oil importing country in the Third World, Brazil had to undergo major adaptations to sustain its economic growth. The main options were to increase domestic oil production, to encourage energy saving technology development and to search for alternative renewable sources of energy. Although the later would have to encompass, among other sources, hydropower and solar energy this paper will focus on the Brazilian biomass feedstock for energy program, which is unique worldwide.

The Brazilian program for energy production using biomass from sugar cane, wood, cassava, bamboo and other sources, represents a giant economic effort in terms of fiscal incentives for energy production and consumption, export and import policies and equipment and machinery development and production. These combined programs contributed to change the structure of energy production and consumption patterns of the country in a relatively short period of time. The programs not only helped to increase the domestic energy supply, but also generated new jobs and opportunities in local economies. There were some positive impacts on the environment and to Brazil's research and development policies.

Energy Consumption and Production

Energy consumption in Brazil in 1991 was based mainly on hydroelectric power (36.7%), fossil fuels (30.1%) and biomass (26%) where the renewable sources accounted for almost two-thirds of the total supply (see Table 2).

Over a period of 20 years, from 1970 to 1990, the consumption of petroleum (as a percentage of total energy) moved from 34% to 30%, hydroelectricity from 16% to 37%, sugar cane products from 5% to 9% and fuelwood and charcoal from 43% to 15%. Imports of petroleum and its derivatives decreased from US$9.9 billion in 1980 to US$4.3 billion in 1991, a significant decrease due to increasing domestic supply and energy substitution programs. The doubling of the supply of hydroelectricity was due to the Brazilian government successfully accomplishing the construction of huge hydroelectric power plants such as Itaipu and Tucurui. Sugar cane products also doubled their contribution as an energy source. Domestic fuelwood use, on the other hand, showed a substantial decrease since it was replaced by subsidized liquid petroleum gas (LPG), as the population moved from rural areas to the urban centers. It is important to mention that although petroleum derivatives use was at about the same percentage of consumption, increased domestic production replaced imports lowering Brazil's external debts. The discovery of the off shore Campos basin in the 1970s helped the country to increase its domestic oil production.

Table 2. Energy consumption in Brazil in 1991 by sources in thousand of tons of oil equivalent (toe)

Sources	Thousand of toe	%
Electricity	71010	36.7
Petroleum derivatives	58280	30.1
Fuelwood and Charcoal	27091	14.0
Sugar cane products	19376	10.0
Coal and derivatives	4095	2.1
Natural gas	10984	5.7
Other fuels	2667	1.4
TOTAL	193503	100.0

Source: Ministério da Infra-Estrutura 1991

From 1980 to 1991, except for electricity, most of the real energy prices declined by more than 50% while consumption increased by around 39%. Despite the generalized subsidies given for energy production and consumption all over the country, the economic recession acted to lower energy demand. Brazil also kept its exchange rate overvalued which is equivalent to having an implicit taxation on exports, making imports cheaper. This was a way to alleviate the burden of the oil import component on the country's trade balance.

Energy Problems

Brazil's hydropower energy amounted to 207 TWh (terawatthours) in 1990 and could reach 400 TWh by year 2010. This represents less than 40% of the potential. The problem is that most of this energy production would be generated in huge projects in the Amazon region involving large construction and transmission costs and the possibility of serious environmental impacts.

The country's attempt to have some nuclear sources of energy by constructing Angra1 and Angra2 nuclear plants in Angra dos Reis were not as successful as expected and posed several environmental problems to this beautiful and famous resort site.

Despite Brazil's huge area which occupies 50% of South America, the country is relatively poor in fossil fuel reserves (oil and coal). Most of the domestic oil production is obtained from off shore basins and the coal has a high level of sulphur and ash. It has become evident that the Brazilian reserves of petroleum may be exhaustible in the foreseeable future. Thus, renewable energy sources are likely to continue to mature as a viable solution to energy problems over the medium and long run.

However, even the renewable biomass feedstocks for energy production pose some major issues, such as those related to the food *versus* fuel. That is, how to make the production of biomass for energy, and crops for food, compatible. As far as empirical evidence is concerned, it has not been clear that food production has suffered from competition by sugar cane and forest plantations for energy. Nevertheless, any time a program for increasing internal production of biomass is presented by some company or institution the issue comes up again, as a counterforce to inhibit further development.

There are also the environmental aspects of increasing the stillage disposal of ethanol production from sugar cane, along with the monocultural issues, when either sugar cane or *Eucalyptus* and *Pinus* plantations are concerned. The large reforestation projects with exotic species like *Eucalyptus* and *Pinus* are the target of criticism by certain segments of the Brazilian society. They claim these projects remove rural people from their lands and from their cultural and local agricultural practices and increase migration to the urban centers and result in poverty. These large reforestation projects are also said to be the major cause of vast native forests deforestation mainly in the savanna-like and Atlantic forests not to mention the well-known Amazon situation.

The lack of a consistent government policy toward research and development is also a very big problem as demonstrated when government-sponsored research in sugar cane productivity was discontinued by the closure of the Brazilian Institute of Sugar and Alcohol in 1990. There is also a shortage of well-trained researchers to address the interdisciplinary area of biotechnology for both basic and applied research, and microbiology relevant to biotechnical industrial processes. Brazilian universities and research institutions have been subjected to tremendous reductions in their budgets, mainly affecting the agriculture and forest research projects directed to biomass production and industrialization. In fact, all support for research work for biogas production, mini-distilleries, bio-digestors, vegetable oils, and other renewable sources of energy, has been discontinued by the government. There is no doubt that the relatively low prices of fossil fuels, make it very difficult for renewable energy to compete in the market and inhibit research for new energy sources.

Policy, Incentives and Energy Programs

The objective of the Brazilian energy program was to bring the country to energy self-sufficiency by 1993. A series of problems including those cited above contributed to Brazil's failure to reach that target. All fiscal incentives have been discontinued, even those directed to forest plantations for energy purposes.

The only energy program that still has some government support is the sugar cane-based ethanol production. This support gives subsidies to the sugar cane producers and to the mills and distilleries via credits and price policies, to consumers (lower prices of alcohol and alcohol-fueled cars, and lower annual vehicle taxes), and to auto-makers (lower tax to produce ethanol-fueled engines). Since inflation has been persistent in the last decade, and most of energy policies are conducted by the federal government, it is not surprising that those policies have been diverted toward artificially keeping energy prices low in order to try to control inflation and raise the income of the poorer segments of the society.

Electricity and liquid petroleum gas are the good examples of where the government monopoly companies, not only subsidize, but can create price discrimination given the level of consumption. For example, farms and agro-industries have lower electricity rates. In many cities, local governments have given subsidies for urban transportation companies. The 1988 Brazilian constitution declares that the workmen cannot expend more than 6% of their income for commuting to work. So, a transportation bonus, paid by the employer was created, to exempt the employee from such charges.

Several other alternative plans for energy substitution were implemented during the 1970s. Several were not successful (cassava, sorghum, vegetable oil, biogas, and others) and the causes will be discussed later in this paper.

The Alcohol Program

Three factors help explain the creation of an Alcohol Program in 1975. First, the technology for use of ethanol as a fuel in motor vehicles had been known since 1922. Second, in 1973 there was an overdependence on petroleum-based fuels - 98% of the energy used in transportation was petroleum-based and 65% of the fuel used in the country's main transportation form (highways) was gasoline. Third, there was a sugar glut in the international market along with depressed prices, thus the ethanol producers were a good alternative market for sugar cane growers. Further, there were additional facets that paved the way for the program, such as availability of unskilled labor, abundance of land, favorable climate, a well-developed sugar cane sector, and easy access to international financial markets for loans and subsidized credit (Biller 1991).

The development of the sugar cane ethanol program can be divided into three different phases. The first was from 1975 to 1979, where the objective was to diminish dependency on imported oil by using the idle capacity of the sugar sector. The sugar cane was dedicated to the production of anhydrous alcohol to be used as gasoline complement (all gasoline sold in Brazil contains 12 to 22% of anhydrous alcohol). The second phase, from 1979 to 1989, demanded major changes in the automobile manufacturing industry since the major priority was the production of hydrous ethanol and vehicles powered by this fuel. In this period, it was necessary not only to improve the hydrous ethanol distribution grid, but also to boost consumer confidence in the new fuel. In this decade, autonomous plants were opened, dedicated to produce only ethanol, instead of ethanol and sugar as did the conventional sugar mills. The third phase, from 1989 to date is still to be defined given low petroleum prices, severe economic recession, all-time record inflation rates and a new political experience in democracy.

Sugar cane is the main source of alcohol in Brazil. Other sources, such as cassava, wood, bamboo and sorghum, have had little use. Sugar cane was largely produced in northeastern Brazil until the end of the last century, when a crisis in the coffee market induced southeastern coffee growers to switch to sugar production. Now the south, mainly the state of Sao Paulo produces two times more sugar cane than the northeast. The combination of soil and climate, the extensive mechanization and good genetic material has provided the south with an absolute advantage in producing sugar cane. For instance, while sugar cane yields an average of 52.8 tons/ha in the northeastern state of Pernambuco, the states of So Paulo and Paraná, in the southern region, produce 75.5 and 76.6 tons/ha, respectively.

Because hydrous ethanol is a direct gasoline substitute and anhydrous ethanol is a component of the gasohol mixture, changes in movements in the international petroleum prices are not necessarily followed by the gasoline market. Moreover, technology is such that only a fixed percentage of gasoline (maximum of 26%) can be produced from a barrel of crude oil. With a falling demand for gasoline, an exportable excess of supply of gasoline is created, linking therefore the opportunity cost of ethanol with the gasoline exporting prices.

After overcoming initial apprehension over using hydrous ethanol, and the technology difficulties such as engine corrosion and low mileage rates, the automobile industry actively rallied behind the Alcohol's program second phase. An impressive growth in domestic sales occurred in the 1979-89 period, where more than 4 million vehicles were sold, most of them light commercial automobiles. After 1989, the trend changed, with a higher demand for gasoline cars (currently 70% of the total). This occurred because of temporary suspension of ethanol production due to price and government indecision about the program's future. The government is now working on taking some action recognizing the long-term importance of maintaining the ethanol program, considering its economic, social, strategic and environmental importance to implementing a new model for sustainable development. The program contributed to a significant reduction in oil imports, opened up new opportunities for the equipment supply industry and for technological innovation. It created 720 thousand directly-related jobs in the rural sector. Whereas the combined oil and electricity industries represents less than 300 thousand jobs, most in the urban, developed, over-populated areas (Brito 1991). Other benefits of great significance are the estimated foreign exchange savings of 9 billion dollars, during the 1975-85 period. These savings may have doubled by now.

In order to analyze ethanol as a fuel it must be kept in mind that there is a distinction between the types of alcohol that are part of the Program. Anhydrous ethanol yields no price at filling stations, since it is mixed directly into gasoline. Its pump price is reflected in the gasoline price. Since there is some flexibility in the mixture of gasoline plus ethanol (gasohol), its demand has no clear trend. If hydrous ethanol demand increases, more sugar cane is used for its production and less for anhydrous alcohol. If domestic stocks of gasoline are high, less anhydrous ethanol will be used in the gasohol mix.

On the other hand, hydrous ethanol has had a sharp increase in its consumption. This is due to its independent use and because the government has provided incentives for the purchase of ethanol-fueled cars. Its real price is substantially lower than gasoline and over the years has kept more or less fixed price ratio with gasoline. In order to continue the public interest in hydrous ethanol, a policy of lower prices has been put into effect, since the mileage rate for ethanol-fueled cars is generally lower than that of gasoline cars. Hydrous ethanol automobiles have been less heavily taxed by the government, and therefore have been more attractive to prospective buyers. Finally, the highways user's tax has been lowered for ethanol vehicles.

The installed capacity of the country's alcohol production is 16 billion liters per year which is sufficient to meet consumption needs to the year 2000. If its present share (22.5%) of the growing market is maintained, this capacity will rise to 23 - 28 billion liters per year in 2010 (Brito 1991).

Emissions from alcohol-fueled vehicles are substantially lower than those of gasoline, although in terms of aldehydes, alcohol tends to be more of a pollutant. Research done by Volkswagen of Brazil, for its Dasher model, indicates that the hydrous ethanol version emits fifty-seven percent less CO_2, sixty-four percent less hydrocarbons, and thirteen percent less nitrogen oxides (Biller 1991). Sulfur oxides emissions from hydrous ethanol vehicles are also insignificant. Another important pollutant, lead emissions, was eliminated since anhydrous ethanol is a perfect substitute as an octane enhancer in gasoline, and hydrous ethanol does not require the use of lead as an additive. A study done by Cetesb, Sao Paulo's environmental monitoring agency, shows that lead levels in the city decreased by 80% between 1978 and 1983. However there was some increase in the level of emissions of aldehydes.

Although the positive environmental impact of ethanol usage is clear in the large cities, there is some negative impacts in the production process. Pollution can occur by: 1) sugar cane field burning (greenhouse gases, solid particles and hot ashes); 2) sugar cane washing (polluted water from the removal of foreign bodies in the sugar cane); 3) filter-pie (byproduct from sugar cane juice treatment, rich in organic matter); 4) stillage (byproduct of alcohol and sugar production process and rich in organic matter and minerals in particular potassium); 5) bagasse burning (its solid particles can cause significant air pollution). Sugar cane burning can be overcome by harvest mechanization and the development of varieties that do not require the burning process. Sugar cane washing can be eliminated by water treatment and filter-pie by its use as fertilizer. Stillage has been successfully used as fertilizer (although it may contaminate aquifers) and there is a great potential for its use to produce methanol through biodigestion. Coopersucar the country's largest cooperative, uses 63% of it's stillage to fertilize the sugar cane plantations. Bagasse burning can be a important source of thermal and electric energy, and many producers are already using it for this purpose (optimistic proponents have argued that over 40% of the country's electricity production could be obtained from this source alone).

In 1984, Coalbra, a state-owned company began to produce ethanol from wood in a demonstration plant located in Uberlandia, Minas Gerais. The objective was to produce about 10.7 billion liters of ethanol annually from wood obtained from *Eucalyptus* plantations in the region. The process was based on a Russian technology which could, in addition to ethanol, generate important by-products such as furfural, charcoal and animal feedstock. Despite its technological success at the demonstration level, this technology was not commercially implemented in Brazil. This was because it could not compete with the sugar cane-based ethanol technology. Hydrolysis of wood was too capital-intensive and demanded a very large supply of raw material. The costs were 10-20% higher than sugar cane ethanol production. Because of this, Coalbra was deactivated and the experimental plant closed in 1988.

Wood-based methanol production was an initiative of Cesp, an energy company located in Sao Paulo. The company received a US$26.4 million loan from the InterAmerican Development Bank (IDB) to built a pilot plant for research purposes. The process converted 1.6 tons of wood to 1 ton of methanol. CESP wanted to use the methanol in Otto-diesel cycle engines, boilers, thermoelectric plants and pilot ignition systems. Despite its potential as a low cost energy production process, the program was also discontinued by the company because had a low energy transformation coefficient when compared to other energy generation process.

The Charcoal and Fuelwood Energy Programs

As mentioned, Brazil's reserves of oil and coal are relatively small considering the extent of its territory. Further, Brazilian coal is of low quality for producing iron and steel due to its high sulphur and ash content. Thus, opposed to most of the industrialized countries of the world, charcoal as a substitute for coal played a very important role in the development of the Brazilian iron and steel production sector. The use of wood placed a heavy burden on Brazil's native forests and also contributed to the development of the large-scale short rotation plantation forestry over the last 25 years. According to the F.A.O. (1991) in 1989 Brazil consumed 182.806 million cubic meters of fuelwood and charcoal and this is projected to continue at that level until year 2010. In 1991 the charcoal-based iron and steel industry in Brazil contributed US$3 billion to the country's economy generating 189,500 jobs and paying US$485 million in tax revenues to the government (ABRACAVE 1992).

It is interesting to note that approximately 10 years ago native forests accounted for 80% of the total supply of charcoal while forest plantations contributed with only 20%. By 1991 the contribution of the native forests to charcoal production in Brazil decreased to 60% of the total with forest plantations rising to 40%. Using 1982 as the base for comparison, utilization of native forest-based charcoal increased 119% while forest plantations-based charcoal utilization increased 351%. This is a positive trend both from the environmental and economic point of view. Currently the Brazilian government has removed some fiscal incentives from the forest sector of several charcoal-based industries. This has caused some switch to imported coal. Decrease in use of charcoal will alleviate the pressure on the native forests. Plantations may be used for other purposes such as woodpulp.

A government program called Our Nature was created in 1989 to generate 100% self sufficiency in the charcoal-based industries within a seven-year period. In the Amazon region those goals would be attained by sustained yield management of the native forests while in the other states of the country they would be accomplished through plantation forestry.

Fuel oil is utilized as a fuel by industries to produce thermal energy, mechanical energy and electricity. Most of these industries can promote partial or total substitution of fuel oil by biomass-based fuels. Among them, woody biomass has all the necessary conditions to substitute for fuel oil if used directly (firewood, chips and logging residues) or transformed (charcoal briquettes, tar, etc...). In 1978 a National Forestry Program (NFP) was created whose main objective was to develop forest energy plantations for industrial purposes. In addition to the traditional energy role wood became very important for charcoal and liquid fuel production and steam and thermoelectricity generation. These processes were used by the cement, pulp and paper, iron, steel-making and other industrial users (Hall 1987). A considerable amount of new knowledge was generated in the biological and manufacturing fields and on the use of short-rotation plantation forestry for both exotic and native species (*Mimosa scabrella, Acacia mearnsii, Eucalyptus sp, Gmelina arborea, Pinus sp, Araucaria angustifolia, Prosopis juliflora, Bambusa vulgaris,* etc...).

Charcoal and wood tar played a very important role as a fuel oil substitute in the cement and steel industry in the 1980s. Thermochemical processes of pyrolysis and gasification for supply of fuel to boilers, kilns and engines also attracted the attention of large companies such as Nestlé and Petrobras. Nestlé initiated a US$40 million program to convert fuel oil use to biomass over its nationwide network of factories.

Copene, a subsidiary from Petrobras also started a project to replace 200 thousand barrels of fuel oil annually by using wood at the Camaćari petrochemical complex in the state of Bahia. An extensive area of *Eucalyptus* plantations was established by COPENER, the forest division of Copene. The plantations were close to the area in order to guarantee the supply of wood for the large energy generation complex. The wood was pulverized and burned in the boilers for steam generation. Low costs of fuel oil caused the project to be discontinued by Copene which is now exporting the plantation's wood and pursuing joint ventures with national and international pulp and paper companies.

In 1981, the cost (as a percentage of oil price) to produce a gigacalorie (GCAL) of fuel oil by using charcoal was 43.8%, by using debarked wood 34.9% and by using logging residues only 9.6%. In 1991 the pulp and paper sector alone consumed 4.3 million steres of wood for energy as a substitute for fuel oil. Of this wood, *Eucalyptus* accounted for 61.5%, *Pinus* for 19.6% and 18.9% from other forest species. To supply their needs for fuel oil substitution and for producing pulp and paper, the Brazilian pulp and paper sector has established 1.4 million hectares of forest plantations and is planning to establish an additional 855 thousand hectares plantation by the year 2000.

Other Biomass Energy Efforts

The use of vegetable oils as substitutes for fuel oil in Brazil was part of the energy policy of the country in the 1980s. A number of significant studies were undertaken by the government and several government-sponsored universities and research institutions. The research efforts were concentrated more in the direct use of the vegetable oils as fuel alone and also in mixtures with diesel, and diesel plus ethanol. Some additives obtained from renewable raw material were also studied to be used in mixture with diesel. Several exotic and native species like baba`cu, macauba, cotieira and even soybean and castor oil were studied as possible fuel substitutes. However, except some local use by specific companies or cooperatives, no commercial production or use occurred for such oils.

Studies conducted by Shell, Chesf and Eletrobras have shown that *ceteris paribus* energy production from biomass cannot presently compete in price with energy generated from oil, coal and natural gas. The only way it can compete is by generating a more valuable form of energy *viz* electricity. This is possible by using a technology developed in the United States. This new technology is the Biomass Integrated Gasification/Gas Turbine (BIG/GT). In this technology the gas is used to power a turbine which produces electricity. The exhaustion gases from the turbine are captured for additional energy production. Compared to the traditional 20% efficiency in the steam-based electricity production systems this new technology has a 40% conversion efficiency. This new technology is the Biomass Integrated Gasification/Gas Turbine (BIG/GT). In 1992 Brazil submitted a technical proposal to the Global Environmental Facility (GEF) to build an experimental BIG/GT plant and to study the economic feasibility of the process. The project was approved and is now underway (Carpentiere et al. 1992).

The Use of Biomass for Energy in Brazil - the Future

Initially forests were used indiscriminately to provide firewood and charcoal for industrial and household consumption. Today, the remaining of the native forests are protected by federal, state and county legislation and their utilization must conform to sustained yield management and biodiversity concerns.

While some companies such Acesita and Belgo Mineira are substituting imported coal for charcoal others such as Mannesmann and Pains, are still using charcoal from their forest plantations to supply their plants. These companies are developing new technologies for a more efficient conversion of wood into charcoal and also obtaining by-products such as tar, chemicals and electricity from the carbonization process. It is clear that charcoal as an energy source in Brazil will only survive if new technologies continue to make its production a viable economic activity.

Despite the huge development of the Brazilian sugar cane-based ethanol industries this fuel cannot compete in price with gasoline without a government subsidy. If, in the short run, international oil prices rise then ethanol industry production may become economically viable. But even if this does not happen, due to the existing capital investment in the sector and its importance as a job-generating activity, ethanol production from sugar cane will likely remain an important biomass energy supplier in Brazil. If the use of anhydrous ethanol is adopted in other countries of the world then ethanol production could enjoy international markets. In the sugar cane-based ethanol production area research continues in the biotechnology area to obtain high yield cane varieties and also more efficient microorganisms to convert the sugar cane carbohydrates into alcohol. Utilization of sugar cane leaves, cuttings and bagasse as future source of energy and animal feed are also under investigation.

The BIG/GT technology will be given emphasis in the future. A project has been developed for evaluating its use over the next six years. The project has five stages. The first stage was to evaluate the technical proposal and pre-investments studies. The second one, to be concluded by 1994, is in progress and involves the development of equipment, basic engineering, economic feasibility studies and preparation of the basic structure for stage three. Stage three will consist of the construction over a 24 to 30 month period of the operational plant using a US$23 million funded by the Global Environmental Facility. Additional capital resources will be provided by the associated companies: Eletrobras, Chesf, Cientec, Cvrd, Shell Brazil S.A. and Shell International Petroleum Company. This joint venture effort is coordinated by the Brazilian Minister of Science and Technology and the experimental facility will be probably built in Bahia close to existing *Eucalyptus* plantations. The fourth stage will be 24 months in duration and will comprise operational demonstration tests with sugar cane bagasse and wood biomass. Finally, the fifth stage will be the commercial operation of the plant.

This BIG/GT project in Brazil is the first of its kind in the world and if successful will bring many advantages such as: small size of the plants which allow decentralization of electrical energy production; reduction of energy transmission costs; small capital investments allowing the private companies to enter the sector; use of marginal agricultural lands for short rotation forest plantations devoted to biomass for electricity energy production; the generation of rural jobs and the utilization of the Brazilian bioenergy potential. The northeastern region of Brazil alone has a potential of using 197.1 million steres of wood and to produce 19.673 thousand megawatts of energy per year.

Canada

Introduction

Canada is a large country where diversified forms of biomass can be found. A number of important institutions and enterprises taking part in the economical development of the country are involved in research and development pertaining to biomass. A large segment of the population is working in various sectors of the biomass such as forestry, agricultural, industrial, urban, food processing, fisheries and peat bogs.

In this presentation, biomass will be covered from the point of view of types and quantities that are available in Canada for producing energy. Forest wastes, as well as the cost involved from a market point of view, along with a few examples of research carried out in this field will be addressed.

Canada covers an area of 997,100,000 hectares and is the second largest country in the world after the Federation of Independent States. Bordered by three great oceans, the Atlantic, the Pacific and the Arctic, it is located between 141° and 53° longitude and 42° and 83° latitude. A trip across Canada shows an impressive climatic and topographical variety. The country is divided into ten provinces and two territories. The population is estimated at 27,300,000 inhabitants of which 90% are located within 350 kilometers of the American border; primarily because the climate is more favorable, but also because we like our neighbor...!

From its total area 453.3 million hectares are covered by forests, 75.5 million hectares by water and 67.8 million hectares by agricultural lands; there is obviously very little doubt that this is a forest country.

Biomass in Canada

Biomass in Canada can be divided into four main categories:

- forestry
- agricultural
- urban, and
- peat.

The bioenergy contribution to the total energy supply in Canada is approximately 7% (EMR Canada). This energy level is equivalent to that produced by nuclear generation, and about half of that obtained from coal. In certain provinces, the biomass contribution is even higher. For instance, it represents 12% of the energy supply in the Maritime provinces and 23% in British Colombia.

Before we discuss forestry biomass, let us consider the Canadian forest.

The Canadian Forest

As mentioned before, there are 453.3 million hectares of forest in Canada. This forest can be divided in three groups. 209 million hectares can be considered commercial, 193 million is classified non commercial (low density, small trees, muskegs, high elevation, etc.). 27 million hectares are protected forests (buffer zones, river banks, etc.). Of this total forest area, 80% is under provincial jurisdiction, 11% under federal jurisdiction (particularly in the case of national parks) and 9% is owned by the private sector (See Figure 4)(Forestry Canada, 1991).

The province of Québec has the largest area of timber productive forest with 22% of the total canadian forest area territory followed by British Columbia and Ontario with 21% and 16%, respectively. Surprisingly, 90% of New Brunswick's area is covered by timber productive forests.

Canada's potential is approximately 24 trillion cubic meters of wood (Forestry Canada, 1988). This volume is concentrated mainly in British Columbia, with 38% of the total volume in Québec and 17% in Ontario. The most productive forests are in British Columbia along the Pacific where forests can be found with a volume of 1500m^3/ha. Put into perspective, it represents more than ten times the volume of the average canadian stand.

Canadian forests are composed of 80% coniferous trees such as spruce, pine and fir. Even though the forest covers a large area, certain forests are not available for the production of ligneous matter, or are simply not accessible. The following information concerns only forests which are accessible and not reserved for particular uses (park, reserves).

Forest Biomass

Forest biomass is the most abundant source of biomass that can be found in Canada because of the area covered by forests. This biomass source is estimated to be over 26 billion oven dry tons (Bonnor, 1985). However, the quantity potentially available for the production of energy is much lower.

Forest biomass usable for the production of energy is termed forest waste, and includes harvest residues, transformation residues and plantations of fast growing species for the purpose of producing energy.

Harvest Residues

Harvest residues include wood from non-commercial forests, surplus merchantable timber, and left over wood residues on cutovers or on roadside such as slag, limbs, tops, branches, residual trees, trunks.

According to a study done in 1985 by Bonnor of the Pacific Forestry Centre, seven billion tons of feedstock available for energy production from accessible forest sites, including commercial and non-commercial forests, becomes 102 million tons per year, over a rotation period of 80 years, if only timber-productive forest are considered. 102 million tons/year is equivalent to 59% of the total oil needed in Canada annually and 22% of all energy needed.

Non-commercial or non-productive forests are so-called because of low density and/or the species involved for which traditionally there is no market in the forest industry. These forests make up 16% of the total forest biomass but is not utilized significantly for energy purposes.

Surplus merchantable timber is the difference between the Allowable Annual Cut (AAC) and the volume of harvested wood. 1991 data show that 163.7 million m^3 of wood has been harvested, of which 88% were coniferous, over an annual potential harvest of 233 millions m3 (Figure 5). Wood surplus from accessible timber-productive and non-productive forests represents an interesting source of energy production. This type of biomass is made up of accessible wood, wood from trees that do not meet commercial standards, or excess wood due to market demand. Accordingly, biomass surplus in timber-productive forests, as well as forests which are over matured, diseased, dead from insect injuries or by fire, as well as forests made up of undesirable species, ready to be converted, could be converted as solid or liquid combustible or as a chemical product with added value. The transformation cost would not be greater than conventional forest operations cost and wood could be transported whether in the form of trees, lengths, logs, or chips.

It is interesting to note that Forest companies in the region of Williams Lake in British Columbia started a salvage operation of forest infested by insects in 1989. According to a study conducted by FERIC in 1992, what started as a clean up operation became an important source of ligneous fibers for many companies.

Until now, most studies have been done on the value of exploitable forest residues, but only few studies have been done on energy value of the biomass contained in unproductive forests. The quantity of residues produced by forest harvesting is directly related, of course, to the type of operation. As a source of energy supply, we are mainly considering slash pile residues on cutovers, those at the landings, and those at the roadside.

From an economical or environmental point of view it does not seem realistic to collect residues from cutting sites. Past and present studies, particularly under ENFOR (Energy from forest) from the Bioenergy Research Program of Forestry Canada, have been conducted to determine the impact of collecting forest residues on the soils physical and chemical properties.

A study conducted in British Columbia in the late 1980s by Commander of Forestry Canada concluded that those plots where a second rubber tire skidder was used to collect wood biomass were 16% more damaged than plots conventionally harvested. The gouges were deeper, the ground more compacted, and more scalping of the surface layers could be observed. Another study conducted in Québec by Bergeron, demonstrated that the extraction of wood residues from the forest floor impoverishes the soil, particularly from carbon and phosphorus and has negative effects on soil erosion, and diminishes the capacity of water infiltration of thin soils.

The quantity of forest residues harvested for energy purposes vary, of course, with the harvesting techniques, but also with the species harvested and the type of equipment used.

In 1992, Maranda and Rycabel estimated that 81.2 oven-dry tonnes (o.d.t.)/ha can be harvested in a maple stand forest in Eastern Canada by a tree-length harvesting system, compared to 75.3 o.d.t./ha in a black spruce stand by a cut-to-length harvesting system.

On the other hand, Commander was able to collect 145 o.d.t./ha (171 m^3/ha) of wood biomass in a central region of British-Columbia on a cutover of red cedar and hemlock stand, after a conversion with a cut-to-length harvesting system. This average figure increases dramatically on the West Coast, where it reaches 1100 tonnes/ha, comparatively to the national average of 89 tonnes/ha per timber productive forest.

On the subject of harvesting systems versus the quantity of harvestable residues, the cut-to-length harvesting system leaving branches, tops, roots, leaves and secondary species on the site is the least interesting from a supply point of view.

Under the tree-length harvesting system, the top and the bark of the trees, transported to the area, represents 15% of the total tree biomass. Also, harvesting full-trees drags out 30% of available biomass for energy. Consequently, it is the least costly and the most interesting method of harvesting.

Evidently, the heating power of wood chips is related to the type of wood, its humidity level, and the efficiency of the furnace use. Assuming an efficiency for a specific burning system is 70%, and a wood chip humidity of 35%, a ton of wood chips generates 9738 MJ of heat.

$(Fh\ (kcal/kg) = Fo\ (kcal/kg)\ X\ \dfrac{100-(H\%/7)}{100+H\ (\%)}$ (Maranda & Rycabel, 1992)),

where Fh is the calorific efficiency of the wet wood, and Fo the calorific efficiency of the dry wood, H is the moisture content.

Even though these residues produced by forestry operations exist in great abundance in Canada, the limiting factor is the cost of harvesting, primary transformation and transportation to the plant.

Numerous studies have been done on this subject. The study by FERIC, estimates at between $22.50 and $26.00 is the total cost of production over a transportation distance of 50 km to the plant. If a cost of delivered wood chip of $40 per oven dry ton is assumed to be competitive with the cost of fossil fuels, wood chips produced by the Nicholson chipper (the purchasing cost of the chipper is not included in the calculation) could be transported as far as 130 km (one way) in Eastern Canada.

The choice of the chipper (off-road or mounted on a semi-trailer) must be based on the annual required production (o.d.t./year) often set by the energy chip market, as well as other factors such as road layout and conditions, the proximity of the slash to roadside, and production costs.

Studies have demonstrated that the production of roadside chipping residues can be competitive, on a cost basis, compared to other fuels. Thus, collecting wood residues on roadside and at the landing has a beneficial effect on the forest, as opposed to collecting them on a cutover. Collecting these piles of debris increases the area available for replanting, diminishes fire hazards as well as the cost involved to reuse the land.

Some large Canadian forest industries are currently pursuing some studies to determine the cost-effectiveness of harvesting and of transforming roadside residues for energy purposes. This demonstrates actual company interest in this form of biomass.

The evaluation of the forest biomass in a national forestry inventory is under consideration by the Canadian Forestry Service in Chalk River, Ontario. To date, Prince Edward Island is the only province which includes this resource in its total forestry inventory. That project would help to greatly increase the sources of forest residues for producing energy.

Transformation Residues

Transformation residues are mostly generated by pulp and paper mills, by sawmills and by veneer and panel mills. It is de-inking slime (called black liquor), bark, sawdust, shavings, and chips.

In May 1993, Kentek Ltd., on behalf of Energy, Mines and Resources Canada, constituted a data base on residues produced, used and disposed of by the Canadian forestry industries.

The annual production of plant residues is 21.3 million tonnes of oven dry wood; of which 19.4 million tons are utilized, and a little more than 3 million tons, approximately 14.9%, discarded. Certain provinces including British Colombia, New-Brunswick and Prince Edward island, use almost all their mill wastes. In fact, New Brunswick and Prince Edward Island have many district heating systems fed with wood chips.

The pulp and paper plants are major consumers of wood residues used to feed their boilers to generate steam and electricity. In 1990, these plants utilized approximately 80% of the production of chips from sawmills. Almost half of these plants burned de-inking slime to produce heat.

In 1990, the Canadian pulp and paper industry was able to meet 52% of its own energy needs, an equivalent of 378 PJ for a total demand of 728 PJ. 267 PJ were generated from spent pulp liquor, 100 PJ from biomass, 9 PJ came from hydraulic power and 2 PJ from other sources. The paper industry is currently studying biomass dehydration to increase the quality of combustion.

Another portion of the transformation residues is also used to make panelboards, sold to farmers for agricultural and sold for horticultural purposes. Some are used for animal bedding and a small quantity is used to make energy pellets: the remainder is incinerated in burners or burned in waste disposal sites. Dried transformation residues are an important biomass source because it is accessible, clean, ready to use with a humidity level which is generally not above 20%.

Usually, the pulp and paper industries can obtain this sort of residues by paying the transportation from the sawmill to the plant. The transportation cost amounts to $5 per oven dry ton for a distance of 50 km. For example, the province of British-Columbia produces enough wood chips derived from plants and forests to produce 1.5 to 2 billion liters of ethanol per year that is enough to replace 4 to 5% of the current annual requirement for gasoline in Canada. The Centre de Recherche en Sylvichimie de l'Outaouais, a Canadian research centre specializing in wood chemistry, is currently studying the potential for producing ethanol from forest residues.

Fast Growing Trees For Energy Use

Energy plantations do not yet exist on a large scale in Canada. We are still at the experimental stage of establishing plantations and wind breaks with clones or hybrid trees, that feature faster than average growth on a short rotation period of time. Plantations incorporating these tree species exist here and there in Canada, but the wood from these plantations is used for pulp and paper making.

Many research centres and organizations, including Forestry Canada, Agriculture Canada, Energy, Mines and Resources, Universities of Toronto, Laval, Guelph and Edmonton, the Department Natural Resources of Ontario, the Centre Québécois de la Valorisation de la Biomasse, the Jardin botanique de Montréal, REAP Canada, Wayerhauser, Domtar, Scott paper, MacMillan Bloedel, are conducting biogeography and biometeorology studies in order to optimize clones and soils, genetic crossing, the establishment and maintenance of plantation, biomass productivity, harvesting methods and loss/benefit analysis.

Associations have been formed in the last few years between research centres and farmers, and small scale energy plantations have been established in agricultural fields. The purpose is to develop sources of biomass located near transformation or utilization centres. Many farmers could also heat their buildings with wood chips from fast growing trees.

However, our maintenance techniques need some improvements to diminish the total costs of production, evaluated, (Kenney, Gables and Zsuffa, 1992), at $60.76/o.d.t.m with an average annual productivity of 12 o.d.t.m/ha.

Research is still needed on the conversion of biomass from fast growing trees into a more refined fuel, rather than direct combustion, through a biochemical or thermochemical process.

Agricultural Biomass

We will now give you a brief outlook on agricultural biomass, strictly from the point of view of the vegetation, on urban waste and paper as a residue, and on peat biomass. In Canada, agricultural land covers extremely large areas, in particular in the Prairies. Land under agricultural cultivation cover 32.3 million hectares, producing annually almost 56 million tons of agricultural products.

The production of ethanol from grains has been developed for some time and offers certain advantages: However, the production of alcohol from grains that could other wise be sold for human consumption increases the real cost of producing that alcohol. This is why agricultural residues such as chaff, stover and straw are preferred as a low cost source of lignocellulosic material. Unlike corn and cereals, crop residues have a little intrinsic value and can be obtained at a fraction of the cost.

According to Agricultural statistics, approximately 25 million tons of agricultural straw waste are generated annually in Canada. Assuming that 20 million tons could be available for conversion to liquid fuels, approximately 290 PJ could be generated, representing 12% of the industrial sector's demand and 3.6% of the national demand.

Sun Root, a western facility produces 10 million liters of ethanol/year from corn. Depending on feedstock prices, which vary considerably, ethanol can be produced for approximately 30 to 45 cents/litre.

Urban Biomass

Millions of metric tons of solid wastes are produced annually in Canada, of which almost 60% is of a biomass nature. One third of these residues is derived from municipal pick up of domestic wastes, and almost half comes from enterprises, institutions and industrial waste.

However, there is currently strong opposition to the creating of landfills and incinerators in urban areas. The "Not in my backyard" syndrome is quite strong everywhere in the country. People are more and more aware of pollution and the 4Rs (reduce, reuse, recycle and recover) are the favoured options. In the beginning of 1991, Bell Canada launched a "Zero Waste" program in some of its buildings in Québec and Ontario to familiarize the workers with the importance of the 4Rs.

The SENES Group from Toronto recently completed a study that estimated the quantity of paper waste and the proportion available for recycling across Canada. It is estimated that 53% of a total quantity of waste that varies between 5.7 and 7.6 million tons is recyclable. It is difficult to obtain a single and exact number because many regions have not carried a survey on this subject. Corrugated cardboard constitutes the bulk of it with almost 30% of the total quantity, but only 30% is recyclable because of the high chemical content of this material. Clearly all variety of materials studied including: printing paper, computer print-outs, corrugated cardboard, newsprint, coated paper, boxboard and other material (telephone books, etc.), can serve as feedstock for incineration. The majority could serve as feedstock for pyrolysis and fermentation depending on the nature of the chemical products involved, on the concentration, and the type of heavy metal contained in the ink, and on the quantity of clay coatings used for certain paper types. Research is currently underway on the fermentation of paperboard.

Temeco Enterprises serves as a good example to demonstrate the type of fermentation that can be applied to urban waste. Temeco is a subsidiary of Tembec Inc., a pulp and paper industry in the province of

Québec. This mill is one of the few remaining in North America to make use of sulphite pulping technology which produced a very low yield high quality pulp. The waste stream of this process (waste sulphite liquor) is a series pollution threat. However, as it contains sugars, Temeco ferments it to produce 10 to 15 million liters per year of alcohol, since 1991. It has a market value of $5 to $7 million.

Currently in Canada, 58.6% of all pulp and paper mills are now making products containing some recycled fibers as part of the process and 20% of these have de-inking facilities (Figure 6). Two-thirds of the fibre now utilized by all the paper mills is made up of wood chips, sawmills residues and recycled paper (See Figure 7). The problem of waste wood from demolition sites has not been dealt with yet and will be addressed in the near future.

Peat Biomass

The total area of peatlands in Canada is estimated at 111,328,000 hectares, covering close to 12% of the country's land surface. Nevertheless, 60% of Canadian peatlands are perennially frozen. Estimated peat resources total approximately 3,004,996 million m^3, equivalent to 338,000 Mt of dry peat. Measured resources are estimated at 1,092 Mt. As a result, Canada is the third largest peat producer in the world. Most Canadian peat production is used in horticulture, nurseries and landscaping, and by mushroom growers. Domestic consumption of peat was estimated, in 1991, at 12% of the total shipments, with the remainder being exported. Shipments comprised peat in bulk, bales and value-added products such as pots and mixes.

Canada exports peat to about 35 countries of which the United States accounts for 89%, followed by Japan at 10% and the Netherlands at 0.6%. Sales to U.S. originate mostly from Québec (51%), followed by Western Canada (35%) and Atlantic Canada (14%). Shipments in 1991 valued at $91.7 million. Peat is harvested primarily in Eastern Québec, New Brunswick, Western Canada (Edmonton, Alta.; Carrot River, Sask., Giroux and Elma, Man.), Nova Scotia, Prince Edward Island and Newfoundland.

From all the provinces, Newfoundland has the largest percentage of its area in peat, 11% (1,114,990 ha). Since 1886, Newfoundland has a plant which supplies peat to numerous institutions in St. John's for energy generation. To date, only a few communities still use peat as a fuel. Climatic conditions typically are the main factor prohibiting its use on a larger scale.

In 1992, Northland Ltd. installed mole drains (using Finland equipment) on sites already drained with open ditches, as well as an undrained sites to determine the most effective drainage system to be employed for different types of peat lands. For the next stage, the Stanton Group Inc. of Boston currently proposed to operate a peat moss generating plant at the Abitibi-Price paper mill in Stephenville. Peat moss would be harvested over an area of 2,000 to 3,000 hectares.

In 1990, the Canadian Sphagnum Peat Moss Association, whose members account for 90% of total Canadian peat output, developed a preservation and reclamation policy for peatlands. The policy aims at protecting the peatland eco-systems and recommends methods for operating and managing a peat log which includes preparation techniques and reclamation measures.

Canadian Conclusions

Clearly, Canada possesses considerable amounts of biomass, the most important being forest residues. Numerous inventory have been made in order to quantify accurately all the different forms of biomass, often by the provinces themselves. However, the process at the national level is not completed. In an era of geomatics, it would now be essential to identify the sources of supply based on a general system of location that should serve as a powerful tool for the assessment of the use of biomass on a local basis, and the selection of the most appropriate biomass types and production techniques that would also serve to evaluate the relevance one source of residue as opposed to another, knowing cost of production and transport to the end-user plant.

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Brazil

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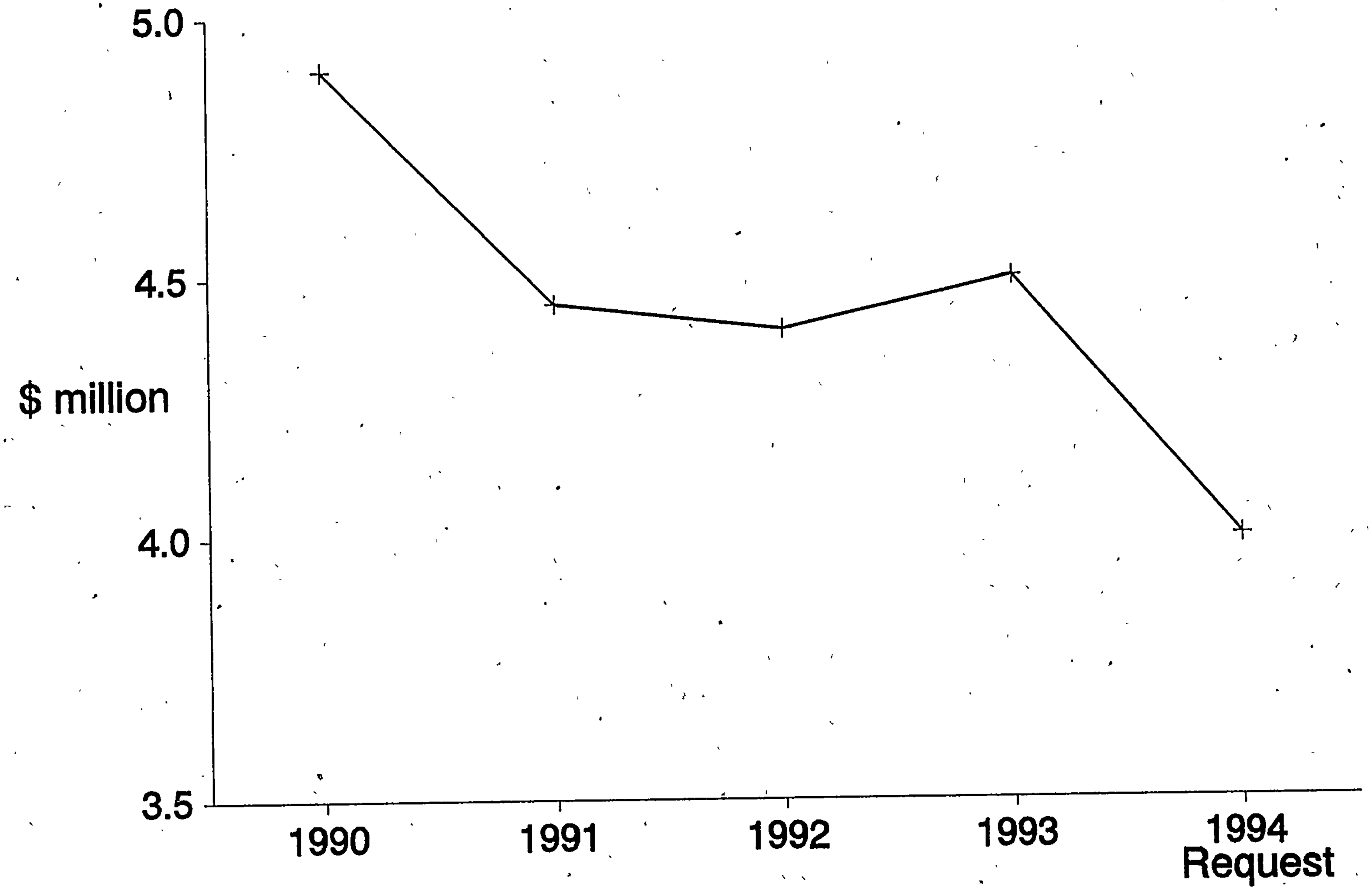


Figure 1. DOE Terrestrial Feedstock Development Budget 1990-94

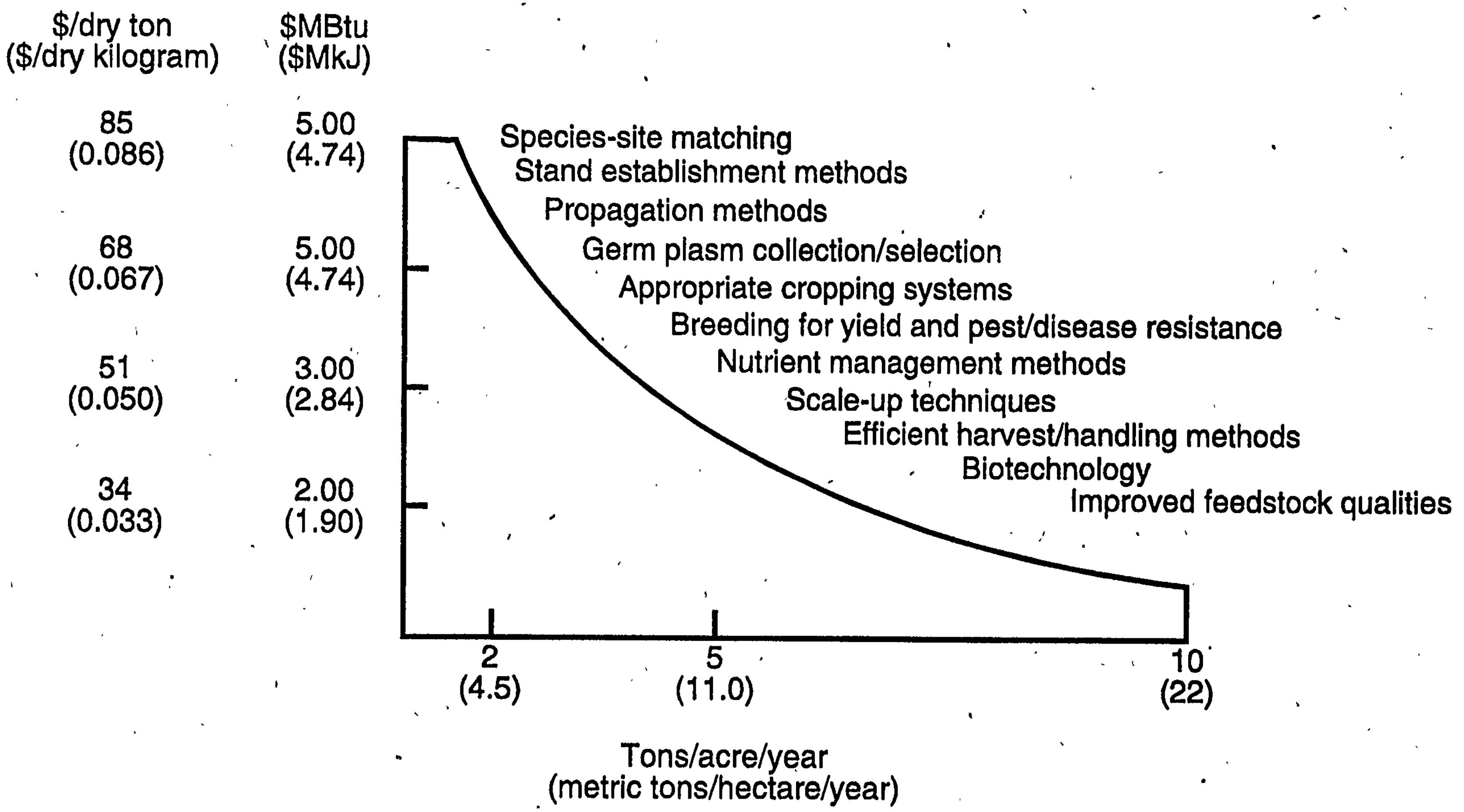


Figure 2. **Projected Feedstock Cost Reductions**

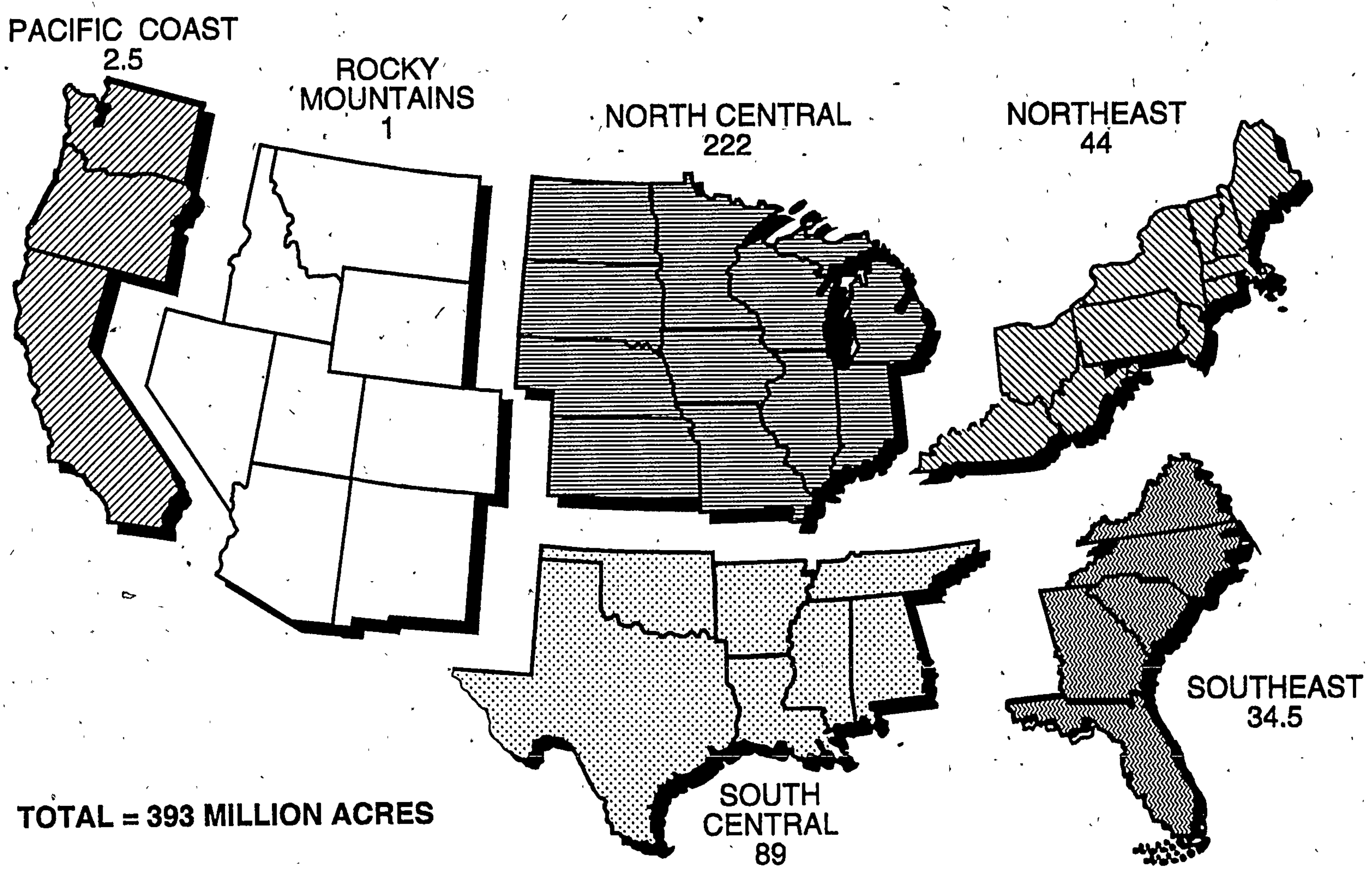
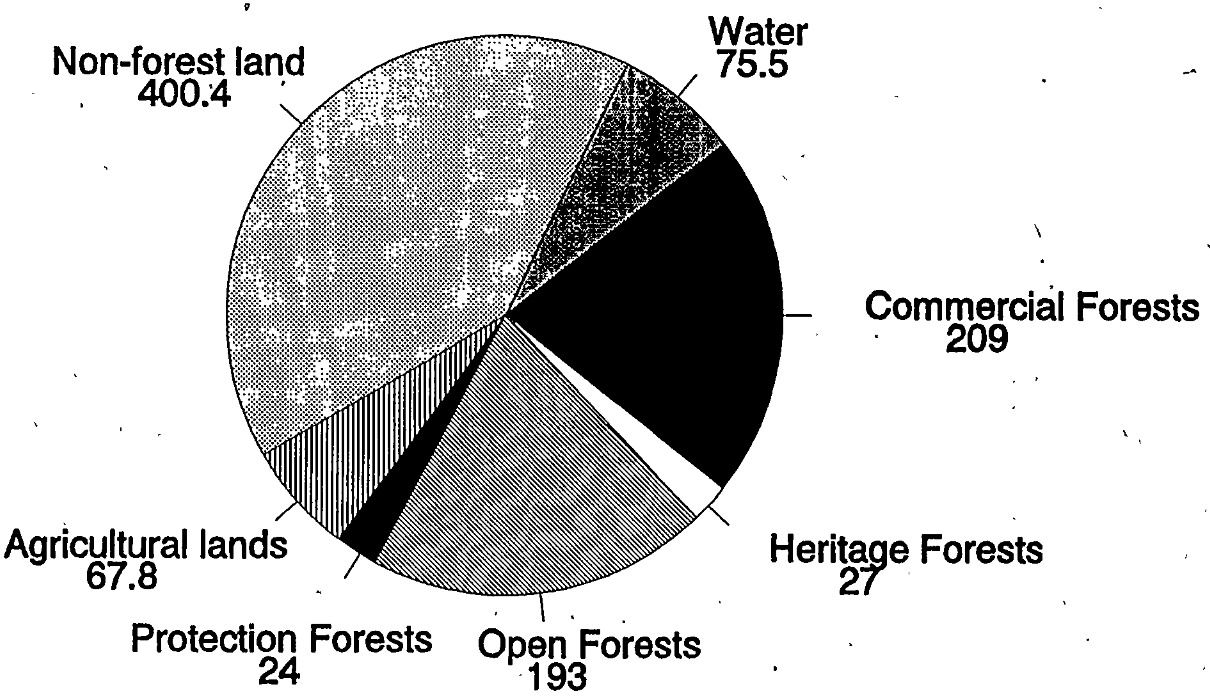


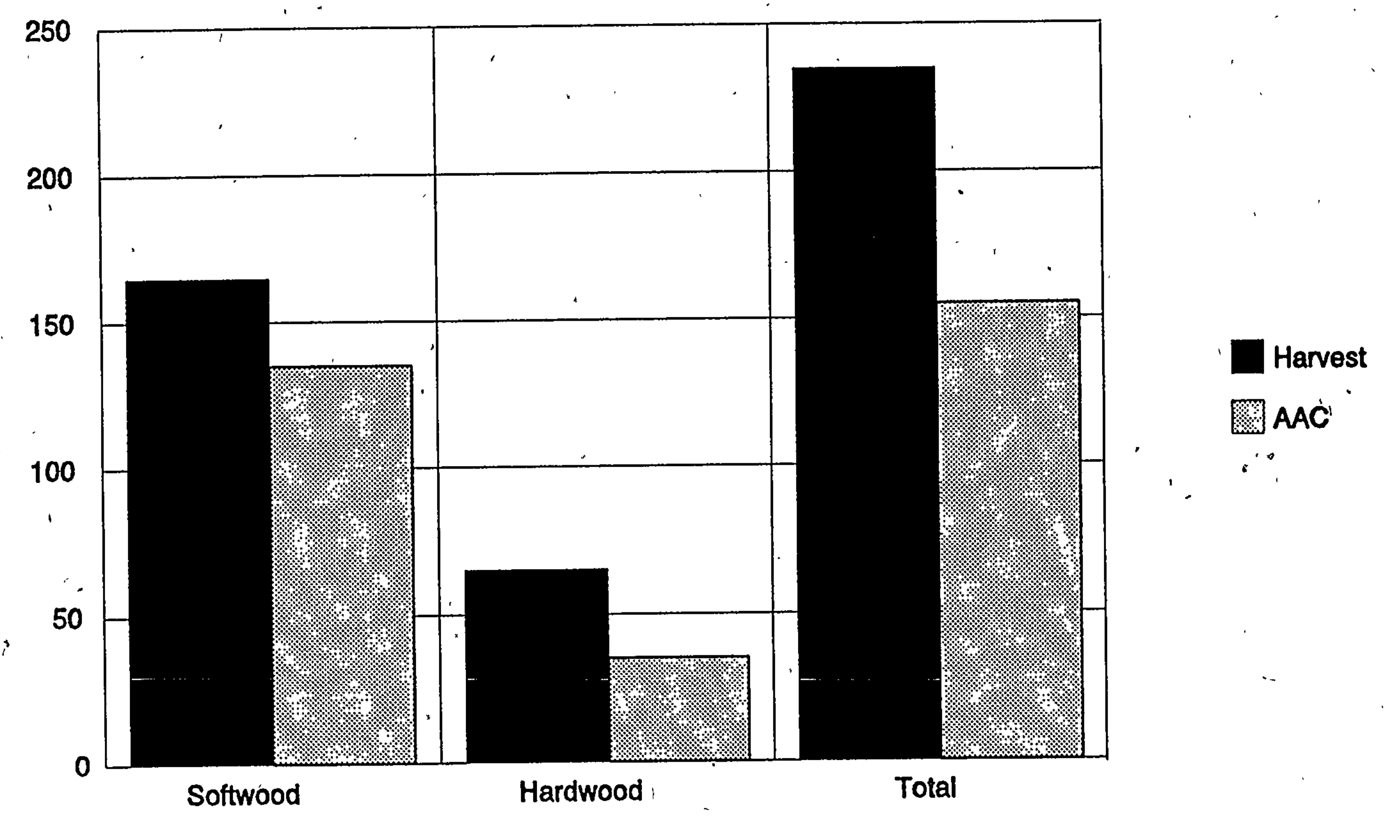
Figure 3. Land Capable of Producing Energy Crops Without Irrigation (Million Acres)



% of the Land area	Jurisdiction
80	Provincial
11	Federal
9	Private Sector

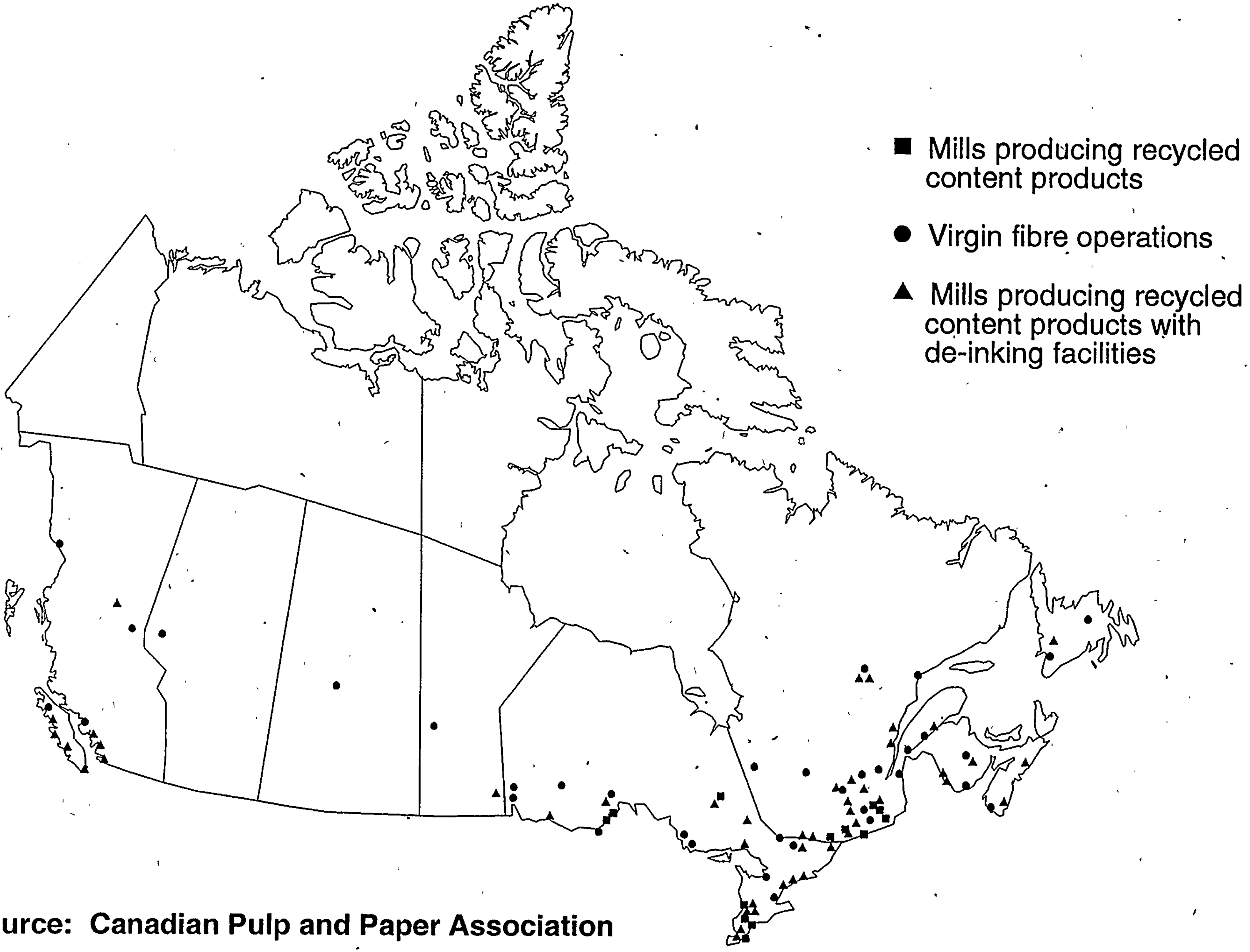
Source: Forestry Canada
Statistics Canada

Figure 4. Canada's Land Area 1990 (million of hectares)



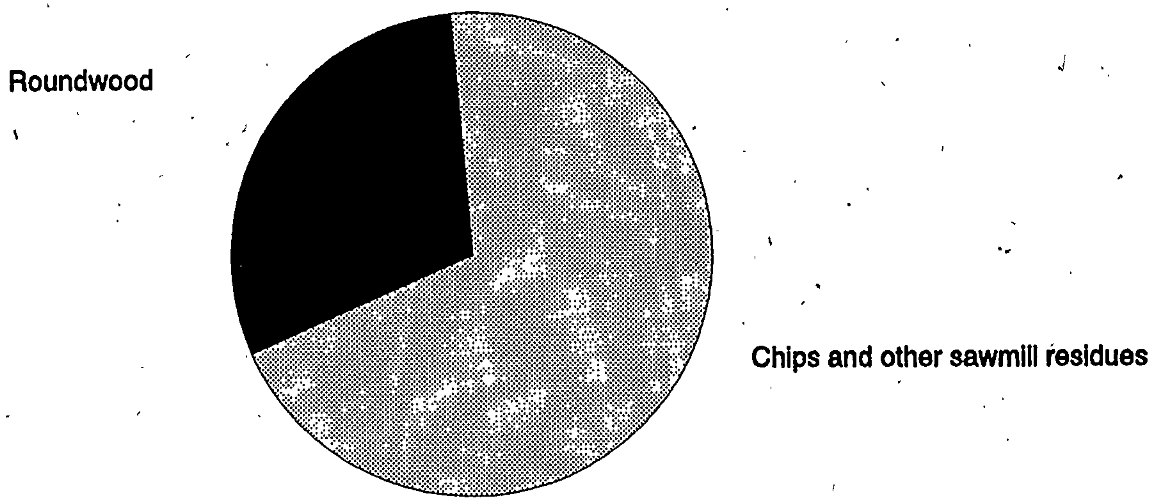
Source: Forestry Canada

Figure 5. Allowable Annual Cut and Harvest 1991 (Million Cubic Meters)



Source: Canadian Pulp and Paper Association

Figure 6. DE-Inking and Recycling Facilities



2/3 of the fibre used to make pulp and paper comes from chips, other sawmill residues and recyclable paper

Source: Canadian Pulp and Paper Association

Figure 7. Canadian Pulp and Paper Sources

WILLOW BIOENERGY PLANTATION RESEARCH IN THE NORTHEAST

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Abstract

Experiments were established in Central New York in the spring of 1987 to evaluate the potential of Salix for biomass production in bioenergy plantations. Emphasis of the research was on developing and refining establishment, tending and maintenance techniques, with complimentary study of breeding, coppice physiology, pests, nutrient use and bioconversion to energy products. Current yields utilizing Salix clones developed in cooperation with the University of Toronto in short-rotation intensive culture bioenergy plantations in the Northeast approximate 8 oven dry tons per acre per year with annual harvesting. Successful clones have been identified and culture techniques refined. The results are now being integrated to establish a 100 acre Salix large-scale bioenergy farm to demonstrate current successful biomass production technology and to provide plantations of sufficient size to test harvesters; adequately assess economics of the systems; and provide large quantities of uniform biomass for pilot-scale conversion facilities.

Fast-Growing Hardwoods Program at SUNY College of Environmental Science and Forestry

The Fast-Growing Hardwoods Program was initiated at the State University of New York College of Environmental Science and Forestry in 1983 to investigate cultural systems for the establishment, tending and harvesting of short-rotation hybrid poplar clones. Existing literature on the culture of *Populus* was evaluated and summarized, and specific techniques developed for the intensive culture of hybrid poplar in New York and the Northeast. Clone-site trials were established on high-quality agricultural soils in the Southern Tier of New York State and on upland soils in Central New York State. Hybrid poplar clones suitable for sites within New York State were identified from these trials and appropriate cultural techniques for successful production determined. Growth and yield of the trees was related directly to individual clones and responsive to inherent site conditions, primarily soil properties. Maximum biomass yields of the short-rotation hybrid poplar was approximately 5 oven dry tons per acre per year (odt/a) on a five year rotation. Other trials demonstrated that no-till techniques can be used successfully to establish hybrid poplar on potentially erosive soils. Trees planted under no-till attained similar survival and growth rates as compared to conventional clean cultivation.

In addition to these major research emphases other important aspects of establishment, maintenance and product recovery in intensively cultured hybrid poplar were explored. Deer browse was shown to have an impact on hybrid poplar establishment and growth. Soil and weather conditions were seen to be collectively important for the successful use of herbicides during establishment and tending. Preliminary wood quality analyses among clones and between sites indicated that the suitability of various hybrid poplar clones as substrate for bioconversion and usable energy products is dependent on both clone and site conditions. Soil solution chemistry was shown to be minimally affected by intensive cultural practices and that there was no measurable affect on soil water quality.

Bioenergy From Willow

Following the effort with short-rotation intensive culture of hybrid poplar, studies were initiated to ascertain the potential suitability of <u>Salix</u> as a high yielding biomass feedstock. Bioenergy plantations utilizing fast-growing tree species for high, sustained wood biomass feedstock is a concept gaining wide acceptance in an energy dependent world. Maximizing the efficient production of energy by means of optimizing the growth of selected tree crops is the goal of bioenergy plantations. In addition, fast-growing woody biomass plantations can provide uniform, high quality, sustained woody feedstocks for a variety of valuable chemical products - a dedicated feedstock supply system.

Wood has always been an important source of energy and, until this century, the world has relied mainly on wood for cooking and heating. Today, in addition to traditional uses, wood biomass is employed for electrical power generation and converted to liquid and gaseous fuels. Production of energy from woody biomass has been the subject of extensive research in recent years because of uncertainties about future fuel supplies. Biofuels use in the United States is expected to increase dramatically by the year 2000. Thus, there is at present again a significant demand for wood for energy. With new, improved technologies for energy conversion, this demand can increase dramatically in the not too distant future.

Use of fast-growing bioenergy plantations of trees as a renewable feedstock for energy production has another critical benefit in addition to the direct energy value. Growing and converting trees to usable energy sequesters and recycles carbon directly from the earth's atmosphere and thus the amount of CO_2 produced by utilizing wood energy merely equals the amount stored in trees while they grow. There is no net addition to the global greenhouse gases and while the trees are growing there is a net reduction in CO_2 in the atmosphere. In addition, current data indicates that the vigorous young bioenergy plantations are growing at 10-20 times the rate of native Northeastern U.S. forests. Assuming that every pound of tree biomass removed half a pound of carbon from the atmosphere, these intensively cultured bioenergy plantations can provide a more rapid mitigation of possible global warming than native forests.

The major pollutants associated with wood combustion are NO_x, VOCs (volatile organic compounds) and CO_2. Products from short-rotation intensive culture are CO_2 neutral as described above. The amounts of fine particulates produced by wood burning would require removal by electrostatic precipitation units. Since wood biomass contains little sulphur, SO_x is a negligible problem. In new boilers currently in operation or available, higher temperatures and adequate oxygen supply reduce NO_x and VOC to very small levels, < 1 ppm, which is considered negligible.

Large supplies of wood for energy can be created in some places by using low-value trees, and wood residues and wastes. However, this supply is often either not sustainable and/or non-uniform, or not available where needed.

In many locations land is available for bioenergy tree crops. This land can be of either marginal quality for agriculture and needing tree cover for protection and environmental improvement, or of good quality where there is a surplus of farm crops. A land base estimated at 200 million acres consisting of agricultural land recently removed from production, and other marginal quality agricultural land, is potentially available for bioenergy plantations in the United States. In such conditions a bioenergy plantation approach can be taken to provide biomass for energy and provide alternative cash crops in a farming community where many traditional farm crops are in a state of overproduction with many farmers surviving only with heavy government subsidies. The concept of the energy plantations is not new; it was developed in response to the "oil crisis" of the 1970s. Projects were initiated in many countries and with a variety of woody species employed. Basic and applied research on the use of bioenergy plantations intensified in the Northeast in the past decade with major programs developed at the College of Environmental Science and Forestry, Syracuse, New York; Reynolds Metals Company, Massena, New York; University of Toronto, Toronto, Ontario, Canada; and Ontario Ministry of Natural Resources.

Salix Clonal Production Trials

Willow bioenergy plantations were established in 1987 at the State University of New York College of Environmental Science and Forestry's Genetic Field Station near Tully, New York (42° 47' 30" N, 76° 07' 30W). The soil was a Palmyra gravelly silt loam (Glossoboric Hapludalf), a good quality agricultural soil, with corn production generally in the range of 5 odt/a. Site preparation was done mechanically and chemically. The site was sprayed with glyphosate (Roundup™, Monsanto Agricultural Company, St. Louis, MO) at the rate of 2.2 lbs ai/a during August 1986, to kill all weeds and upon confirmation of herbicide effectiveness, the site was plowed, cross-disked and raked. Simazine (Princep 4L™, Ciba-Geigy Corp., Greensboro, NC) was subsequently applied at the rate of 4.5 lbs ai/a to prevent weed growth during the first part of the 1987 growing season.

Unrooted 10-inch long cuttings from five willow clones, plus a hybrid poplar clone known to be well adapted to the site (Table 1), were collected from one-year-old stems during winter 1986 from nursery stool beds and stored at 0°C until planting. Willow clones were selected for above-average biomass production potential in a genetic selection trial in Ontario, Canada. Cuttings were planted flush with the ground during the first week of April 1987, at 1.0 x 1.0 ft. spacing.

Experimental plots were 20 x 20 ft. in size including two exterior border rows. Experimental design was a split-plot with three replicates per treatment for the whole-plot factor. Fertilization treatment was the whole-plot factor and clone was the sub-plot factor.

Three of the whole-plot replications received fertilizer shortly after trees sprouted in each of the six years. Fertilizer was applied to minimize nutrient availability as a growth-limiting factor. Elemental N, P and K was applied as ammonium nitrate, treble superphosphate and muriate of potash at rates of 300, 100 and 200 lbs/a/yr, respectively. Nitrogen was applied as urea through an irrigation system in 1990 at the equivalent elemental rate. Each year's initial application consisted of the entire amount of P and K and 50 lbs/a of N. Subsequently, five additional applications of N at 50 lbs/a were hand broadcast every three weeks until August of all years, except in 1990 when it was applied through the irrigation system.

Plots were irrigated in 1989-1992 using a line system with distribution so that soil moisture tension remained below 20 centibars. Amounts of water added ranged from 1.0 to 2.4 inches per acre per week, with the larger amounts required during August. Irrigation was terminated in mid-September each year. Trees were harvested annually during December, except first-year growth was harvested in January-March 1988.

First-harvest (non-coppice, 1987) oven dry biomass production was significantly affected by clone (Table 2). Fertilization did not significantly affect overall biomass production in 1987, although willow clone SAM3 did respond dramatically to fertilization. Second-harvest (first coppice, 1988) survival and oven dry biomass production were significantly affected by clone (Tables 2, 3). Survival after the first coppice was 80 (SA22) to 97 percent (NM5), averaging 92 percent. The most productive clone and treatment, hybrid poplar clone NM5 with fertilization, yielded 4.1 odt/a. Clonal biomass production rankings were different in 1988 compared to 1987. Fertilization significantly increased biomass production during 1988, averaging 1.8 and 2.5 odt/a for non-fertilized and fertilized trees, respectively, with some clones responding better than others. Precipitation during the growing season was less than normal.

Trees were first irrigated in 1989. Third-harvest (second coppice, 1989) biomass production was significantly affected by clone (Table 2). The most productive clone and treatment, willow clone SV1 with fertilization, yielded 6.3 odt/a.

Fertilization significantly increased biomass production, averaging 3.6 and 5.0 odt/a for non-fertilized and fertilized trees, respectively. With fertilization, all but one of the willow clones produced more biomass than hybrid poplar clone NM5. Clonal biomass production ranks of willow clones did not change from 1988 to 1989, though hybrid poplar clone NM5 decreased in rank.

Fourth-harvest (third coppice, 1990) survival and biomass production were significantly affected by clone (Tables 2, 3). Highest overall production was 6.6 odt/a by fertilized willow clone SV1. Fertilization did not significantly increase production, averaging 4.9 odt/a for both non-fertilized and fertilized trees. Fertilization significantly reduced survival (77 vs. 90%). Significant clone-by-fertilizer interaction for

Table 1. Origin of Clones Planted at SUNY Genetics Field Station

Clone	Origin
NM5	Populus nigra x P. maximowiczii (cl. "Max-4"). Munden, West Germany
SV1	Salix x dasyclados. Brantford, Ontario, Canada
SA22	S. alba. Zagreb, Yugoslavia.
SA2	S. alba var. sanguinea. Novi Sad, Yugoslavia.
SAM3	S. x rubens. Toronto, Ontario, Canada.
SH3	S. purpurea. Munden, West Germany.
SP3	S. purpurea. Brantford, Ontario, Canada.

Table 2. Biomass Production (Standard Errors in Parentheses) of Five Willow Clones and One Hybrid Poplar Clone, Fertilized or Non-Fertilized, Harvested Annually

		Oven Dry Biomass (tons/acre)					
CLONE	TRT	1987[1]	1988	1989	1990	1991	1992
SV1	F	0.5	3.7	6.3	6.6	7.3	4.0
		(0.03)	(0.39)	(0.66)	(0.08)	(0.35)	(0.12)
	NF	0.5	2.6	4.8	6.2	6.7	3.9
		(0.11)	(0.25)	(0.53)	(0.14)	(0.33)	(0.09)
SH3	F	0.6	2.1	5.3	5.3	5.7	4.0
		(0.07)	(0.49)	(0.09)	(0.26)	(0.36)	(0.07)
	NF	0.6	1.8	3.9	5.4	5.9	4.6
		(0.07)	(0.14)	(0.09)	(0.35)	(0.40)	(0.11)
SAM3	F	0.5	1.7	3.4	3.5	3.8	1.9
		(0.01)	(0.06)	(0.19)	(0.65)	(0.24)	(0.25)
	NF	0.2	0.7	2.0	3.8	3.1	1.1
		(0.02)	(0.11)	(0.23)	(0.42)	(0.40)	(0.19)
SA22	F	0.3	1.6	4.9	3.3	3.7	2.7
		(0.03)	(0.27)	(0.22)	(0.49)	(0.47)	(0.66)
	NF	0.2	1.2	3.0	3.6	2.5	1.3
		(0.05)	(0.23)	(0.27)	(0.18)	(0.17)	(0.27)
SA2	F	0.3	1.7	5.6	5.9	6.0	3.9
		(0.03)	(0.28)	(0.24)	(0.33)	(0.27)	(0.11)
	NF	0.2	1.3	2.9	4.7	4.8	2.6
		(0.06)	(0.35)	(0.65)	(0.36)	(0.93)	(0.60)
NM5	F	1.4	4.1	4.4	4.5	5.1	3.4
		(0.12)	(0.11)	(0.14)	(0.06)	(0.12)	(0.06)
	NF	1.1	3.4	4.9	5.8	6.0	3.4
		(0.15)	(0.26)	(0.18)	(0.29)	(0.04)	(0.18)

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[1] Data from 1987 is non-coppice production. All other years are coppice production.

Table 3. Survival (Standard Errors in Parentheses) of Five Willow Clones and One Hybrid Poplar Clone, Fertilized or Non-Fertilized, Harvested Annually

		SURVIVAL %		
CLONE	TRT	1988	1990	1991
SV1	F	93 (0.6)	83 (2.2)	74 (4.5)
	NF	97 (0.3)	94 (0.6)	90 (0.7)
SH3	F	90 (0.3)	80 (2.2)	70 (1.4)
	NF	94 (0.3)	93 (1.2)	91 (1.9)
SAM3	F	93 (1.5)	83 (0.5)	77 (2.5)
	NF	92 (2.6)	90 (1.7)	85 (3.8)
SA22	F	78 (1.8)	76 (2.0)	70 (3.3)
	NF	82 (3.1)	82 (3.2)	75 (5.3)
SA2	F	92 (3.2)	81 (4.4)	70 (3.1)
	NF	98 (0.3)	94 (0.7)	87 (2.7)
NM5	F	97 (0.6)	60 (0.7)	48 (0.5)
	NF	97 (0.7)	87 (1.9)	70 (2.7)

biomass production was detected; three of the six clones produced more with fertilization than without. Clone biomass production ranks of willows were similar from 1989 to 1990, with only the poorest two clones changing ranks, and hybrid poplar clone NM5 decreased in rank.

Fifth-harvest (fourth coppice, 1991) survival and biomass production were significantly affected by clone (Tables 2, 3). The range in survival was 48 (NM5 fertilized) to 90% (SV1 non-fertilized) and in production was 2.5 (SA22 non-fertilized) to 7.3 (SV1 fertilized) odt/a. Clone rank for biomass production was the same as in 1990 except willow clone SA2 and hybrid poplar NM5 reversed ranks. Fertilization with N, P and K significantly decreased survival (68 vs. 83%) and slightly increased overall biomass production (4.9 vs. 5.3 odt/a). Significant clone-by-fertilizer interaction for biomass production was observed, with two clones (SH3 and NM5) producing less biomass with N, P and K fertilization than without, the remainder producing more with fertilization.

Sixth-harvest (fifth coppice, 1992) biomass production by all clones dropped dramatically, averaging 40% less in 1992 than in 1991 (Table 2). This reduction across all clones was related to the cool, wet 1992 growing season in which growing degree days were 33% less than in 1991. Variability in production related to yearly growing season weather fluctuations are strong reasons that long-term data is critical to establishing the viability and sustainability of dedicated feedstock supply systems.

Serious insect or disease pests were not observed with one exception. Potato leafhoppers (Empoasca fabae Harris) were observed on willow clone SA22 (Salix alba) in 1989-1991, causing leaf necrosis and tree stunting. Damage appeared minimal during 1989, but was severe enough in late summer 1990 to warrant spraying with malathion, resulting in production of foliage larger than that produced prior to spraying. Damage in 1991 was severe in early June so trees were sprayed again with malathion. Two applications failed to control the leafhopper population. Potato leafhoppers were also observed on Salix viminalis clones in other experiments for the first time in 1991. Willow clone SA2, a Salix alba clone, and willow clone SV1, a hybrid of Salix dasyclados and uncertain other species, were not attacked by the leafhoppers. Low production by willow clone SA22 relative to other willow clones in this study may be attributable to damage by potato leafhoppers.

Clonal variation in every trait examined was large, suggesting that clone selection is critical to efficient biomass production. Clonal ranks of willows were reasonably stable after three years, suggesting willows could be reliably selected after three growing seasons with annual harvests. Large clonal variation implies that a genetic improvement program could rapidly achieve large gains. Willow clones in this experiment were selected based on performance in a nursery trial at Kemptville, Ontario, yet some willow clones produced more biomass than hybrid poplar clone NM5, a well-tested clone known to be well adapted to the region. This suggests that with genetic improvement and matching clones to sites, biomass production by willows probably will far exceed that of hybrid poplars.

When annual biomass production of the best producing clone SV1, fertilized and non-fertilized trees is plotted over time, it is apparent that annual fertilization with N, P and K accelerated the rate at which trees reached their highest production on the site by one year (Figure 1). In addition, fertilization generally resulted in increased biomass production, but data in Table 2 indicates that the clone x fertilizer interaction is critical. Likewise, since fertilization with N, P and K was met only to minimize fertility as a limiting production factor, additional well-designed fertilizer trials are needed to truly access clonal response to specific nutrients.

Foliar nutrient values during 1990 and 1991 were similar to those reported for experimentally grown willows in the literature. Foliage nutrient concentrations were not affected by fertilization in 1990 or 1991, except foliage potassium concentration was significantly higher in fertilized trees in 1991. Clones differed significantly in foliage concentration of all nutrients tested during 1990 and 1991 except nitrogen in 1990. Clonal foliage nutrient status was not clearly related to biomass production. It was not clear which element(s) trees responded to during 1988 and 1989, the two years when fertilization significantly increased biomass production. Speculatively, nitrogen is the most likely element to which trees are responding since fertilization did significantly increase stem nitrogen concentrations in three of five years.

Fertilization since 1987 reduced soil pH, averaging 5.9 and 5.3 in non-fertilized and fertilized plots, respectively, in 1990. Reduced soil pH may be related to reduced survival and less stocking could affect growth in the near future. The rate of nutrient removal by stemwood harvest of willows was high (100 lbs/a of nitrogen for the most demanding clone during 1991) and similar to traditional agricultural crops where fertilization is considered essential. The nitrogen application rate (300 lbs/a annually) may have been excessive, contributing to reduction in soil pH, but it appears that fertilizer application will be necessary to sustain high production levels for sustainable repeated harvests.

Willow Spacing Trial

Plantations were established in 1987 to determine the influence of tree spacing and fertilization on biomass production of willow clone SP3, Salix purpurea, with annual harvests. Spacings were 0.5 x 0.5, 1.0 x 1.0, and 1.5 x 1.5 ft. and plot sizes were 20 x 20 ft. with two exterior border rows. All site preparation, planting, fertilization and irrigation was as in the clone-fertilizer study. The experimental design was a split-plot (randomized complete block) with three blocks; fertilization was the main-plot factor and spacing was the sub-plot factor.

Biomass production differed among spacings in 1987 (non-coppice) (Table 4). The densest spacing yielded the most biomass in 1987 (1.0 odt/a with fertilization), but the difference between spacings was not as large as might be expected given the number of trees planted, suggesting there was competition among trees planted at 0.5 x 0.5 ft. and 1.0 x 1.0 ft. spacings during the first year. Fertilization with N, P and K slightly increased first-year biomass production (0.5 vs. 0.6 odt/a).

First-coppice (1988) biomass production was equivalent among spacings, averaging 2.5 odt/a with fertilization (Table 4). Fertilization with N, P and K slightly improved biomass production (2.0 vs. 2.5 odt/a). The most productive spacing-treatment combination (1.5 x 1.5 ft., fertilized) yielded 2.6 odt/a. Survival was unaffected by fertilization or spacing, averaging 91 percent (Table 5). Clearly, competition among trees limited individual tree production at the narrower two spacings.

In 1989, with little or no water stress due to irrigation, the two narrowest spacings produced significantly more biomass than the widest spacing, but the narrower spacings were not different from each other (Table 4). Highest production was 5.5 odt/a at the 1.0 x 1.0 ft. spacing with fertilization. Fertilization with N, P and K significantly increased biomass production (3.2 vs. 4.8 odt/a).

Spacing significantly affected third-coppice (1990) biomass production (Table 4). The 1.0 x 1.0 and 1.5 x 1.5 ft. spacings produced significantly more biomass than the 0.5 x 0.5 ft. spacing, but the two wider spacings were not different from each other (Table 4). Best production, 5.5 odt/a, was by fertilized

Table 4. Biomass Production (Standard Errors in Parentheses) of Willow Clone SP3 Grown at Three Spacings, Fertilized or Non-Fertilized, Harvested Annually

OVEN DRY BIOMASS

(tons/acre)

SPACING (ft)	TRT	1987[1]	1988	1989	1990	1991	1992
0.5 X 0.5	F	1.0 (0.09)	2.5 (0.23)	4.8 (0.14)	4.8 (0.04)	4.2 (0.75)	3.4 (0.12)
	NF	0.7 (0.10)	2.1 (0.08)	3.3 (0.14)	4.1 (0.40)	5.1 (0.13)	2.8 (0.14)
1.0 X 1.0	F	0.5 (0.06)	2.4 (0.38)	5.5 (0.35)	5.2 (0.19)	5.7 (0.12)	3.8 (0.14)
	NF	0.4 (0.08)	2.0 (0.42)	3.7 (0.13)	5.3 (0.09)	6.2 (0.27)	3.2 (0.01)
1.5 X 1.5	F	0.4 (0.03)	2.6 (0.08)	4.1 (0.21)	5.5 (0.09)	6.0 (0.16)	3.7 (0.11)
	NF	0.3 (0.05)	2.0 (0.31)	2.6 (0.25)	5.2 (0.25)	6.2 (0.16)	3.3 (0.28)

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[1] Data from 1987 is non-coppice production. All other years are coppice production.

Table 5. Survival (Standard Errors in Parentheses) of Willow Clone SP3 Grown at Three Spacings, Fertilized or Non-Fertilized, Harvested Annually

		SURVIVAL %		
SPACING (ft)	TRT	1988	1990	1991
0.5	F	94	75	67
X		(3.1)	(1.3)	(1.3)
0.5	NF	92	90	85
		(5.5)	(4.4)	(6.7)
1.0	F	93	88	87
X		(1.5)	(1.6)	(2.3)
1.0	NF	80	80	80
		(17.5)	(15.8)	(17.9)
1.5	F	91	86	86
X		(2.4)	(3.3)	(3.3)
1.5	NF	94	92	92
		(4.4)	(3.5)	(3.5)

trees spaced at 1.5 x 1.5 ft. Fertilization with N, P and K did not significantly affect biomass production. Survival was not affected by spacing or fertilization, averaging 85% (Table 5). Soil pH was decreased by fertilization, averaging 6.1 and 5.4 in non-fertilized and fertilized plots, respectively.

Fourth-coppice (1991) biomass production was significantly affected by spacing, with the 1.0 x 1.0 and 1.5 x 1.5 ft. spacings yielding significantly more biomass than the 0.5 x 0.5 ft. spacing. The most productive spacing-treatment combination (1.5 x 1.5 ft. spacing, non-fertilized) produced 6.2 odt/a. Survival was not affected by spacing, averaging 83% (Table 5). Fertilization with N, P and K did not affect biomass production or survival.

Fifth-coppice (1992) biomass production of clone SP3 dropped substantially from the 1991 production in a manner similar to the reductions seen with the other clones. Again, the lower production was related to the poorer growing season of 1992, as compared to 1991 (Table 4).

Biomass production of fertilized and non-fertilized trees over time (Figure 2) was similar to that of the clone-fertilizer study. Fertilized trees produced nearly 5.0 odt/a in 1989 and yielded approximately the same amount of biomass during 1990 and 1991, but the non-fertilized trees did not reach the same level until 1990, a year later.

Biomass production of the three spacings over time (Table 4) showed that trees planted at 0.5 x 0.5 and 1.0 x 1.0 ft. spacings began to slow in their rate of increase in biomass production in 1989, while the 1.5 x 1.5 ft. spacing did not begin to slow until 1990. Production at the two wider spacings was similar in 1990 and 1991, approximately 1 odt/a more than the 0.5 x 0.5 ft. spacing. Percent survival at the three spacings in 1991 was similar, so inter-tree competition, not tree mortality, was the reason for lower production at the narrowest spacing than in the two wider spacings. Assuming irrigation supplied adequate moisture, and since there was no difference in biomass production between trees fertilized with N, P and K and those that were not-fertilized, it appears that competition was primarily for growing space. The 0.5 x 0.5 ft. spacing was too dense for efficient biomass production after two growing seasons with the clone and management system used, and the 1.5 x 1.5 ft. spacing appears preferable to the 1.0 x 1.0 ft. spacing because of reduced planting costs. Speculatively, it is likely that the widest spacing would appear even more favorable if trees were not irrigated, since irrigation may have benefited the narrower spacing most due to a higher level of competition for water.

Summary

The Fast-Growing Hardwoods Program at the State University of New York College of Environmental Science and Forestry has successfully demonstrated the potential suitability of Salix in short-rotation intensive culture as a high-yielding biomass feedstock as one component of a dedicated feedstock supply system. The research has documented plantation establishment, tending and maintenance techniques for specific Salix clones, with complimentary results on breeding, coppice physiology, pests, nutrient use and bioconversion to energy products. Current yields utilizing selected Salix clones developed by the University of Toronto in short-rotation intensive culture bioenergy plantations in New York approximate 8 oven dry tons per acre per year. Immediate future objectives are to continue the strong integrated research program on short-rotation intensive culture of woody biomass plantations developed over the past decade at ESF utilizing results to establish large-scale Salix bioenergy farms to demonstrate current biomass production technology; provide plantations of sufficient size to test prototype harvesters; provide opportunities to accurately assess economics of the systems; and provide large quantities of uniform biomass for pilot-scale conversion facilities.

Acknowledgments

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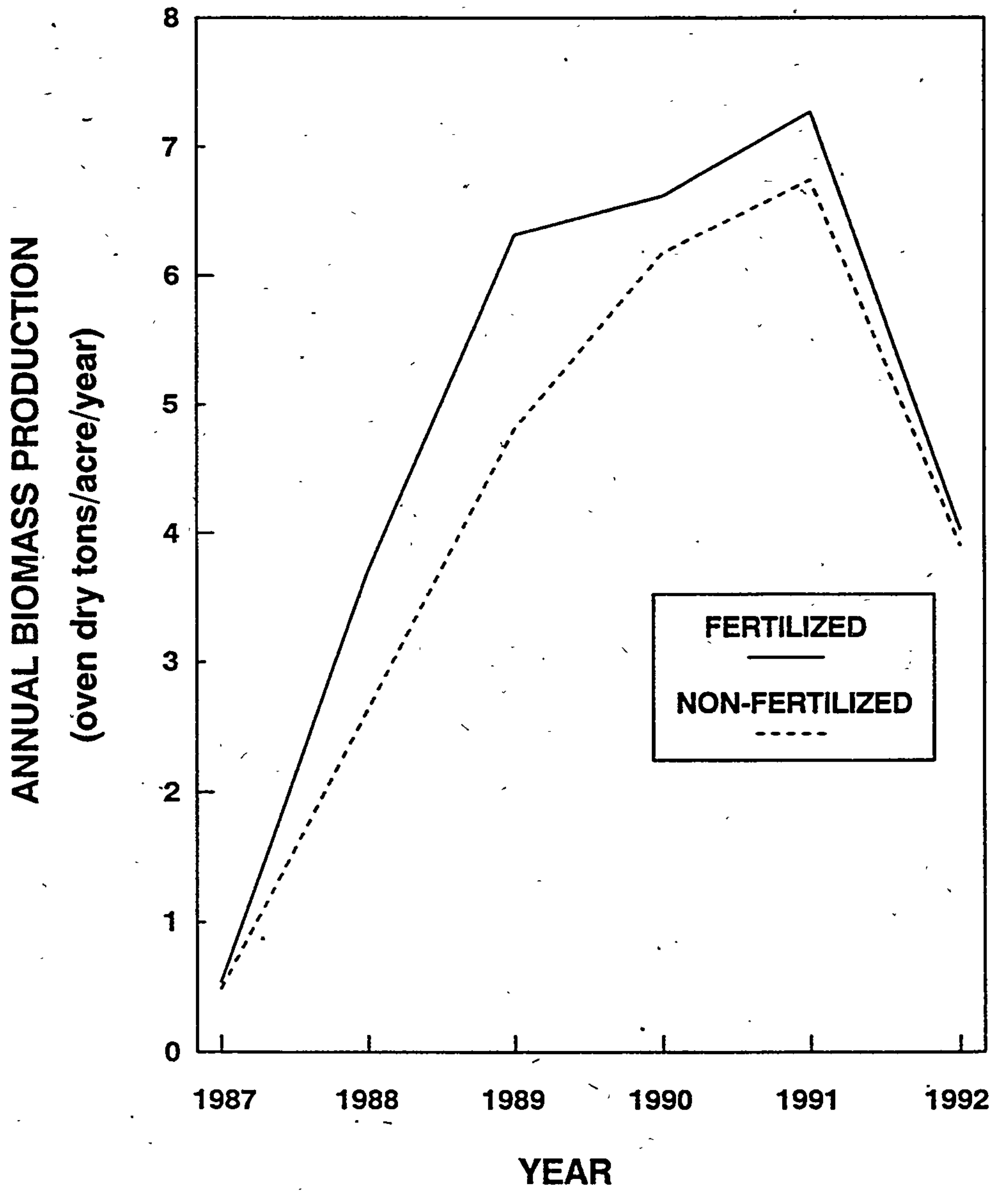

Figure 1. Average Annual Oven Dry Biomass Production of Willow Clone SV1, Fertilized and Non-Fertilized.

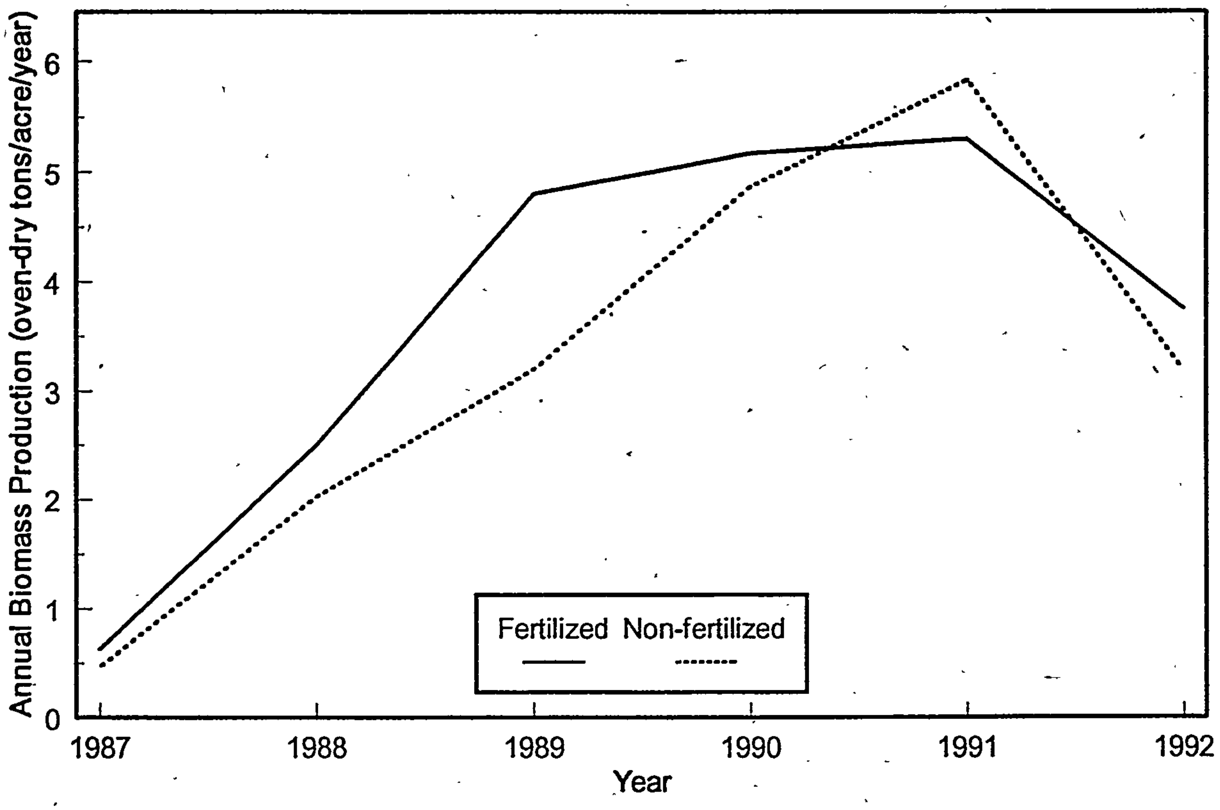

Figure 2. Average Annual Oven Dry Biomass Production of Fertilized and Non-Fertilized Willow Clone SP3.

THE ROLE AND SIGNIFICANCE OF *SALIX* PLANTATIONS FOR ENERGY IN SWEDISH AGRICULTURE

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Abstract

Fifteen years of research and development of energy forestry with *Salix* species has lead to a firm basis of knowledge concerning the basic biology, stand ecology and production systems of fast growing willows in Sweden. The biology research program continues to emphazise studies of plant biology and diseases as well as areas such as clone/site interactions, mixed clonal plantations and breeding. The technological research and development concentrates on functional and effective machinery for planting, harvesting etc. A large variety of field tests and practical application on farm level have resulted in the recent commercialisation of Salix plantations for energy production in Sweden. Until now about 8000 hectares have been established as an agricultural crop on private farm land (1993). Most producers have a contract for delivering wood chips to a district heating plant. Plantations are established with about 18 000 cuttings of selected willow clones per hectare. During the first summer weed control is the most important treatment. Fertilizers are applied in order to keep a high production level, but should be adjusted for economic optimum. Harvesting is performed during winter at 3-5 years intervalls. The machines used are either a direct chipping or a whole stem harvester. The average annual production is about 10 - 12 tonnes DM per hectare. The duration of Salix plantations is estimated to be 25-30 years. There is an estimated potential of 300 000 hectares of Salix plantations, which would result in 15-20 TWh of energy corresponding to 5% of the need of energy in Sweden. Wood fuel from the conventional forest equals 60 TWh today, with a potential of being doubled within 10-20 years.

The economic outcome for the farmer of growing *Salix* mainly depends on the price of chips and the level of production. A fundamental requirement for establishing plantations is that there is a wood fuel market within a reasonable distance (about 50 km). In a calculation stretching over a period of 24 years with a production level of 12 tonnes DM per hectar and year, and at an interest rate of 6%, the net return is about 1,000 - 1,500 SEK/ha/yr (about 7 SEK/US$) if simultaneous chipping is used. With separate harvest and chipping the enterprise in this calculation breaks even. Interest in the utilization of sludge, ash, waste water and leakage water as nutrients for energy forests is increasing from local and regional authorities.

Introduction

Why Willow?

A crop which is to be used for energy cultivation must be as effective as possible in its utilization and storage of solar energy. The energy crop must effectively utilize plant nutrients and also be simple to grow and handle. Rapidly-growing deciduous trees of the *Salix* family (willow) have these properties. The most efficient species have been selected in a breeding programme that has been ongoing since the mid-1970's. Different clones (varieties) of osier (*Salix viminalis*) and water willow (*Salix dasyclados*) are grown. Work on improved breeding for higher production and better resistance to diseases is being done at the Swedish University of Agricultural Sciences and at the breeding company Svalöf Weibull AB.

Today, when there is a surplus of food crops in many western countries, farmers are looking for an alternative crop. In addition to the requirement of being economically sound, such a crop should be easy and inexpensive to establish and, if it is a woody species, it should have the ability of resprouting. Willows naturally respond to these requirements although there is a wide variation within the genus Salix regarding different characteristics of importance for biomass production.

Energy production is an interesting possibility for agricultural land which is no longer needed for food production. By replacing fossil fuels (oil, coal, gas, etc.) with biofuel, it is possible to create a more environmentally-desirable energy production system and employment in rural areas. However, one of the conditions is that the grower, the farmer, can market his product at a reasonable price. Salix is now entering a stage as a commercial agricultural crop in Sweden. Until 1993 about 8000 hectares have been established on private farmland. This paper gives a description of *Salix* production, possible acreage in the future, explains how the crop can be grown and discusses the economic conditions associated with the production.

Research in Short Rotation Forestry

Research into short rotation forestry using *Salix* started in the mid 70' ies. Fifteen years of research and development has lead to a firm basis of knowledge concerning the basic biology, stand ecology and production systems of fast growing willows in Sweden. The biology research programme continues to emphazise studies of plant biology and diseases as well as areas such as clone/site interactions, mixed clonal plantations and breeding. The technological research and development concentrates on functional and effective machinery for planting, harvesting etc. A large variety of field tests and practical application on the farm level have resulted in the recent commercialisation of Salix plantations in Sweden.

Extension in Short Rotation Forestry

Extension advisers have now been appointed within the energy forestry programme operated by the Swedish Farmer's Selling and Purchasing Association. These advisers have generally been concerned with training in agriculture. They have degrees or certificates in agriculture and have previously given production advices to farmers. Some are still working in this area on a part time basis. The farmers are also offered the possibility to purchase cuttings and to hire certain machines through the extension officers.

The Production System

Plant Once and Harvest Six Times

A new energy plantation is established by planting cuttings taken from 1-year-old shoots of willow. The cuttings are 20 cm long and about 18,000 are planted per hectare. After four years, the plantation is 6 m tall and it is time to take the first harvest. This is done during the winter when the leaves have fallen off and the soil is frozen. In the following spring, the plants start regrowing from the cut stumps. After a further four years the next harvest is taken, etc (Figure 1). The plantation is estimated to have a life of at least 25 years, i.e. to give at least six harvests.

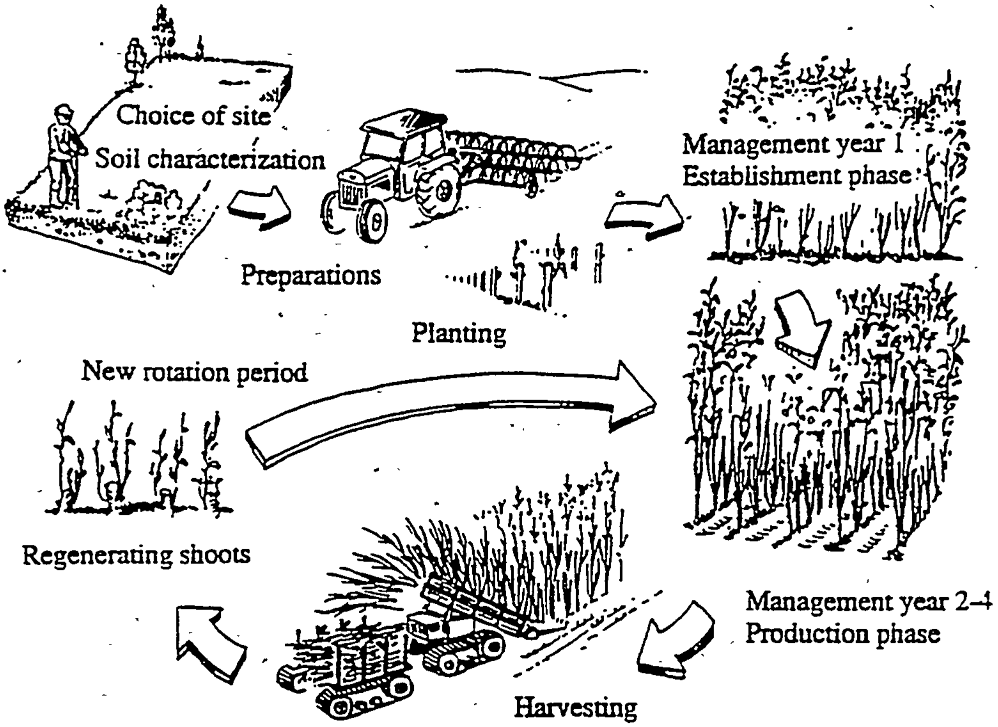

Figure 1. The principles used in growing Salix (Drawing: Sigge Falk).

Choose Suitable Land

Salix can be grown on all types of agricultural land. However, this species is more dependent on water than other agricultural crops and thus the driest land should be avoided. *Salix* has the best growth on fine sand soils with a good supply of water and nutrients. The soil pH should be above 5.5; if this is not the case then liming must be done before planting. In order to supply itself with water, the plants of *Salix* produce fine roots which penetrate to fairly great depths and they may enter the drainage pipes. This implies that the drainage system may need to be re-laid at the end of the cultivation period.

Low areas, where there is risk of frost during the early summer and early autumn, are unsuitable for growing *Salix*. In the same way, small fields surrounded by forest with abundant game are also unsuitable. Grazing damage caused by moose and deer is worst at the start of the growing period, and a fence may be one way of protecting the plantation for the first few years.

At each harvest, about 100 tonnes of material will be transported from each hectare. Plans should be made for storage places, and a suitable direction of planting should be chosen so that the rows will end as close to the road as possible. Small fields of irregular shape are difficult to harvest and thus the profitability of the plantation is not as good.

Site Selection May Influence Other interests

Because of its tall mode of growth compared to conventional agricultural crops and its long period of cultivation, energy forests will affect the profile of the countryside. Consequently, the plantation must be located with consideration to the landscape and to the directives of the legislation on Nature Conservancy. Other legal problems may also arise, e.g. whether the drainage system or access roads affect other landowners.

Prepare the Land Carefully

The establishment of an energy forest may be compared with sowing for several future harvests at one time. It is extremely important for the plantation to get a good start. Weeds are the worst enemy of the energy forest during the establishment phase. Once the plantation has become established after a couple of years, it will compete successfully with the weeds. Consequently, the land selected for growing *Salix* must always be cleaned of perennial weeds before planting. This is best done by spraying with Roundup or with a mechanical fallow during the year before planting. In the spring before planting, the field must be harrowed to a relatively deep and fine bed (5-8cm). Larger stones must be removed. The final harrowing should be done immediately before planting in order to remove the weeds that have started to germinate. Sometimes the field could be rolled to preserve moisture and to press down stones.

On organic soils, the planting can be done after spraying with Roundup without tillage in the spring in order to reduce the stand of seed-propagated weeds. This method is more risky and is not recommended on old grassland.

Planting is Done With a Machine

Planting is done in the spring at the time of normal spring tillage. The cuttings are prepared during the winter and are stored at -4°C. They are collected and placed in water for a couple of days before planting. It is important to take the cuttings out of cold-storage in pace with the planting. Shoots and roots must not have time to develop before the cuttings are planted.

The *Salix* cuttings are placed in double rows with a row spacing of 75 cm and 125 cm between the double rows. The plant spacing in the row is 55 cm. This will give 18,000 plants per hectare. The cuttings must be planted with the top end upwards and pressed down into the soil so that only a couple of centimetres emerge.

Planting machines for *Salix* have developed rapidly during recent years. With a 2-row planting machine it is possible to plant 1 hectare in about 4 hours (two planters and a tractor driver).

More automatic machines are currently being developed. With one of the machines the 20 cm cuttings are cut from whole shoots in the same operation as they are planted into the soil. With a four row machine of that type, 1 hectar is planted in 1 hour.

Effective Weed Control is Essential

The weed control must be started immediately after planting. During the entire first year, the *Salix* plantation is extremely weak in its competition with the weeds. When it has become established and can effectively shade the soil, then the weeds are a minor problem.

The soil-applied herbicide Gardoprim is sprayed on "black soil" immediately after planting. This herbicide prevents the weed seeds in the soil surface from germinating. Its effect depends on the moisture in the soil. Dose recommendations vary between 2 and 6 litres per hectare. The higher dose is required on soils with high organic contents and high clay contents, but an excessively high dose on lighter soils will lead to a risk of damage to the *Salix*. The effectiveness is diminished on organic soils. Gardoprim will remain effective until the early summer, but a new generation of weeds often appears when the rain starts to fall in July. It is now that mechanical weed control must be used. Harrows, rotary cultivators or cultivators with spaced tines can be used. The tractor is driven in the same way as when the cuttings were planted and straddles a double row.

How Should the Salix Crop Be Fertilized?

One of the advantages of growing *Salix* is that it has a low nutrient requirement per kilogramme of dry matter produced. This is because the nutrient-rich leaves fall to the ground and remain there, since the harvest takes place during the winter. The leaves decompose and the nutrients re-circulate. However, the nutrients removed with the stems must be returned if production is to continue. An average application of 60-80 kg N, 10 kg P and 35 kg K is suitable. The first year, the year of planting, generally requires no fertilizer as there is a risk that the weeds will benefit more than the *Salix*. In the beginning of the rotation period, before the leaf litter has become accumulated, the fertilization rate may be slightly higher. The fertilizer regime should be adapted to the soil type.

In the year after planting and after each harvest, applications can be made using conventional equipment. In tall stands, it is necessary to use appliances for high-level spreading. Alternatively, smaller machines which can enter the plantation below the canopy may also be used. Both principles are used in practice.

A growing interest in the utilization of sludge, ash, waste water and leakage water as nutrients for energy forests is noticed from local and regional authorities. These components will return phosphorus, potassium and micro-nutrients, at the same time as the ashes have a pH-increasing effect.

Is *Salix* Attacked by Diseases and Pests?

A *Salix* plantation provides a good home for many different insects, birds and animals. Most of them cause very little or no damage to the plantation. Damage has been caused by leaf beetles, caterpillars and gall midges in *Salix* plantations. Damage has also been caused by fungi such as *Fusicladium saliciperdum* and rust. However, the different clones have varying susceptibilities to fungi and insects, and it has been possible to discard the most sensitive and breed for better resistance. There is generally little reason to introduce inputs to control fungi and insects in *Salix* plantations. There may possibly be justification to control insects in cutting production since they cause early tillering of the shoots.

Considerable damage to the plantations may be caused by moose and deer during the establishment phase. When the stand has reached a height of three metres, the grazing only takes place along the edges. However, small areas of *Salix* should not be grown in districts with abundant game. Minor problems with game can be solved with fencing during the establishment phase. Voles may gnaw the stems during the winter; their preferred habitat is under withered weeds, so careful weed control also reduces the risk of attacks by voles.

Frost

Under Swedish conditions frosts during the growing season may be a serious problem. The Salix breeders are continously selecting for frost hardy clones.

Harvest and Handling

Energy plantations are harvested in the winter when the leaves have fallen off. Harvesters have been developed to either harvest entire shoots which are dumped in piles for chipping later, or for chipping directly. The method and equipment that is most suitable depends on how the chips are to be handled and used. In large heating-plants the chips can be combusted at the harvesting moisture content (ca. 50%). In these cases, direct chipping can be used. If burning is to be done on the farm or in other smaller plants, then drier chips are required. Shoots that are harvested whole and allowed to dry in piles during one summer will have reached a moisture content below 30% by the subsequent winter. Choice of harvesting system also has a major influence on the economics (Figure 2).

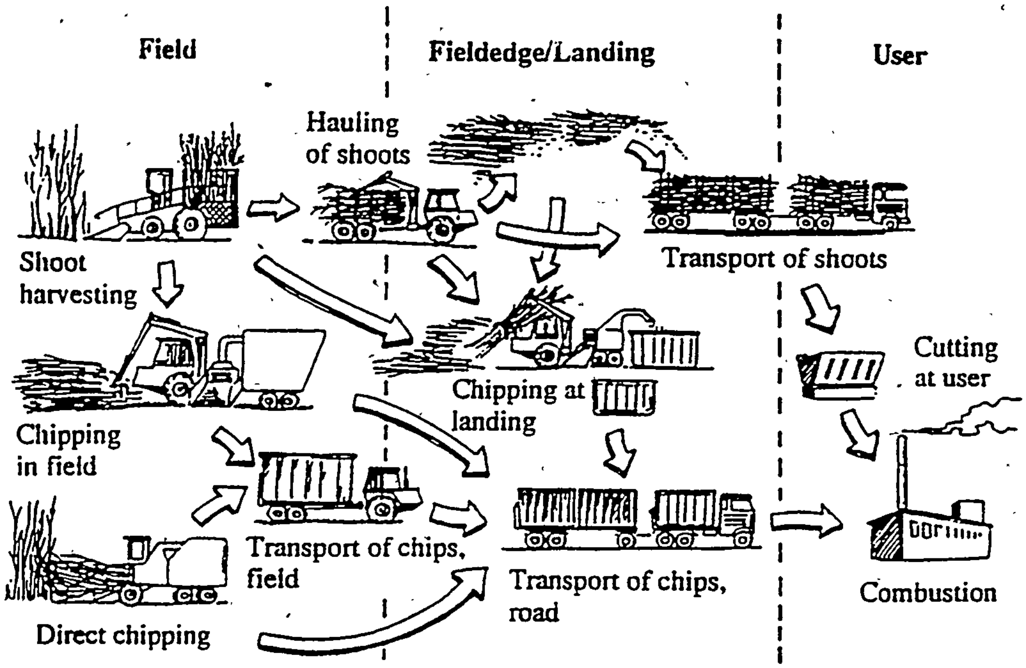

Figure 2. Harvesting and handling systems for Salix. (Drawing: Sigge Falk).

There are effective machinery for the harvest. Today there are three different machines for direct chipping and also three different machines for whole shoot harvesting. All machines are still prototypes, but for example the Claas harvester is built on an ordinary machine for harvesting of maize. There is also a sugar cane harvester, Austoft, beeing converted for salix harvesting.

How Much Energy is Produced?

Production in an energy plantation is most easily measured as oven-dry tonnes per hectare per year (odt/ha/yr). An established energy plantation produces 10-15 odt/ha/yr. The production during the establishment years is lower.

A growth rate of 12 odt/ha during one year corresponds to about 5.5 m^3 oil or the heat requirement for about 1.5 one-family villas. At each harvest after a 4-year period of growth approximately 50 odt (or 100 tonnes fresh weight at 50% moisture content) is harvested. The energy from 8000 hectares grown today represents only a very small fraction of the energy need in Sweden. However, there is an estimated potential of 300 000 hectares, about 10% of the agricultural area in Sweden, which would give 15-20

TWh. The main source of bioenergy in Sweden is the conventional forest of pine, spruce and birch. The contribution from forest wastewood is today about 60 TWh and the potential is at least 100 TWh. Energy from woody biomass originating from conventional forest and energy forests on farmland may amount to 125 TWh within 10-20 years, equivalent to about 30% of the energy need in Sweden.

Removing the Plantation

An energy plantation which is still growing well need not be ripped out as long as the chips can be marketed. A rotation (stool life) of about 25 years has been chosen on the basis of, for example, the period required to develop higher yielding material which may result in it being economically attractive to change clone. The conditions may also have changed so that other crops can be grown. It is then fairly simple to remove the energy plantation and return the soil to conventional cropping.

Economy in Salix Plantations

The economic outcome of growing *Salix* mainly depends on the price of chips and the level of production. A fundamental requirement for establishing plantations is that there is a market for chips within a reasonable distance (about 50 km).

The difference between growing *Salix* and growing annual crops is that there is a major investment at planting and then the income from the plantation is only obtained after harvesting.

Establishment of a *Salix* plantation costs about 9,000 SEK per hectare (about 7 SEK/US$), including the farmer's own work. In some cases, a subsidy may be obtained to assist with establishment costs.

Salix chips have a value of about 0.55 SEK per kg DM when delivered to a heating plant. Harvesting, chipping, transport and marketing cost about 0.30 SEK per kg DM with whole shoots harvesting and separate chipping, and about 0.20 SEK per DM with simultaneous chipping.

In a calculation stretching over a period of 24 years with a production level of 12 tonnes DM per hectar and year, and at an interest rate of 6% the net return is about 1,000 - 1,500 SEK/ha/yr if simultaneous chipping is used. With separate harvest and chipping the enterprise in this calculation breaks even.

Location of Salix Plantations

When research into energy forestry was started in the mid-1970's, experimental areas were established in different parts of the country. Experiments showed that the highest production was obtained on arable land in southern Sweden. During the mid-1980's, large-scale and smaller experiments were established on private farms in southern and central Sweden (Skåne/Halland, Östergötland and Mälardalen). In 1988, the Swedish Farmers' Selling and Purchasing Association and the Federation of Swedish Farmers started a development programme and are today conducting projects in seven regions of central Sweden.

An interesting new development is a group of 20 farmers, who in order to guarantee a market for their woodchips, formed a private company and built a heating plant of 2 MW. They will grow 200 hectares of *Salix*, burn it and sell hot water to the lokal district heating system in the village of Kolbäck in central of Sweden (Västmanland). Since the farmers owning the company, handle all production stages themselves they have good control of the economy. The amount of shares each farmer has in the company is correlated to their area of the *Salix*. The heating plant was installed in February 1992 and some of the plantations were established during 1991 and 1992 and additional areas have been planted in 1993. Until the *Salix* plantations are ready for harvesting the company will use woodchips from forest residues.

Conclusions

Growing Salix on agricultural land is an interesting alternative for farmers in Sweden. Since the introduction of environmental taxes on fossil fuels there has been an increasing interest for biofuels from the side of the authorities. Most cities and villages have a central heating system with a big boiler and pipes for hot water distribution. The existing equipment for burning of woodchips from forest residues are sufficient also for Salix chips. As the harvest and handling of Salix material is done effectively and sufficient machinery have been developed there are now good opportunities for the farmers to establish *Salix* on their land in pace with an increasing market of bioenergy. However the local market is most important, as the volume wood per unit of energy is quite big.

The use of Salix as well as other bioenergy does not result in net increase of carbon dioxide in the atmosphere and therefore the environmental-desirable and renewable energy sources will be even more important in the future.

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FROM RESEARCH PLOTS TO PROTOTYPE BIOMASS PLANTATIONS

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Abstract

The development of biomass energy plantations is now expanding from the research plot phase into the next level of development at larger scale plantings. This is necessary to provide: more accurate information on biomass yields, realistic production cost figures, venues to test harvesting equipment, demonstration sites for potential producers, and a supply of feedstock for prototype conversion facilities.

The paper will discuss some of these objectives and some of the challenges encountered in the scale-up process associated with a willow prototype plantation project currently under development in Eastern Canada.

Introduction

As in many parts of the developed world, Canada's energy from biomass programmes have gained new life over the last few years. This is primarily in response to a need for alternatives to the fossil fuels that contribute to the buildup of carbon dioxide in the atmosphere. Basic and applied research has progressed in many areas. These include the conversion of woody biomass to liquid and gaseous fuels, technologies relating to the production of woody biomass and the development of clones of poplars (*Populus* spp.) and willows (*Salix* spp.) for the production of feedstocks in dedicated plantations involving the principles of short rotation intensive culture (SRIC). Of necessity, much of the developmental work in the latter aspect of the production of woody feedstocks must be carried out in small plots (single-tree to a few hundred trees). While much work remains to be done for which small plots are well suited, the time has come to begin the process of scaling-up. The establishment of plots which are more representative of the types of systems that will eventually be used in the production of energy feedstocks have many advantages. One such project in Ontario is currently in its third year and will form the basis of the following discussion of the movement from research plots to prototype plantations.

This paper will present some of the objectives of scaling-up from research plots. The technical challenges have been addressed at many meetings, symposia and workshops in the past and will also be addressed by many in the future. We will take this opportunity to address some institutional challenges that we have encountered in our efforts to move from research plots to prototype farms.

The Roles Of Prototype Plantations

Demonstrating the Concept

While many principles of SRIC are similar to conventional agriculture, it is essential that prototype plantations be available to demonstrate the concept to farmers, funding agencies and others who may be involved in the production system. As will be discussed later, the concept differs from conventional agriculture enough to warrant demonstration. For example, while ratooning of some agricultural crops is not foreign to farmers, the coppicing of trees or shrubs is less commonly understood. The principle of coppicing is important to the economic viability of SRIC for the production of energy biomass. Similarly, by eliminating the need for site preparation and planting for each harvest, coppicing will improve the energy balance of this system over the production of conventional agricultural crops such as corn.

The investment of millions of dollars into the establishment of a conversion facility will only come about if a secure and dependable supply of feedstock is available, at an appropriate price. For example, a moderately sized ethanol plant producing 100 million litres per year would require in the order of 24,000 ha of plantation assuming an annual yield of 12 oven-dry megagrams (odMg) per hectare. While the prototype farms *per se* cannot be expected to provide sufficient quantities of biomass to support a full scale operation, they will be essential to demonstrate the concept to potential investors and to provide some feedstocks for prototype conversion facilities.

A sustainable bioenergy programme must ultimately be the responsibility of the private sector. Initially, however, governments at all levels must be involved to ensure that the desirability of bioenergy is based on all the long-term benefits of such programmes and not just the return on investment to one sector. Governmental support will come about only if the public can be convinced that the system will be in their best interest. Prototype farms will help to promote the concept to the public and will provide an opportunity to demonstrate their economic and environmental benefits.

Information for SRIC Financial Analyses

While bioenergy has been promoted for its many environmental benefits, it will be adopted and survive only if it can be shown to be economically viable. As one component of the bioenergy system, dedicated energy biomass plantations must also be shown to be economically viable. Many financial and economic analyses of SRIC for the production of energy feedstocks have been carried out. However, because of the lack of large scale plantations many of the data for such analyses must either come from conventional forestry or from agricultural systems, or they must be based on assumptions of costs and revenues. Prototype farms will provide an excellent opportunity to gather the much needed data relating to the production of feedstocks in SRIC plantations.

Yield Verification

Consistent among the various financial analyses mentioned above is the observation that the economic viability of SRIC for the production of energy biomass is particularly sensitive to variation in annual yields (Berguson, 1987; Hansen, 1988; Kenney *et al.*, 1991; Rose *et al.*., 1981). As has already been mentioned, breeding and clonal selection programmes must be able to handle large numbers of entries (families or clones) in the field-testing phase. The need to minimize within plot variation, and the expense associated with the establishment and tending of these test plots requires that each plot be small. Yield figures from such tests are most meaningful when considered as relative values to identify superior entries when compared with others. Since the so-called "edge effect" can result in significant overestimation of yields when small plots are used (Cannell and Smith, 1980; Hansen, 1988; Johnson and Erickson, 1987; Zavitkovski, 1981), such tests should not be used to estimate yields from operational plantings. All stages of the planning for commercial-scale plantations will require accurate estimates of the expected yields from various plantation designs, using specific clones on particular sites. These data can only be provided by the intermediate sized plots established in prototype farms.

Field Testing of Equipment

The financial analyses have also identified the cost of harvesting and chipping as a major component in the total cost of production. Some estimates are as high as 70% of the total cost. Significant progress has been made in Europe in reducing these costs, primarily with modified agricultural equipment. This approach has reduced the unit costs by virtually eliminating the developmental costs associated with machines that are expected to have a small market (compared with conventional agriculture). One example of this approach is the use of the Claas Jaguar forage harvester. Modifications to this machine have been limited primarily to the cutting head. This machine also completes harvesting and chipping in one operation resulting in a more desirable cost and energy balance than that exhibited by systems which carry out the two operations separately. Progress in this area is encouraging and will be critical to the development of SRIC for energy production. The development and testing of such machinery will require large areas of SRIC plantations, hence the need for prototype farms.

Environmental Impact Assessment

Bioenergy is considered more acceptable than the use of fossil fuels since carbon released to the atmosphere when biomass-derived fuels are burned can subsequently be fixed by the process of photosynthesis. If this closed system were to be established in practice however, the biomass would have to be produced on a sustainable basis and fuels used in the process would also have to be derived from biomass or other non-fossil sources. As with the economic estimates mentioned above, the validity of any estimates of the true benefits of using biomass derived fuels associated with the CO_2 balance can only be confirmed once prototype farms approaching commercial-scale have been developed.

One of the major driving forces for the development of bioenergy in Europe is the use of SRIC plantations as biofilters for the treating of sewage sludge. Pot studies and small scale trials can be used to test the potential benefits but again larger-scale plantations will be needed to determine optimum sludge application rates and the logistical problems associated with the fertilization of SRIC plantations with sludge.

Prototype farms will also provide a venue to assess the suitability of large-scale energy plantations as habitat for birds and small mammals.

Considerable progress has been made in many facets of the production of biomass for energy. While basic research must continue, it is imperative that prototype plantations or energy farms are established to demonstrate the technology and validate the findings of research to date. The development of prototype farms will encounter many new technical and institutional challenges.

Institutional Challenges

Many of the following comments may be unique to our situation in Ontario in the early 1990s; they may have less significance to specific SRIC programmes in other times and/or places. They are cited here to illustrate some challenges that may be encountered while scaling-up from test plots to prototype plantations.

We have used the term prototype farms in referring to the intermediate stage between research plots and commercial-scale plantations. Our choice in using this term serves as a basis for a clarification of the role of these intermediate-scale plantations. The desire by many people involved in bioenergy to demonstrate the technology to various audiences initially resulted in the use of the term *Demonstration Farms* when referring to the larger scale plantations that were to be established. The term demonstration may be something of a misnomer since it can imply that the technology is mature and that we now have all of the answers (or at least most of them) and are about to demonstrate this technology to the energy or agricultural community. Given the short time over which the technology has been developing (perhaps 20 years), we *don't* have all of the answers, in spite of the considerable progress that has been made. Because of this, the term Prototype Farm (which was used by Jeff Peterson of the New York State Energy Research and Development Authority) seems more apropos.

One might think of the development of SRIC for energy as a land-use system that is in its early stages of evolution. Many variations of a similar system will be developed based on sound basic research and the experience of practitioners. Ultimately, the "phenotypes" must be exposed to real world selection pressures to guide it along its path to being a well adapted system for the particular ecological and socio-economic environment for which it is intended. Using an engineering analogy, the current level of scale-up plantations should be considered closer to the prototype vehicle intended for the rigours of the test track and not the final design headed for the assembly lines. It is also important to keep in mind that in both the natural selection or the engineering analogy even while the current phenotypes or model is being "tested" the next generation must be in development to ensure continual improvement and an ability to adjust to changing environments or consumer demand. The same is true for the various components of SRIC based energy production systems, including the development of new planting stock. While poplar and willows have been cultivated and selected for hundreds of years, the intensive breeding and selection of the two genera have a relatively short history. Unlike domesticated agricultural crops, the planting stock that is currently available for SRIC Biomass Plantations is not far removed from their wild parents. The financial support and basic research available for the development of new varieties of agricultural crops is not seen in the development of SRIC crops. While the need for continued breeding and selection work does not relate directly to the development of prototype plantations, it is mentioned here to highlight the need for an integrated approach to the development of SRIC that incorporates both basic research and the scaling-up process with an active interaction between all phases. Just as the basic research and development should provide information and material to the prototype farms, the prototypes must also be expected to feed information back to the basic R&D.

The integrated nature of SRIC for biomass production means that the individuals involved will come from diverse backgrounds: foresters, agronomists, farmers, engineers, economists, etc. With such diversity, it is essential that mechanisms are in place to facilitate the exchange of information among all participants and that consensus is built to identify the optimum system for the given conditions. For example, to the agricultural engineer developing a prototype harvester, uniformity in the crop may be a very important factor. The tree breeder or agriculturalist however, will not want to achieve this uniformity through a dramatic reduction in the genetic base. The integrated nature of the production of energy from biomass can result in what might be called a "reverse turf war; is SRIC the responsibility of Energy, Agriculture or Forestry agencies? Although energy biomass from SRIC is promoted as an alternative crop for farmers, to be grown on agricultural land using quasi-agricultural techniques, some representatives of both the Federal and Ontario Provincial Agricultural agencies have suggested that SRIC for energy is not within their mandate. Arguments have been made that it is an energy issue presumably since the product is not intended for human consumption, and still others contend that it is a forestry issue, presumably since the crop is a woody perennial. Provincially, some in the energy sector sees it as a forestry or agricultural issue since it is a matter of growing a crop and the Forestry agency chooses not to become involved since SRIC is promoted as an alternative crop for farmers, to be grown on agricultural land using quasi-agricultural techniques and, "we have enough unused fibre already."

Promoting SRIC for the production of biomass for energy requires considerable care. The many advantages of the system in terms of environmental benefits and the role it can play in providing farmers with an alternative crop can (and should) result in an eagerness to expand the programme and move from the research phase into the developmental phase. This eagerness must however, be tempered by the need to test the current genetic material, the silvicultural systems and the associated equipment. Failure to move into this phase quickly enough may result in the loss of momentum gained in the research programmes; moving too quickly into this phase or without adequately explaining the potential risks or anticipated setbacks, could result in the disillusionment of some individuals or agencies.

While our breeding programme in willows produced many clones for consideration, most clonal screening trials consisted of relatively small plots. Consequently, no large base was available which could produce the number of cuttings needed to establish demonstration or prototype farms. For every hectare of plantation to be established approximately 1,000 stools are required to produce the needed cuttings. In the establishment year, very few cuttings are produced (two to three per stool) where as after the first coppicing, approximately 15 cuttings per stool can be expected. Because of this, advancing from the research plot phase to prototype plantations will require the establishment of sufficient stool-bed capacity to produce the required stock. Scaling-up may require up to two years just to produce the required planting stock. This delay may seem unacceptably long for some who are unfamiliar with the production of tree nursery stock.

Among the potential risks associated with scaling-up are increased losses due to pests and diseases. Insect and pathogen populations may increase at a greater rate in larger scale plantation than in research trials since the genetic diversity of the latter is likely to be greater. While early species, family or clonal screening trials may remain relatively disease free it is important that funding agencies and the potential users of the technology be made aware that pest problems may become significant only after larger-scale plantations have been established. It is important that funding agencies recognize that pest problems may develop which were not seen in earlier trials. Set-backs due to insects and disease outbreaks at the prototype farm phase may be discouraging if this important role of the prototypes is not recognized at the outset.

Conclusion

The development of programmes to produce energy from biomass must integrate all aspects of the system from biomass production, to harvesting, to conversion and finally the marketing of both the system and the products. An integral component of these phases associated with biomass production, is the progression from small research plots to larger-scale prototype plantations. Because of the need for the promotion of the technology and the diversity of the individuals involved, care must be taken to identify the objectives of the prototype plantations while clearly outline the potential set-backs that should be anticipated. By encouraging good communications among all sectors prototype farms will form an essential link between continuously improving technologies and well adapted land-use systems that can fulfil many needs in a sustainable manner.

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COMPATIBILITY OF SWITCHGRASS AS AN ENERGY CROP IN FARMING SYSTEMS OF THE SOUTHEASTERN USA

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Abstract

The objective of this paper is to examine the compatibility of switchgrass as an energy crop in farming systems in the southeastern USA, relative to other regions. In particular, the issues addressed are (1) competition between switchgrass as an energy crop and existing farm enterprises, based primarily on economic returns, (2) complementarity between switchgrass and existing farm enterprises, and (3) environmental benefits. Because projected economic returns for switchgrass as an energy crop are highest in the Southeast, and returns from forestry and beef pastures (the major existing enterprises) are low, there is a very strong economic incentive in this region. In contrast, based on current information, economic viability of switchgrass as an energy crop in other regions appears doubtful. In addition, switchgrass in the southeastern USA would complement forage-livestock production, row crop production and wildlife and would provide several additional environmental benefits. It is concluded that the southeastern USA offers the greatest opportunity for developing switchgrass as an economically viable energy crop.

Introduction

Although isolated commercial plants that convert biomass to energy in the USA are currently in operation, the concept of producing energy from biomass on a commercial scale is still in its infancy, relative to other technologies. In addition, several technologies for producing energy from biomass have not yet proceeded beyond the experimental stage. For example, the U.S. Department of Energy proposes to install commercial scale demonstration plants over the next several years for the conversion of biomass to ethanol by enzyme hydrolysis (Chum *et al*, 1991) while the private sector is investigating similar options for other technologies, such as Biomass Gassification and Fuel Cells (Anonym., 1993). The apparent intention for these demonstration units is to verify commercial viability of the technologies, thereby providing the incentive for large scale commercial development by the private sector. Clearly, the success of this whole process will depend heavily on the commercial success of the demonstration plants. Therefore, it is critically important to maximize the probability of commercial success of these plants.

Since cost of biomass production can account for close to half the total cost of energy production from biomass, this factor should be a major consideration in development of demonstration units. Clearly, cost of biomass production will be strongly related to biomass yield of energy crops, which varies widely among different regions of the United States. In addition, successful commercial development of biomass for energy production will depend on the compatibility of energy crops with existing farming systems, which also vary widely by region. Consequently, the choice of region for location of demonstration plants and initial commercial development will probably be critically important to the success of the whole commercialization process.

The objective of this paper is to examine the compatibility of switchgrass as an energy crop in farming systems in the southeastern USA, relative to other regions. In particular, the issues addressed here are (1) competition between switchgrass as an energy crop and existing farm enterprises, (2) complementarity between switchgrass and existing farm enterprises, and (3) environmental benefits.

Competition from Existing Farm Enterprises

In order for switchgrass to be adopted by producers as an energy crop in place of existing enterprises, it is necessary that it be more profitable than existing enterprises. Therefore, introduction of switchgrass as an energy crop to any particular region is most likely to be successful if (a) profitability of existing enterprises in the region is low, and (b) potential profitability of switchgrass is high.

Profitability of Existing Enterprises

Forestry and pastures for beef production are the two enterprises which occupy most land on which switchgrass is likely to be established in the Southeast. Both of these enterprises currently offer low returns (on average, less than $40/acre/year) when compared to row crops such as corn in the mid-West (mostly $100 to $150/acre/year). Production of the more profitable row crops (as opposed to forestry and beef pastures) in the Southeast is restricted mainly by unproductive soils which are very erosive and often already highly eroded, and a prevalence of diseases and pests compared to the mid-West. This reduces yields and increases production costs, thus diminishing returns. Consequently, even under the most suitable conditions for row crop production in the Southeast, yields and returns for crops such as corn and soybeans are considerably lower than in the mid-West, and are often less than $100/acre/year.

Potential Profitability of Switchgrass

Potential profitability of switchgrass as an energy crop will be highest in regions where biomass yields are highest and where yields vary least from year to year, provided production costs per acre are similar across regions. Clearly, research data on biomass yields of switchgrass throughout the eastern USA indicate that yields in Alabama have been, on average, at least 50% higher than in any other state, and among the least variable from year to year (Table 1; Martin and McLaughlin, 1992).

Table 1. Productivity Ranges for Switchgrass in Several States in the Eastern and Mid-Western USA (Martin and McLaughlin, 1992)

Productivity Ranges			
State	Best cultivar	Year	Yields dry tons/acre (dry Mg ha^{-1})
Alabama	'Alamo'	1990	15.4 to 11.0 (34.6 to 24.7)
Indiana	'Cave-in-Rock'	1989	9.2 to 2.5 (20.7 to 5.7)
Iowa	'Cave-in-Rock'	1988	3.7 to 2.2 (8.3 to 5.0)
Nebraska	'Pathfinder'	1990	2.8 to 1.8 (6.2 to 4.1)
New York	'Cave-in-Rock'	1989	5.8 to 1.8 (13.1 to 4.0)
North Dakota	'Sunburst'	1990	5.6 to 3.3 (12.5 to 7.5)
Ohio	'Cave-in-Rock'	1989	4.6 to 3.6 (10.3 to 8.1)
Virginia	'Cave-in-Rock'	1989	7.2 to 5.3 (16.2 to 7.0)

The reasons for the high yields obtained in the Southeast are (a) a long growing season with a high and well distributed rainfall, (b) adaptation of highly productive varieties such as 'Alamo', which break winter dormancy early (often 4 to 6 weeks earlier than other varieties) and are therefore able to take advantage of the extended period of favorable growing temperatures in the South, (c) relative insensitivity of switchgrass to soil type, and (d) little evidence of serious pest and disease problems, possibly because it is a native grass.

To project potential returns of switchgrass as an energy crop at this stage, without an established switchgrass-to-biofuel industry, is clearly difficult. However, considerable applicable information is available from hay production which can serve as a useful guide. If it is assumed that it costs $60/acre/year to produce switchgrass (fertilization, prorated establishment costs, etc.), $121/acre for producers to cut and bale it themselves (as opposed to $20/ton for custom harvesting and baling) and $5/ton for the producer to haul switchgrass 10 miles to a collection depot (as opposed to $8/ton for custom hauling), and the price received by the producer for switchgrass delivered to the collection depot is $35/ton, then the cost and return figures in Table 2 apply.

Table 2. Effect of Switchgrass Yield on Gross Return, Costs and Net Returns for (a) Self-Operated Production (Production, Harvesting and Hauling Done by the Producer), (b) Custom Harvesting but Hauling and Production Done by Producer, or (c) Custom Harvesting and Hauling, and Only Production Done by Producer

Switchgrass Yield	Gross Return	(a) Self-Operated		(b) Custom Harvest Only		(c) Custom Harvest and Hauling	
		Costs	Net Return	Costs	Net Return	Costs	Net Return
(tons/acre)	---------- $/acre ----------						
4	140	201	- 61	160	- 20	172	- 32
6	210	211	- 1	210	0	228	- 18
8	280	221	59	260	20	284	- 4
10	350	231	119	310	40	340	10
12	420	241	179	360	60	396	24
14	490	251	239	410	80	452	38
16	560	261	299	460	100	508	52

Information in Table 1 and 2 allow several conclusions to be drawn. First, break even yield is around 6 tons/acre for self operated enterprises or where only harvesting is done on a custom basis, but is over 8 tons/acre if both harvesting and hauling are done on a custom basis. Secondly, custom harvesting and/or hauling substantially reduces net returns and makes economic feasibility questionable. This is entirely understandable with a low-value commodity like biomass for ethanol production, priced at $35/ton, as opposed to higher value commodities such as hay, which usually sells for $50 to $75/ton. Thirdly, projected net returns for self operated switchgrass production appear comparable with row crops if yields of 10 tons/acre or more can be achieved. Finally, the only state that has consistently provided profitable yields to date is Alabama (Table 1). Given that these yields were achieved in research plots and do not take into account harvesting and storage losses, economic feasibility of producing switchgrass as an energy crop outside of the Southeast has to be considered extremely doubtful at this point.

Complementarity with Existing Farm Enterprises

The southeastern USA is essentially a mixed farming region. While the acceptance of switchgrass as a new crop in the region will depend largely on its projected returns relative to existing enterprises, its complementarity with existing enterprises will also likely play an important role in its acceptance. In this regard switchgrass has much to offer, especially in association with forage-livestock production, row crops and wildlife.

Forage-Livestock Production

Switchgrass and existing forage-livestock enterprises complement one another in several ways. Switchgrass itself is an excellent forage, although it has not been used for this purpose in the Southeast. It can be used for both hay and grazing, and provides high yields of excellent quality feed. For example, Burns *et al* (1984) obtained average daily weight gains of 2.1 lb per animal and seasonal weight gains of 967 lb/acre for beef steers grazing 'Kanlow' switchgrass in North Carolina over a 3-year period. This is almost double the production commonly achieved from traditional forage species such as bahiagrass and bermudagrass. On the other hand, existence of a large forage industry in the Southeast means that many producers already own hay-making equipment that is required to harvest and bale switchgrass as an energy crop. Therefore, at least initially, large scale purchase of equipment will not be necessary.

Row Crops

Poor soils with low organic matter and impervious plow pans, and pests pose major restrictions on yield and profitability of row crops in the southeastern USA. Nematodes are a particularly devastating pest of soybeans, cotton and peanuts, but recently, many nematicides have been removed from the market because of environmental concerns. Those that remain are expensive and are also under scrutiny by environmental agencies. However, recent research has shown that use of bahiagrass in medium- to long-term rotations with soybeans and peanuts can dramatically increase yields (Rodriguez-Kabana, *et al*, 1991). Bahiagrass provides multiple benefits in the rotation, including nematode control, puncturing of impervious plow pans with a powerful root system, and addition of organic matter to the soil. Ongoing research at Auburn University suggests that switchgrass could provide equivalent benefits, but would have added advantages over bahiagrass as both a forage and an energy crop.

Wildlife

Although not generally recognized as such, wildlife is an economically important enterprise for landowners in the Southeast. For example, Stribling *et al* (1989) estimated that in Alabama alone, more than $600 million are spent annually on hunting and hunting-related activities. This included $30 million for land leases and fees, and $34 million for food plots. Switchgrass is well recognized among wildlife specialists for providing preferred habitat and/or food for deer and quail in particular, but also for many other species of wildlife. Therefore, it is quite possible that fields of switchgrass on a property could elevate hunting leases and fees.

Environmental Benefits

Several environmental benefits of switchgrass as an energy crop have already been mentioned in previous sections. These include improved soil productivity from addition of organic matter and puncturing of impervious plow pans, reduction in nematodes harmful to row crops, reduced use of hazardous nematocides, and therefore reduced contamination of groundwater with chemicals and harmful effects on non-target organisms, and enhanced wildlife. In addition, switchgrass will play a major role in reducing soil erosion, especially if it replaces annual row crops currently grown on marginal land. It could also play an important role in reducing contamination of ground and surface water because it is extremely efficient in assimilating soil nutrients, probably because of a very extensive root system. For example, in Alabama 'Alamo' switchgrass biomass contained over 270 lb of nitrogen per acre, after only 100 lb of nitrogen per acre had been applied as fertilizer (Sladden and Bransby, 1991). This very large excess of accumulated nitrogen over that applied as fertilizer suggests that 'Alamo' switchgrass may even have a nitrogen-fixing association with soil microorganisms.

Conclusions

Evidence in this paper indicates clearly that, based on competition from existing farm enterprises, complementarity with existing enterprises and environmental benefits, the Southeastern USA offers greater opportunity to develop switchgrass as an economically viable energy crop than any other region. In fact, based on current information, economic viability of switchgrass as an energy crop in any other region is indeed questionable. Consequently, this should be the major influencing factor in locating demonstration ethanol plants, even if prospects for cost sharing in these plants may be more promising in other regions.

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INTEGRATED PRODUCTION OF WARM SEASON GRASSES AND AGROFORESTRY FOR BIOMASS PRODUCTION

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Abstract

Increased research on C_3 and C_4 perennial biomass crops is generating a significant amount of information on the potential of these crops to produce large quantities of low cost biomass. In many parts of North America it appears that both C_3 and C_4 species are limited by water availability particularly on marginal soils. In much of North America, rainfall is exceeded by evaporation. High transpiration rates by fast growing trees and rainfall interception by the canopy appear to indicate that this can further exacerbate the problem of water availability. C_4 perennial grasses appear to have distinct advantages over C_3 species planted in monoculture systems particularly on marginal soils. C_4 grasses historically predominated over much of the land that is now available for biomass production because of their adaptation to low humidity environments and periods of low soil moisture. The planting of short rotation forestry (SRF) species in an energy agroforestry system is proposed as an alternative production strategy which could potentially alleviate many of the problems associated with SRF monocultures. Energy agroforestry would be complementary to both production of conventional farm crops and C_4 perennial biomass crops because of beneficial microclimatic effects.

Introduction

Studies involving fast growing plantations of trees have been ongoing since the early 1970's in North America. More recently herbaceous feedstocks have received increased attention for their biomass production potential. However, few attempts have been made to understand climatic influences on the choice of biomass feedstocks or the potential to integrate production of woody and herbaceous biomass crops. This paper will discuss the major constraints to monoculture production of short rotation forestry (SRF) and warm season grasses and outline the potential advantages of an integrated production of the two feedstocks. It is believed that a better understanding of the native vegetation of North America and how climatic conditions influenced its development will help biomass scientists understand the choice of biomass feedstocks and strategies to modify the climatic conditions to favour biomass production.

Developing Efficient Biomass Production Systems

Crop production strategies need to be developed which are as efficient as possible in capturing sunlight (solar energy) and storing it in plants (solar battery). Desirable characteristics for energy feedstocks include:

1. Efficient conversion of sunlight into plant material ;
2. Efficient water use as moisture is one of the primary factors limiting biomass production in most of North America
3. Sunlight interception for as much of the growing season as possible;
4. Minimal external inputs in the production and harvest cycle (ie. seed, fertilizer, machine operations and crop drying).

We know that to achieve these objectives:

1. There are two main photosynthetic pathways for converting solar energy into plant material: the C_3 and C_4 pathways. The C_4 pathway is approximately 40% more efficient than the C_3 pathway in accumulating carbon (Beadle and Long, 1985).
2. C_4 species use approximately 1/2 the water of most C_3 species (Long et al., 1990).
3. In northern climates, sunlight interception is more efficient with perennial plants because annual plants spend much of the spring establishing a canopy.
4. Perennial crops do not have annual establishment costs (seed, tillage etc.) . As well they are N efficient because N is cycled internally to the root system in the fall (Clark, 1977). Nutrient leaching and surface nutrient loss through soil erosion is minimal with perennial crop production compared to annual crop production. C_4 grasses have a higher N use efficiency than C_3 grasses (Brown, 1985).

Based on these criteria, the fastest, most resource efficient crops to grow would be perennial C_4 grasses. Since 1986 the US Department of Energy (DOE) has extensively evaluated herbaceous and woody biomass crops for biomass production. It is not surprising then that the lowest cost feedstock production that has been achieved in North America has been with switchgrass (*Panicum virgatum*), a C_4 prairie grass. Several studies have estimated production costs below US$30.00/tonne (Sladden et al., 1991; Parrish et al., 1990).

Recent reports by European biomass scientists have further highlighted the significant yield and physiological advantages that C_4 grasses hold over C_3 species (i.e. cool season grasses or fast growing trees) for biomass production (Long et al. 1990; Stander, 1989; Rutherford and Heath, 1992). As a result of a number of these reports and promising early biomass yields from C_4 species, much of the current research in Europe is now evaluating the perennial C_4 grass *miscanthus* and the annual C_4

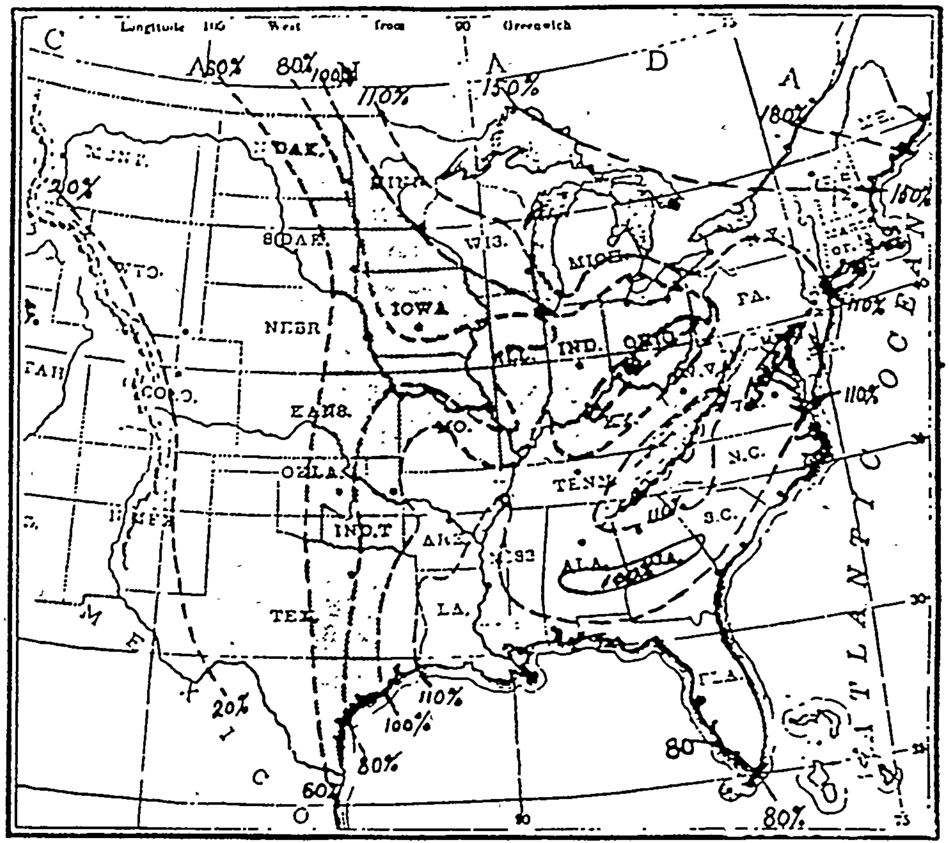


Figure 1. Map of eastern United States showing the ratio of rainfall to evaporation in perecentages in different regions; prairie region is the 60 percent to 100 percent ratio.

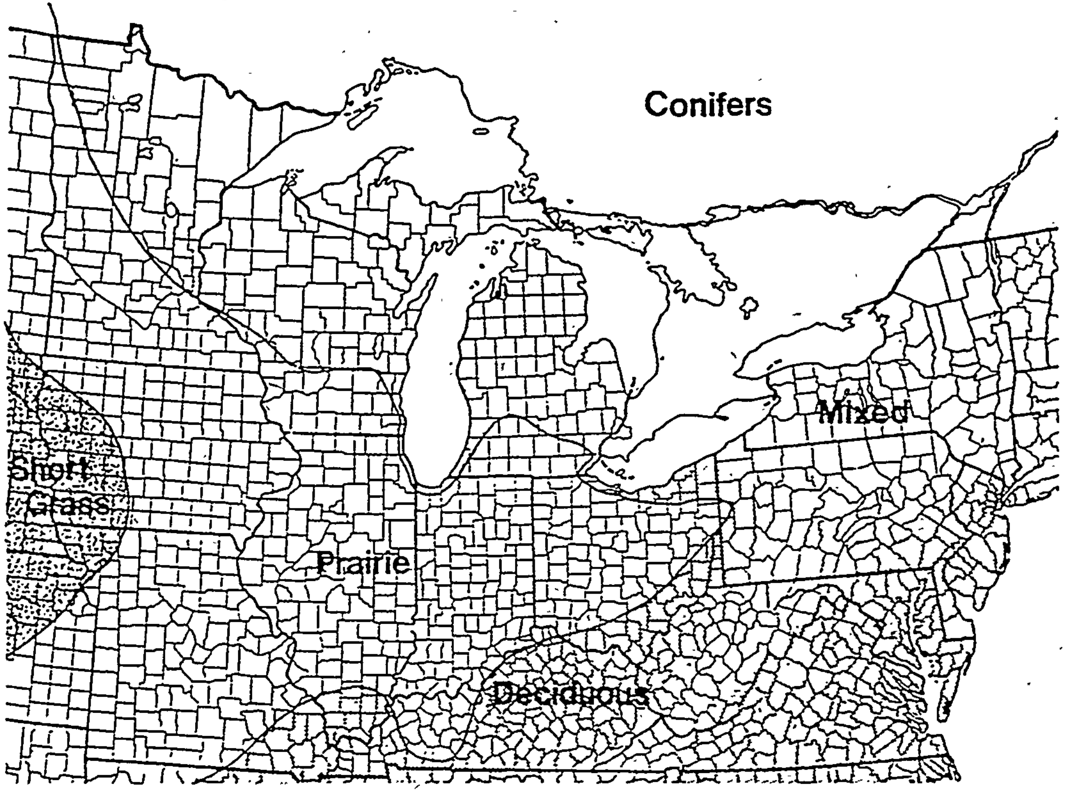


Figure 2. Map of north-central united States showing peninsula-like projection of prairie vegetation between the shortgrass region and the forested areas at the time of the "Xerothermic period" as viewed by Transeau (Stuckey, 1981).

species sweet sorghum.

Effect of Climatic Conditions on the Centers of Plant Distribution in North America

American ecologists early in the 19th century demonstrated that water relations had a powerful influence on the distribution of plants. Most authors have credited much of the development of the concept to Transeau (in Stuckey, 1981) who in 1905 wrote:

> *"Investigation shows that forests, grasslands and deserts are arranged about certain centers, which owe their positions on the continent mainly to climatic causes. That such centers cannot be correlated with the distribution of heat or rainfall alone is evidenced by examination of the monthly, seasonal and annual distribution of these elements.*
>
> *The fact that so large a part of early adaptations shown by plants are more or less directly connected with transpiration, led the writer to construct a map [see figure 1.] combining the figures for rainfall and evaporation. The amount of evaporation depends upon the temperature of the evaporating surface, the relative humidity of the air and the velocity of the wind. Therefore if we combine the figures for rainfall and evaporation we have a number which will represent at least four climatic factors, that must powerfully influence the water relations and distributions of plants.*
>
> *The Great Plains are marked by an amount of rainfall equal to 20-60 percent of the evaporation. Where the ratio rises to between 60 and 80 percent, the prairie region, where dense forests are confined to the river bottoms, is indicated. The region where "open forests", "oak openings" and "groves" occur on the uplands and dense forests on the low grounds, is indicated by the 80-100% ratios.*

The two maps (Figure 1 and Figure 2) that originated from Transeau's work provide a general indication of how vegetation in North America evolved as a result of climatic conditions. Biomass scientists need to understand the native vegetation and climatic conditions of an area to more effectively understand constraints to biomass production. Few biomass scientists may realize that a prairie peninsula (Figure 2) once extended from the north central region of the United States into the northeastern states of Ohio and Michigan and that low soil moisture periods combined with low humidity were among the primary reasons that this ecosystem evolved. The information provided by Transeau's search for an explanation for the prairie peninsula in North America may prove invaluable for scientists looking to understand ecological constraints to maximizing biomass production. For example, many North American SRF researchers working in unirrigated monocultures frequently find that low biomass yields are obtained in the areas where the rainfall to evaporation ratio is lower than 100%. Even in areas where the natural landscape has a rainfall to evaporation ratio from 100-150%, the yield potential of SRF systems may be water limited because rapid accumulation of biomass increases water loss through transpiration.

The low water use efficiency of SRF systems may be the primary reason that yields have not increased when researchers have left small plots and gone to field scale conditions. A summary of large plot and field scale studies (unirrigated sites with borders) from a recent International Energy Agency (IEA) publication indicates current yields being obtained (Table 1).

Table 1. Summary of recent production data from the IEA Report: How to Grow Short Rotation Forests (Ledin and Alriksson, 1992)

Europe	Species	Yield (ODT/ha/yr)
Austria	Willows	10.5
Sweden	Willows	11
England	Willows & poplars	6 - 11
Denmark	Willows	8.1
USA		
Pennsylvania	Poplars	10.4
Wisconsin	Poplars	7.5
Washington	Poplars	15.1

- ODT = Oven Dry Tonne

Data from other recent reports with relatively large plots or field scale plantings

France	Poplars	7.9 ODT/ha/yr	Auclair and Bouvarel, 1992
Eastern Ontario	Poplars	2-3 ODT/ha/yr	Hendry, 1990

The Washington study was the only study to have average yields above 11 ODT/ha/yr. This was performed in a high rainfall area of the Pacific Northwest of the United States. If this study is observed as an anomaly for North America (because of the area's unique climatic conditions relative to the rest of North America), it appears that most field scale yields are in the range of 7-11 ODT/ha/yr. This would agree with Hansen (1988), in his review of SRIC (Short Rotation Intensive Culture) yields, who states 7-11 ODT/ha as a reasonable estimate of potential SRIC field yields.

The problem of low water use efficiency by the trees in field scale plantations has been identified by several researchers (Dickmann et al., 1992; Grip et al., 1989; Persson and Jansson, 1988; Halldin and Lindroth, 1989). In some areas in Sweden where plantings have been made on bogs, willows have lowered the water table (Persson, 1989). A water balance study in Sweden which simulated a production of 12 ODT/ha indicated an evaporation of 526 mm, of which 375 mm was transpiration, 56 mm canopy interception and 95 mm soil evaporation. This rate of evaporation was 22% higher than the Penman open water evaporation rate of 430 mm (Grip et al., 1989). Several other Swedish studies have also indicated evaporation rates of SRF systems being 10-50% higher than the potential evaporation by the Penman formula (Persson and Jansson, 1988; Halldin and Lindroth, 1989). It should not be surprising that water availability is proving to be a primary factor limiting yield for high biomass producing systems. Forage scientists have demonstrated that biomass production is water limited for C_3 and C_4 grasses on marginal sites in northeastern North America (Stout et al., 1988; Stout, 1992), and that forage productivity of C_3 grasses is a good predictor of SRF yields on a site (Wells and Fribourg, 1992). While average rainfall in northeastern North America may be similar to that of Sweden, the intensity of rainfall (frequent storms resulting in higher runoff) and the more continental climate of North America (lower relative humidity), suggest that the moisture use problem would be exacerbated in North America for SRF, particularly on marginal soils (due to low water holding capacity).

The low water use efficiency of monoculture plantations of willows or poplars (C_3 species) indicates that the real yield potential for SRF in most of North America is only about 1/2 of that required for economic production, 23 ODT/ha (Kenney et al., 1991) . Yields of 7-11 ODT/ha would put biomass costs in the range of US$ 65-85/ tonne (Turhollow, 1992). Thus, an alternative to monoculture SRF systems needs to be developed if plantation forestry is to have a viable energy future in North America, since plantations using irrigation systems are not an option (economically or ecologically) for energy production. In summary, the agronomic and economic problems with the monoculture SRF include:

1. low productivity because of low water use efficiency and low solar energy conversion compared to C_4 grasses,
2. greater reliance on N, P and K fertilizer inputs than warm season grasses if a relatively short rotation period is used (ie. 4 years or less),
3. significant disease and pest problems associated with fast growing trees and clonal material
4. planting, weeding, fertilizing and harvesting may require new equipment or custom operators to perform farm operations,
5. lack of adaptability to marginal soils with low water holding capacity,
6. expensive and difficult harvesting process,
7. cost of reconverting the land back to agricultural production is high,
8. high initial capital investment,
9. not a farmer friendly crop because of long harvest interval compared to conventional crops.

C_4 Grasses As Biomass Crops

Most land suitable for biomass production from plantations in North America has a rainfall to evaporation ratios of 50-110% (Figure 1).. The prairie region, found in the 60-100% rainfall/evaporation area, occupies a major portion of this land base. The native prairie grasses that were dominant in this area were the C_4 perennial grasses. Among the most common were big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparium*), Indiangrass (*Sorghastrum nutans*), switchgrass (*Panicum virgatum*) and prairie cordgrass (*Spartina pectinata*) (Weaver and Fitzpatrick, 1934). These species have all shown potential to produce biomass yields greater than 10 t/ha on unirrigated sites (Stubbendieck and Nielsen, 1989; Gould and Dexter, 1986; USDA, 1991). The most thoroughly researched species has been switchgrass. It has many desirable characteristics for biomass production including:

High Productivity: When appropriate cultivars are chosen, productivity is high across much of North America. Yields of 20 to 30 ODT/ha have been obtained with lowland switchgrass ecotypes in Alabama (Sladden et al. 1991). In studies near the Canadian border, winter hardy upland ecotypes of switchgrass have produced yields of 9.2 ODT/ha in northern North Dakota (Jacobson et al., 1986) and 12.3 ODT/ha in northern New York (Thomas and Lucey, 1987).

Moisture Efficient: Switchgrass uses water approximately 2 times more efficiently than traditional cool season grasses (Stout et al., 1988; Parrish et al., 1990; Stout, 1992). Its root system extends up to 3.3 metres and has a greater distribution of root weight at deeper soil depths than other prairie species (Weaver and Darland, 1949).

Low N requirements: Compared to cool season grasses, optimal yields of switchgrass can be obtained with much lower N requirements and response to N may not be observed in the early years of production (Jung et al. 1990). N levels in switchgrass biomass are in the order of 0.5% N at full maturity (Balasko et al. 1984) which is approximately 1/2 that of most cool season grass species.

Low P requirements On soils with low levels of available P, warm season prairie grasses have higher dry matter yields and have P concentrations approximately 1/2 that of cool season grasses (Morris et al. 1982). An adaptive advantage of C_4 grass species is their use of mychorhizal symbiosis for nutrient uptake. This may help explain the abundance of C_4 plants in prairie soils low in available nutrients (Hetrick et al. 1988).

Low K requirements Switchgrass has a lower critical K level than cool season grasses and seldom shows response to K fertilizer (Smith and Greenfield, 1979).

Stand longevity Adapted switchgrass cultivars harvested for hay have excellent persistence, minimal disease and insect problems and good cold tolerance.

Acid soil tolerance Switchgrass will tolerate extremely low pH soils (<5.0) which do not support the growth of cool season grasses or legumes (Jung et al., 1988)

Low harvest costs In studies in the northern United States, 1 cut per season maximized biomass yields from switchgrass while most cool season grasses generally require multiple cuts (Wright, 1990).

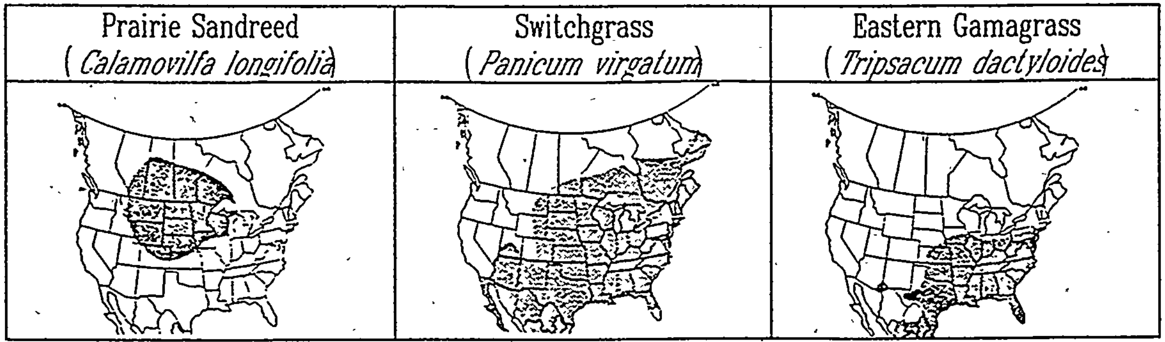
Soil restoring Switchgrass is one of the dominant species of the North American prairie that built some of the most productive and rich soils in the western hemisphere.

High ethanol yield Switchgrass has a higher combined cellulose and hemi-cellulose content than cool season grasses or legumes (Cherney et al. 1988).

Farmer friendly Compared to other warm season grass species, switchgrass is inexpensive to seed and establishes well. It has good seedling vigor, low seed costs, low seeding rates and good herbicide tolerance.

Environmentally friendly Switchgrass provides nesting cover and seeds act as a food source for birds. The re-establishment of prairie grasses will improve water quality in several ways: annual grain crops responsible for increasing erosion potential will be replaced, ground water nitrate levels (Ramundo et al. 1992) and surface P loading (Sharpley and Smith, 1991) will be reduced: Pesticide impacts on wildlife would be reduced because herbicides would be used probably only in the establishment year unlike the annual use of insecticides and herbicides in field crop production.

Several other prairie species have also shown potential to produce biomass yields as high or higher than the tallgrass prairie species, particularly outside of the main prairie region. Two of the more promising species are prairie sandreed (*Calamovilfa longifolia*) and eastern gamagrass (*Tripsacum dactyloides*) which have performed well in biomass trials in the Northern US Great Plains (USDA, 1989) and Southern Illinois respectively (Faix et al., 1980; Kaiser, 1989). The native range of these plants, compared to that of switchgrass, gives an indication that they may be as well, or better adapted than switchgrass to these particular areas (Figure 3).


Prairie Sandreed (*Calamovilfa longifolia*)

Switchgrass (*Panicum virgatum*)

Eastern Gamagrass (*Tripsacum dactyloides*)

Figure 3. Native Range of promising biomass feedstocks (Maps from Stubbendieck et al., 1992)

Energy Agroforestry As An Alternative

Many of the problems inherent in the SRF system may be reduced or eliminated if an agroforestry approach to energy production is taken. This approach to using trees for energy production has been suggested by others including Newman et al. (1990), Soltner (1991) and Ronneberg (1992). The trees grown in a SRF production system would be used as windbreaks on high value land in order to protect adjacent agricultural crops. The main reasons why an agroforestry approach may be more successful in North America than the monoculture plantation concept are the following:
(1) by limiting the plantation to at most a few rows of trees, the interception of sunlight and availability of water would be increased, thereby improving tree productivity;
(2) compared to conventional windbreaks which can be harvested after 25-35 years for timber, SRF windbreaks for energy would make it possible to get a financial return after 5 years. The trees would be seen more as an asset and not occupiers of valuable crop land.
(3) while the reduced competition from the adjacent agricultural crops would benefit the trees, the crops would also benefit from the trees. The benefits of windbreaks have been well documented and include reduced wind speed, increased humidity levels, higher day time temperatures, higher soil moisture, reduced wind and water erosion and increased snow trapping (reviewed by Kort, 1988);
(4) in most instances where short rotation windbreaks would be grown in conjunction with field crops, they probably would not need to be fertilized as most farmers tend to overfertilize their crops. The deep root system of the trees would help to recycle nutrients lost in the deepest layers of the soil.

Regarding crop yields, studies have indicated that perennial forage crops (alfalfa and mixed hay) are highly responsive to windbreaks (Kort, 1988). Establishment of windbreaks could potentially have a very beneficial effect on C_4 grass growth, particularly in its northern range, because of their ability to reduce the chilling effect of high winds and increase daytime temperatures. Thus, systems could be developed where fast growing trees would be planted in windbreaks while a C_4 grass such as switchgrass would be grown in between. Those systems would be entirely dedicated to energy production. Because perennial grasses such as switchgrass can be grown effectively on marginal agricultural land: those systems would also help to take out of production, either temporarily or permanently, land that cannot sustain annual field cropping. In this case, the trees will probably have to be harvested at longer intervals due to slower growth rate. However, the lower land cost of those marginal soils should compensate for the longer rotation.

Finally, because SRF harvesting technologies are not well developed, trees planted in windbreaks could be harvested using a chain saw and tractor pulled wood chipper. One two row design of this simplified energy agroforestry scheme has been proposed by Soltner (1991) (Figure 4). This system would enable at least one row to remain as a windbreak while the other row was harvested or in early coppice regrowth. REAP-Canada is currently assessing this approach to energy agroforestry using combinations of willows, poplars and black locusts in an on-farm research program in central Canada. The combination of one row of black locust with a row of poplar or willow may enable an opportunity to reduce/ eliminate the competition problems that have sometimes been reported with legume/ non-legume tree mixtures in block plantings (Heilman and Stettler, 1985; Heilman, 1989) and the need for N fertilization.

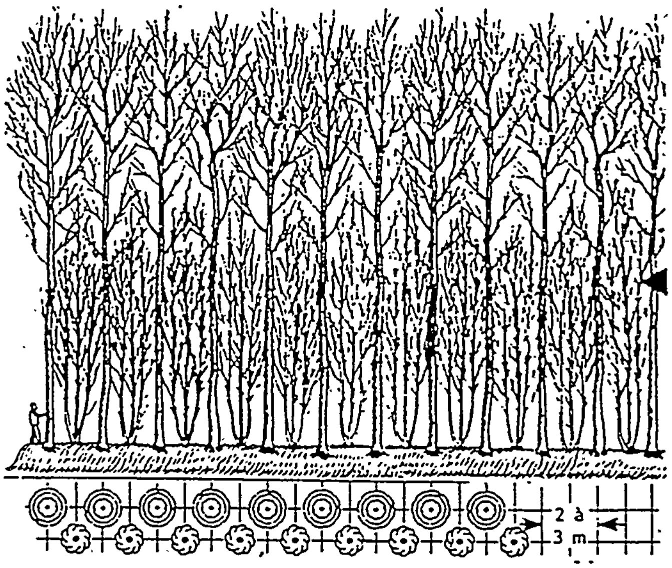


Figure 4. Two row windbreak system with two different species and harvest cycles (Soltner, 1991)

Summary

If biomass production systems are to advance significantly in achieving the goal of low cost and abundant biomass, a greater understanding of ecological and physiological processes needs to be achieved. Much of the land base that is available for biomass production in North America has significant moisture limitations. C_4 grasses have well developed characteristics for optimizing growth under these conditions compared to C_3 species. The best opportunity to use fast growing trees for biomass production appears to lie with their application in agroforestry systems. Energy production in the form of windbreaks would enable an optimization of growth of the fast growing trees while complementing production of traditional farm crops or C_4 perennial biomass energy crops. The production of "green energy" from biomass can only be realized if an ecological approach to biomass production is taken.

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SWITCHGRASS AS A BIOFUELS CROP FOR THE UPPER SOUTHEAST

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Abstract

Switchgrass (Panicum virgatum) has been identified in DOE-sponsored studies as a widely adapted, productive herbaceous candidate for biofuels cropping. It is a perennial that has been planted using no-till procedures, and it appears to have positive effects on the soils in which it grows. We have been looking at this species as a potential fuelcrop (as well as a valuable forage) for several years. In this presentation, we note several "lessons learned" about switchgrass establishment and management as an energy crop. Data include results from recent plantings in the upper Southeast U.S.A. and from cutting management studies. Six varieties of switchgrass (Alamo, Cave-in-Rock, Kanlow, Shelter, and two breeder's lines) varied markedly in the success of their no-till establishment at eight locations across the upper Southeast. Better weed control, which was achieved at later planting dates, seemed to be the key. Yields obtained in the establishment year varied from 0 to 8.0 Mg/ha. Cutting-management studies with established stands revealed that two harvests per season are more productive (by 2 to 3 Mg/ha) than one, but the date of first cutting is crucial. First cutting should be from late-June to mid-July. A two-cut system may not be economically advantageous, however. Another cutting-management study detected losses of standing biomass at the end of the growing season. As much as 15% of the above-ground biomass present in early-September was no longer harvestable in early-November. We think this loss results from translocation of dry matter to below-ground parts. This work is supported by a DOE contract administered through Oak Ridge National Laboratory, which is managed by Martin Marietta Energy Systems.

Establishment Study

Planting of six switchgrass varieties at eight different sites across the upper Southeast occurred between 13 May and 23 June 1992 (Table 1).

Table 1. Schedule of Planting for Switchgrass Establishment Study.

Site	Planting Date (1992)
Princeton, KY	13 May
Jackson, TN	14 May
Knoxville, TN	18 May
Raleigh, NC	22 May
Orange, VA	22 May
Morgantown, WV	28 May
Blacksburg, VA I	23 June
Blacksburg, VA II	23 June

Table 2 shows seeding rates and how they were determined for each variety used. The goal was to plant a similar number of potential germinants (discounting dormant, dead, and empty seeds), i.e., pure live seeds (PLS), per unit of soil area. While the seeding density varied by over two-fold, the projected stands would all be much more than adequate.

Table 2. Switchgrass Seed Characteristics and Pure Live Seed (PLS) Planting Rate for Plantings Made in Spring 1992.

Variety	Germination	100-Seed Weight	Seeds/ kg	PLS Planted	Predicted Germinants
	%	mg	no.x1000	kg/ha	no./m^2
Cave-in-Rock	60	155	645	8.2	530
Alamo	75	91	1100	7.7	845
Kanlow	71	90	1110	7.3	805
Shelter	75	194	515	10.2	525
NC-1	45	96	1040	3.1	320
NC-2	46	76	1315	3.1	410

The stands achieved were somewhat to much less than the projected levels at most sites (data not shown). While the seedling populations were lower than predicted, the number of seedlings was still quite adequate in most cases. Early weed pressure at some sites, however, was cause for concern in spite of herbicide (atrazine) use.

The sites with the best establishment were the two planted in Blacksburg, VA. These were the last to be planted (23 June versus 13 to 28 May for all other sites). The probable explanation for the greater success at Blacksburg is at least two-fold. By waiting until late June and killing all newly emerged weeds before planting, we had essentially no weed pressure (a few broadleaf species that were easily controlled with 2,4-D). In addition, it appeared that the warmer, longer days in late June permitted the switchgrass seedlings to grow more rapidly than they did when planted earlier. By contrast, the plantings at the other locations grew slowly during their first few critical days, while some hard-to-control weeds were making rapid growth.

Differences between varieties in vigor of establishment were seen at all sites. The contribution of weed competition to those differences is difficult to determine, since we did not have uniform weed stands at the various sites. The Blacksburg sites, which were essentially weed-free, provided non-confounded evidence of vigor differences between varieties (Table 3). Cave-in-Rock provided excellent stands at both Blacksburg sites, and the two lines from North Carolina (NC-1 and NC-2) were decidedly inferior in vigor 25 days after planting.

Table 3. Vigor Ratings on 18 July 1992 of Switchgrass Varieties No-till Planted on 23 June 1992 at Two Sites near Blacksburg, VA. For the Visual Ratings of Vigor, 10 = Pure, Thick Stand; 0 = Only Weeds Present.

Variety	Previous Crop	
	Fallow	Tall fescue
	----------Rank----------	
Cave-in-Rock	10.0	10.0
Alamo	8.1	8.5
Kanlow	6.9	7.5
Shelter	7.9	7.1
NC-1	2.6	3.8
NC-2	2.5	3.8
L.S.D. 0.05	0.8	1.1

At the end of the growing season, after above-ground plant matter was dead, we harvested the standing biomass of the study at six of the sites. We estimated the amount of biomass represented by switchgrass in each plot, and we report here yields only of switchgrass (Table 4). In some cases, weeds were clearly dominant; but their biomass is not included in the reported values. (In most cases, the switchgrass became dominant in 1993.)

Table 4. Yield and Percentage Composition of Six Switchgrass Varieties Planted in early 1992 at Six Locations. Yields Taken in November 1992.

	Switchgrass Variety						
Site	Cave-in-Rock	Alamo	Kanlow	Shelter	NC-1	NC-2	L.S.D. 0.05
	% Switchgrass						
Knoxville, TN	73	45	42	38	12	10	22
Jackson, TN	90	70	50	31	14	16	35
Morgantown, WV	68	66	66	68	0	0	NS
Orange, VA	44	42	38	9	2	5	25
Blacksburg, VA I	100	100	100	100	100	100	-
Blacksburg, VA II	100	100	100	100	100	100	-
	Switchgrass Yield (Mg/ha)						
Knoxville, TN	5.0	3.1	3.0	2.5	0.8	0.7	1.9
Jackson, TN	5.0	4.5	3.0	1.2	0.4	0.7	2.2
Morgantown, WV	0.3	0.3	0.2	0.1	0	0	NS
Orange, VA	0.6	0.7	0.5	0.1	0.1	0.1	0.3
Blacksburg, VA I	3.2	4.7	4.4	2.3	3.1	3.7	0.9
Blacksburg, VA II	5.3	8.0	6.8	3.4	6.0	6.9	0.7

Cutting Management Study

Switchgrass had been planted previously at two Blacksburg (VA) locations, Whitethorne and Kipps. Each location was harvested in a randomized, complete block experiment at several different dates for the first cutting (15 June to 20 July). The second harvest was made on 11 November after all evidence of green tissue had disappeared. One area was harvested only on 11 November. These data (Table 5) indicate that harvesting between 25 June and 25 July (plus end of season) resulted in higher biomass yields than harvesting only one time at the end of the season. On 25 June, the plants were in a boot stage or late boot stage, with a height of about 110 cm. By 4 July, the plants were about 140 cm tall and in an early heading stage. On 20 July, all tillers were heading, with most seedheads being about one-third fully emerged. Anthesis occurred about 7 August. These data indicate that maximum seasonal dry matter can be achieved by taking two harvests. The first harvest should be from early heading until dominant tillers have approximately one-half of each seedhead emerged. Optimal first harvest was in mid-July for the conditions that occurred in the Blacksburg area during 1992. We note, however, that the additional yield from a two-cut management might be offset economically by the cost of an additional harvest.

Table 5. Switchgrass Yields at Two Blacksburg, VA, Locations when Cut at Several Dates for the First Harvest and Again (or Only) on 11 November 1992.

Location	First Harvest	Yield/Harvest Date First	Nov. 11	Total
		----------------Mg/ha	--------------	
Whitethorne	15 June	2.7	6.2	8.9
	25 June	5.9	5.8	11.8
	04 July	7.4	5.7	13.2
	20 July	9.9	3.9	13.8
	11 Nov.	-	11.5	11.5
Kipps	15 June	3.2	6.6	9.8
	25 June	4.7	5.2	9.9
	04 July	7.4	3.5	10.9
	20 July	8.9	3.9	12.8
	11 Nov.	-	8.0	8.0
Combined	15 June	2.9	6.4	9.3
	25 June	5.3	5.5	10.8
	04 July	7.4	4.6	12.0
	20 July	9.4	3.9	13.3
	11 Nov.	-	9.7	9.7
LSD 0.05				
one location		2.5	1.3	3.0
combined locations		1.8	0.9	2.1

We have also been interested in end-of-season biomass yield changes. (Earlier studies suggested standing biomass declines after September.) Plots that had been cut at various times for a first harvest (from 15 June to 20 July) were harvested on 4 September. We also harvested a check plot that had not been previously cut. These yields established biomass present near the end of the growing season. A final harvest for the season was obtained on 14 November from all subplots by again harvesting portions that had not been cut since their first harvest in the earlier part of the growing season. Biomass in the check plots declined by 15% between 4 September and 14 November (Table 6). Yields for the subplots cut twice during the season did not differ if the second cut was on 4 September or on 14 November. With the check at least, there is apparently significant translocation of biomass from top growth to underground storage.

Table 6. Yields at the Second Harvest when it is Delayed and when the First Harvest was Taken at Several Dates. Yield Change is Difference Between 4 September and 14 November 1992 harvests.

First Harvest	Date of Second Harvest		
	4 Sept.	14 Nov.	Yield Change
Date	Mg/ha		
15 June	6.3 a*	6.5 a	0.2
25 June	6.3 a	5.3 a	-1.0
04 July	3.9 a	3.5 a	-0.3
20 July	3.3 a	3.9 a	0.6
04 Sept.[1]	14.6 a	12.3 b	-2.3 A[2]

*Yields in rows followed by similar lower-case letters do not differ.

[1] Yields for 4 Sept. first-harvest date are from a different field and should not be compared with yields from other treatments.

[2] Upper case letter indicates the yield change differs from zero at the 0.05 level.

Conclusions

These and additional studies not reported here support key conclusions concerning the management of switchgrass as a biofuels crop. 1) It can be established successfully with no-till methods. 2) Weed control is crucial during establishment. 3) Both variety and site affect first-season performance. 4) Yields of biomass can be substantial, even in the establishment year. 5) Two harvests may provide more biomass per season (but may not be economically advantageous). 6) The end-of-season harvest date is crucial, since above-ground biomass is lost after early September.

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PRODUCTION OF BIOMASS/ENERGY CROPS ON PHOSPHATIC CLAY SOILS IN CENTRAL FLORIDA

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Abstract

Phosphatic clay is a byproduct of phosphate mining. Presently more than 40,470 ha have been created, most in central Florida, and about 810 ha are being added each year. Phosphatic clays have high fertility and high water holding capacity, reducing fertilization costs and producing high yields without irrigation. Based on 10 years of research, scientists have selected tall annual-regenerating perennial C-4 grasses as having the greatest potential for biomass production in Florida. The purpose of this work was to determine the feasibility of growing these tall perennial grasses for biomass on phosphatic clay. Elephantgrass (*Pennisetum purpureum* L.), sugarcane and energycane (*Saccharum* sp.), and erianthus [*Erianthus arundinaceum* (Retz)] were planted in duplicate replications on phosphatic clay soil in late August, 1986. Yield was measured by one harvest in December or January each year for four years. Nitrogen fertilization included 112 kg ha^{-1} the first year followed by 134 kg ha^{-1} for the next three years. Nitrogen is the only supplemental nutrient needed to grow tall grass crops on phosphatic clay. The average annual oven dry matter yield over the 4-yr period was 36.3 Mg ha^{-1} for PI 300086 elephantgrass, 45.2 for N51 elephantgrass, 42.5 for L79-1002 energycane, 49.0 for US72-1153 energycane, 49.7 for US78-1009 sugarcane, 52.2 for US56-9 sugarcane, 56.2 for CP72-1210 sugarcane, and 48.8 for IK-7647 erianthus. More recent work has utilized domestic sewage sludge as a nitrogen source for the tall grasses. Preliminary sugar yields of selected sugarcane accessions & sweet sorghum were 4.7 Mg ha^{-1} for CP72-1210, 12.5 for US67-2022, 3.4 for US78-1009 and 1.3 Mg ha^{-1} for sweet sorghum (cv. grassl). The high yields of the tall grasses grown on phosphatic clay with low inputs indicate a great potential for these crops as a source of renewable energy. A sustainable cropping system may be maintained by utilizing municipal sewage sludge as a nitrogen source with tall grasses on phosphatic clay.

Introduction

An agreement between the University of Florida Institute of Food and Agricultural Sciences and the Gas Research Institute stimulated a 10-yr research effort to use energy crops for the manufacture of methane. After studying many plants, scientists settled on tall-growing perennial bunchgrasses as having the most potential as biomass plants. These grasses are indigenous to the tropics, utilize the C_4 pathway of carbon fixation, and produce long hardened stems (Prine *et al.*, 1988). Examples included elephantgrass (*Pennisetum purpureum* L.) (often referred to as napiergrass), sugarcane, and energycane, (*Saccharum* sp.), and erianthus [*Erianthus arundinaceum* (Retz)]. In addition to manufacture of methane, these same crops may be used for the manufacture of ethanol for fuel or for generation of electricity through direct combustion (Stricker *et al.*, 1992).

Cost of producing these crops is a concern because of the high volume of biomass to be handled and relatively low value per unit of volume. Reclaimed phosphate land, especially phosphatic clays, in central Florida holds promise for efficient production. Phosphatic clays have high fertility and high water holding capacity which results in reduced fertilization costs and produces high yields without irrigation (Stricker, 1991). Phosphatic clay soils have a high pH (>7.0) and high P, K, Ca, and Mg levels. Only nitrogen is required for fertilization.

The phosphate mining district in central Florida is located near a number of urban areas. Because of the large urban population, domestic sewage sludge presents a disposal problem. Using sewage sludge as a source of nitrogen for biomass crops offers an opportunity to help solve an important community problem while providing an economical source of nitrogen.

The annual production cycle for the tall grasses also fits the central Florida weather pattern. Field operations for planting and harvesting normally fall in the dry season of the year while the plant growth phase is during the wet season. There are presently more than 40,470 ha (100,000 acres) of phosphatic clays in Florida and about 810 ha (2,000 acres) are being added each year (C. Albin and S. Windham, 1992, Florida Dept. of Natural Resources, personal communication). Most of the phosphatic clays are located in Polk County, in central Florida.

The long growing season and ample summer rainfall in central Florida makes a climate suitable for growing the tall grasses. During the winter, the top growth is often killed by frost but the underground rhizomatous clump survives and initiates growth the following spring. Polk County, Florida is located near 28° N lat and has a mild subtropical climate. The growing season lasts from 240 to 300 d. With this length of season, elephantgrass is very competitive with sugarcane and energycane for total biomass yield. In the humid tropics sugarcane and energycane are more productive than elephantgrass (Alexander, 1985). However, elephantgrass initiates growth earlier in the spring than sugarcane or energycane and may be more productive under the central Florida climate.

Sugarcanes and energycanes are efficient producers of both sugar and lignocellulose (Alexander, 1986; Rodriguez, 1986). For production of ethanol, the juice may be squeezed and the sugars fermented. The remaining lignocellulose may also be converted into ethanol by utilizing one of the emerging lignocellulose conversion technologies. However, no commercial facilities are available in the U.S. for converting lignocellulose to ethanol. It could be a number of years before the costs of emerging lignocellulose conversion technology will permit commercial application (Chum *et al.*, 1993). At the present time, it may be economically feasible to produce ethanol from fermentation of sugars in the juice. Consistent high per ha yields of sugar will be needed, however, for this to be feasible. An additional factor will be economical utilization of the press cake for either direct combustion, cattle feed, compost or other productive use.

The objective of these studies is to evaluate the biomass energy potential of tall bunchgrasses when grown on phosphatic clay soil.

Materials and Methods

Replicated plots of PI 300086 and N51 elephantgrass; L79-1002 and US72-1153 energycane; US78-1009, US56-9, and CP72-1210 sugarcane were established in late August 1986. Plots of 1K-7647 erianthus were established in the fall of 1987. The experiment was established on phosphatic clay soil at the Polk County Mined Lands Research/Demonstration Project's AGRICO site. Each plot contained 5 rows. Row length was 9.1 m (30 ft) and row spacing was 91 cm (3 ft). Hardened stalks were planted in shallow furrows and covered with 5 to 7.6 cm (2 to 3 in) of fine clay soil. Stalks were double planted and cut to provide at least one plant per 61 cm (2 ft) of row. Vacant spots were replanted in mid-February 1987. To help the new planting compete, top growth of earlier planted material was mowed until the new plants were established. The last mowing was in May 1987 and all plants were left to grow for the remainder of the season. Plots were sprayed with Weedmaster[1] (DMA salt of dicamba/DMA salt of 2,4-D) at 4.2 L ha^{-1} (1.5 qt acre^{-1}) in June 1987 to control broad leaf weeds.

Plots were fertilized in July 1987 with 112 kg ha^{-1} (100 lb acre^{-1}) of N and 93 kg ha^{-1} (83 lb acre^{-1}) of K. In the spring of 1988, plots received 134 kg ha^{-1} (120 lb acre^{-1}) of N and 112 kg (100 lb) of K. In 1989 and 1990, plots received a spring application of 134 kg ha^{-1} (120 lb acre^{-1}) of N in the form of ammonium sulfate (Anderson, 1991). No additional fertilizer was applied during this 2-yr period.

Plots were harvested only once per year in December or January. Biomass from a 4.88 m (16-ft) portion of the center row of each plot was harvested for yield determination. Subsamples were taken and dried at 60° C in a forced air oven until weight stabilized to determine dry matter percentage. Experimental design was a randomized block with two replications.

Selected accessions from the yield study were planted in .08 ha (.2 acre) demonstration plots at a different location on 30 January 1992. A sugarcane accession US67-2022, developed in Puerto Rico, was also included in the demonstration. In addition, approximately .04 ha (.1 acre) of sweet sorghum (cv. grassl) was planted on 10 April 1992. Plantings were made in 152 cm (60 in) rows. All plots were fertilized with 53.8 Mg ha^{-1} (24 tons acre^{-1}) of 11.1% DM domestic sewage sludge on 6 March 1992. The sludge application was designed to provide 224 Mg ha^{-1} (200 lb) of actual N to the crop during the first year. No other fertilizer was applied.

The main sorghum crop was harvested on 31 August 1992 and a ratoon harvest was taken on 8 December 1992. Other crops were harvested on 14 & 15 December 1992. Yield estimates and samples for juice extraction were taken as follows: A 3-m (10 ft) piece of PVC pipe was randomly placed in the row of individual plots. All stalks over chest high, adjacent to the pipe, on both sides of the row were counted and five stalks were selected at random and cut. When 4 counts were completed, 20 stalks were bundled together. This procedure was repeated 4 times for each accession for a total of 16 stand counts and 80 stalks (4 bundles). Stripped and

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[1] The mention of a proprietary product name is for identification purposes only and does not imply warranty or endorsement to the exclusion of other products.

unstripped bundle weights were recorded. Subsamples were taken and dried in a forced air oven until weight stabilized for dry matter determination. Bundles were transported to the Everglades Research and Education Center at Belle Glade where the juice was extracted and sugar content determined.

Sugar was converted to ethanol by using the formula 1.68 kg of sugar = 1 L of ethanol (14 lb = 1 gal) (Frank Moore, 1993, Bartow Ethanol, Inc., personal communication).

Results And Discussion

Although all of the selected tall bunchgrasses made good growth, no significant yield differences were found due to large plot to plot variation and only two replications. Annual yield and 4-yr average yield for eight energy crop accessions are shown in Table 1. Accessions of elephantgrass, energycane, and sugarcane yielded an average of 40.8, 45.8, and 52.7 Mg ha^{-1} (18.2, 20.4, and 23.5 ton $acre^{-1}$), respectively, over the 4-yr period. Mislevy, *et al.* (1989) reported a 4-yr average yield of 56.5 Mg ha^{-1} (25.2 ton $acre^{-1}$) yr^{-1} of dry biomass for PI 300086 elephantgrass with one harvest per year on another phosphatic clay site in Polk County. In a harvest frequency study on Ona fine sand, near Ona, Fla., Mislevy *et al.* (1992) reported a yield decline for L79-1002 energycane over a 4-yr period with more frequent harvest than one per year. Yields persisted best with one harvest per year at a mature stage of growth.

Table 1. Dry Biomass Yield of Several Tall Bunchgrasses Grown on Phosphatic Clay Soil in Central Florida.

	Dry Biomass Yield					
Accession & Crop	1987	1988	1989	1990	4-Yr mean	
	Mg ha^{-1}†					
PI 300086 elephantgrass	34.5	33.8	36.1	40.6	36.3	(16.2)‡
N51 elephantgrass	45.2	66.3	39.2	30.2	45.2	(20.2)
L79-1002 energycane	45.7	45.4	39.6	39.2	42.5	(19.0)
US72-1153 energycane	45.9	49.8	42.2	58.1	49.0	(21.8)
US78-1009 sugarcane	54.0	55.1	45.2	44.4	49.7	(22.2)
US56-9 sugarcane	33.8	67.9	51.6	55.6	52.2	(23.3)
CP72-1210 sugarcane	51.1	62.8	44.3	66.8	56.2	(25.1)
1K-7647 erianthus	--	46.9	51.6	47.9	48.8	(21.8)

† 1 Mg ha^{-1} = 839 lb $acre^{-1}$ or .446 Ton $acre^{-1}$
‡ Ton $acre^{-1}$

Year-to-year yields for individual accessions were variable. However, four of the eight accessions exhibited a trend of increasing yield over the 4-yr period. Those accessions exhibiting an increasing yield trend were: PI 300086 elephantgrass, US72-1153 energycane, US56-9 and CP72-1210 sugarcanes. Only 3-yr of data were available for 1K-7647 erianthus and no trend was apparent. Accession N51 elephantgrass, L79-1002 energycane, and US78-1009 sugarcane appeared to have a declining yield trend over the 4-yr period.

A stable or increasing yield trend can be taken as an indication of vigor and stand longevity. While high yield per acre is important, a long productive stand life is also important because the costs of establishment may be spread over more years and more total production.

Results of the first year analysis of sugar content on selected accessions of sugarcane are presented in Table 2 along with fresh biomass yield and dry matter. The new introduction US67-2022 exhibited the highest yield. Only one row of this accession was planted because of limited planting material. The one row was planted on the edge of the block and partially accounts for the higher yield. Sweet sorghum was planted in 152 cm (60 in) rows which likely resulted in slightly lower yields than had it been planted in more conventional 91 or 102 cm (36 or 40 in) rows.

Table 2. Preliminary Biomass and Sugar Yield of Selected Sugarcane Accessions and Sweet Sorghum Grown on Phosphatic Clay.

Accession & crop	Fresh Biomass	Dry matter	Juice sugar	Total sugar	Ethanol[†] yield
	Mg ha^{-1}	%	Brix	Mg ha^{-1}	L ha^{-1}
CP72-1210 sugarcane	137.6 (61.4)[‡]	27.1	11.9	4.7 (2.1)[‡]	2798 (300)[§]
US67-2022 sugarcane	198.6 (88.7)	27.1	15.9	12.5 (5.6)	7440 (800)
US78-1009 sugarcane	150.3 (67.1)	25.5	11.1	3.4 (1.5)	2023 (214)
Grassl, sweet sorghum	22.2 (9.9)	27.4	12.0	1.3 (0.6)	774 (86)
Grassl, ratoon	6.5 (2.9)	21.0	2.9	0.0 (0.0)	0 (0)

[†] 1.68 kg of sugar = 1 L of ethanol
[‡] Tons acre^{-1}
[§] Gal. ethanol acre^{-1}

Conclusions

Accessions of elephantgrass, energycane, sugarcane, and erianthus produced high yields of biomass on phosphatic clay soil with minimal inputs. Four of eight accessions appeared to have an increasing yield trend over the 4 yr of the study. An increasing yield trend indicates that stand life and productivity will extend well beyond the 4 yr of the study. The high yields of the tall grasses on phosphatic clay indicate a great potential for these crops as a major source of renewable energy in central Florida. A sustainable cropping system may be maintained by utilizing municipal sewage sludge as a nitrogen source with tall grasses on phosphatic clay.

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SPACE/AGE FORESTRY: IMPLICATIONS OF PLANTING DENSITY AND ROTATION AGE ON SRIC MANAGEMENT DECISIONS

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Abstract

Short-rotation intensive-culture (SRIC) of promising tree crops is being evaluated worldwide for the production of methanol, ethanol, and electricity from renewable biomass resources. Planting density and rotation age are fundamental management decisions associated with SRIC energy plantations. Most studies of these variables have been conducted without the benefit of a unifying theory of the effects of growing space and rotation age on individual tree growth and stand level productivity. A modeling procedure based on field trials of *Eucalyptus* spp. is presented that evaluates the growth potential of a tree in the absence and presence of competition of neighboring trees in a stand. The results of this analysis are useful in clarifying economic implications of different growing space and rotation age decisions that tree plantation managers must make. The procedure is readily applicable to other species under consideration for SRIC plantations at any location.

To provide competitively priced feedstocks for the manufacture of methanol, ethanol, and electricity from renewable biomass resources, short-rotation intensive-culture (SRIC) management strategies of promising hardwoods are under rapid development and evaluation worldwide. Economic success will depend upon optimizing yields and minimizing costs of the desired product. The best species and provenances must be selected and matched with suitable sites, and managed for both economic success and environmental integrity. After deciding which germplasm to plant where, the next most important decision a SRIC forest plantation manager must make is how many trees to plant. Planting density strongly affects establishment costs and individual tree growth and stand development. Individual tree and stand growth as well as rotation age largely influence harvesting costs. A successful SRIC tree venture must design a viable strategy from this complex set of biophysical and economic considerations.

Our group at the University of Hawaii has developed an empirical yield and economic system model that is sensitive to the effects of growing space and age. In this paper, the model is applied to estimate diameter growth and to indicate some management implications of the effects of growing space and rotation age on the economics of SRIC forest plantations. The model is conceived from a common precept of silviculture -- annual diameter growth is a function of the potential growth multiplied by a growth modifier that represents the effects of competition. The uniqueness of our model is that it is based on the potential growth of a free-grown tree (FGT) and the ratio of the growing space a tree has available to the space it would need to reach its potential growth.

The founding studies from which our model was developed were the correlated curve trend (C.C.T.) projects conceived and conducted by O'Connor (1935). The C.C.T. results have provided the descriptive graph forms depicting the relationship between age and DBH developed by Burgers (1976) and illustrated here in Fig. 1. Potential diameter growth is defined as the growth of a free-grown tree. Annual growth can be derived from the following Chapman-Richards cumulative growth function.

$$\text{FGT Diam} = \text{FGT Diam max} * (1-\exp(-\text{K1} * \text{Age}))^{\text{C1}}$$

By setting the shape constant C1 = 2.0 and estimating the age at which the diameter reaches 99 percent of its maximum, the rate constant K1 can be derived.

The model separates the cumulative effects of past competition from the expected effects of current competition (Merriam 1987). Past competition is reflected in the size difference of a free-grown tree and a competition-grown tree (CGT). We assume that CGT potential growth is a function of FGT potential growth and the CGT/FGT size ratio. Current competition is expressed as a function of the growing space available for the average CGT to the growing space it would need to reach its potential growth. Available growing space is a function of the number of trees planted and mortality. The growing space requirement of a competition-grown tree is a function of the growing space that a free-grown tree requires to achieve its potential growth. This competition threshold space (CTS) was derived for the *Eucalyptus* spp. in this study from the results of Burgers (1976). As with potential growth we assume that the size ratio reflects the relation between CGT and FGT growing space requirements.

These concepts are synthesized in the potential growth modifier:

$$\text{Pot Grow Mod} = (1-\exp(-K2 * \text{Space Ratio}))^{C2}$$

where:

$$\text{Space Ratio} = \text{CGT Space Avail} / (\text{CTS} * \text{Size Ratio})$$

Assuming that CGT growth reaches 99% of its potential with a space ratio of 1.0, and that C2 has a value of 1.1, then K2 = 4.70. Estimated diameter is then utilized with a variety of site factors (e.g., temperature, rainfall, solar radiation, elevation, soil nitrogen content and pH, and nitrogen fertilizer) to calculate an average tree diameter for the specific site being studied. Stand productivity is calculated from a local yield equation.

Although it is meaningful to analyze growth data in the traditional fashion of growth vs. age, we have chosen to use growing space and age as axes to illustrate diameter growth and stand productivity (Fig. 2). By presenting both individual tree growth (DBH) and stand productivity (dry Mg/ha) variables on the same graph, the tradeoff of increased individual tree size and decreased stand productivity that occurs with increased growing space is emphasized. This trade-off has dramatic implications in economic analyses and SRIC management decisions.

The cost of delivering hardwood feedstocks to a biomass energy production facility has been modeled for several locations in Hawaii (Phillips *et al.*, 1992). Economic factors included are feedstock costs related to establishment, cultural management, harvesting, chipping, transport, and storage. Present net values in delivered cost per dry Mg are derived for many possible management schemes (Fig. 3a). This graph demonstrates that a minimum average cost is obtained within a narrow range of growing space and rotation age. The reasons for increased average cost with deviations from the optimum are illustrated in Fig. 3b.

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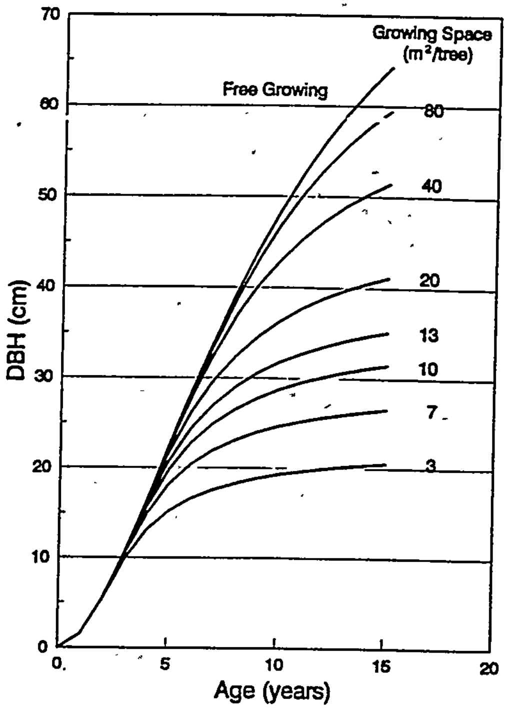

Fig. 1. Average tree diameter as a function of rotation age and growing space in *Eucalyptus grandis* plantations.

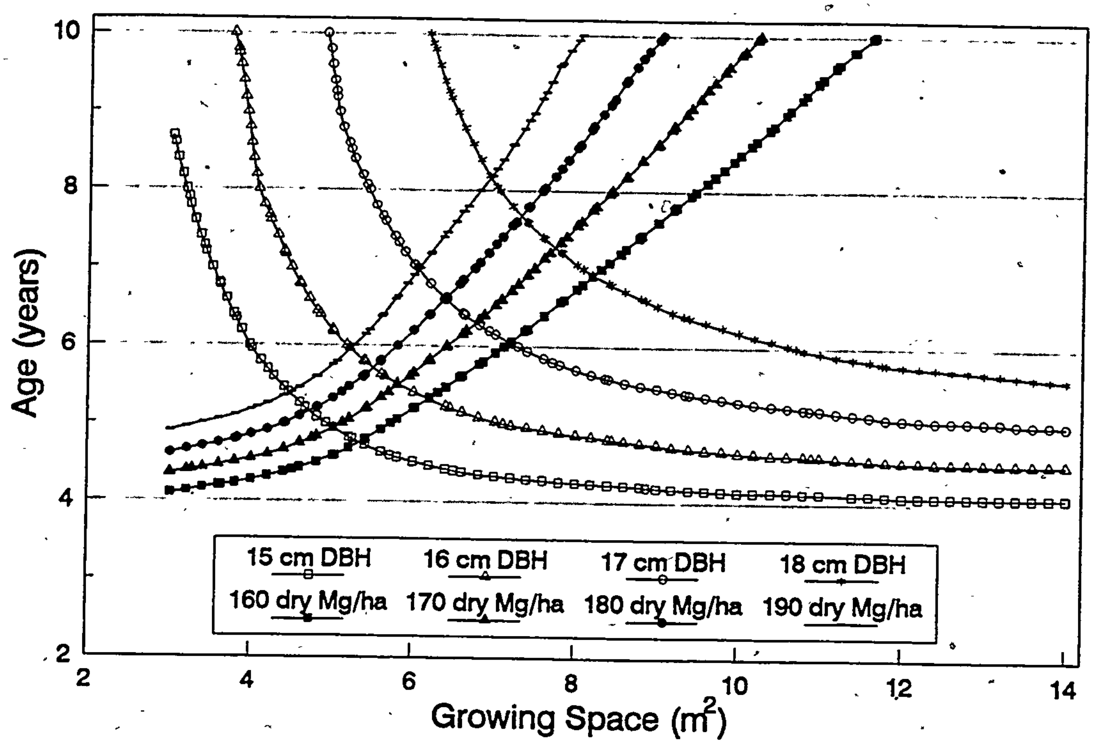

Fig. 2. Estimated average tree diameter and total stand yield of *Eucalyptus saligna* as a function of growing space and rotation age in Hilo coast plantations, Hawaii.

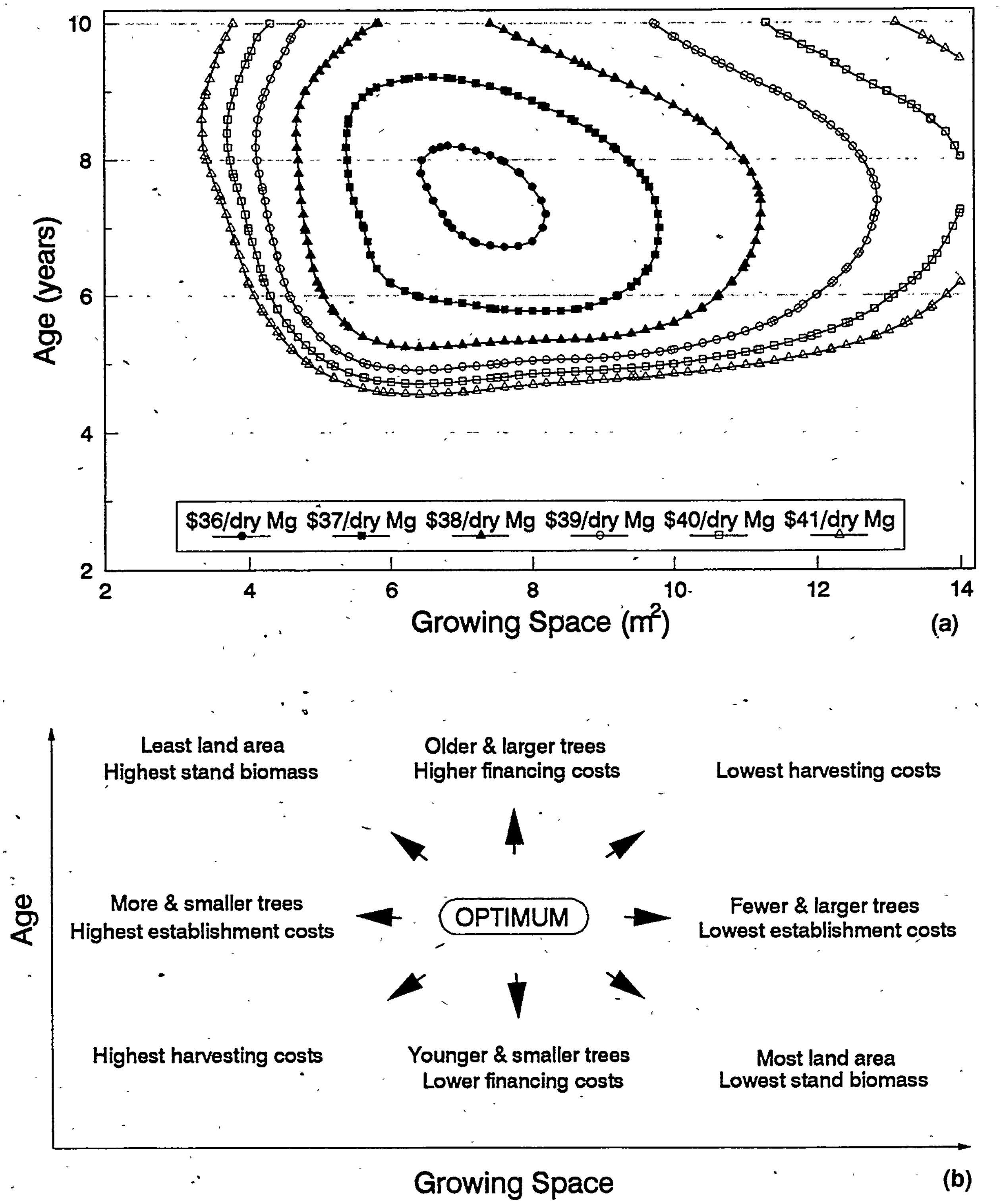

Fig. 3. Optimum SRIC management strategy: (a) for *Eucalyptus saligna* plantations, Hilo coast, Hawaii; (b) reasons for increased average cost with deviations from the optimum.

AN OPTIMAL STAGGERED HARVESTING STRATEGY FOR HERBACEOUS BIOMASS ENERGY CROPS[1]

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Abstract

The biofuel research over the past two decades has revealed that lignocellulosic crops serve as a reliable source of feedstock for alternative energy. However, under the current technology of producing, harvesting and converting biomass crops, the resulting biofuel is still not competitive with conventional biofuel in terms of costs. While there are tremendous research effort is being spent on finding ways to produce low cost biofuel, this study looks into minimizing biofuel feedstock cost under the current technology. The study recognizes the fact that cost of harvesting biomass feedstock is a single largest component of feedstock cost. It is argued that there is a tremendous cost advantage in taking into account various techno-economic and institutional factors associated with current technology in designing a biomass harvesting system. The traditional system of farmer-initiated harvesting operation for biomass crops causes an over investment in agriculture. This over investment is nothing but a *social cost* to the society. Instead, this study develops a least-cost, time-distributed (staggered) harvesting system for switch grass, as an example, that calls for an effective coordination between farmers, processing plant and a single third-party custom harvester. A linear programming model is developed to explicitly account for the trade-off between yield loss and benefit of reduced machinery overhead cost, associated with the staggered harvesting system.

Total cost of producing and harvesting switch grass will decline by 17.94 percent from conventional non-staggered to proposed staggered harvesting strategy. Harvesting machinery cost alone experiences a significant reduction of 39.68 percent from moving from former to latter. The net return to farmers is estimated to increase by 160.40 percent. Per tonne and per hectare costs of feedstock production will decline by 17.94 percent and 24.78 percent, respectively. These results clearly lend support to the view that the traditional system of single period harvesting calls for over investment on agricultural machinery which escalates the feedstock cost. This *social loss* to the society in the form of escalated harvesting cost can be avoided if there is a proper coordination among farmers, processing plant and custom harvesters as to when and how biomass crop needs to be planted and harvested. Such an institutional arrangement benefits producers, processing plant and, in turn, end users of biofuels.

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The biofuel research over the past two decades has revealed that lignodellulosic crops serve as a reliable source of feedstock for alternative energy. However, under the current technology of producing, harvesting and converting biomass crops, the resulting biofuel is still not competitive with conventional biofuel in terms of costs. While there are tremendous research effort is being spent on finding ways to produce low cost biofuel, this study looks into minimizing biofuel feedstock cost under the current technology.

Several techno-economic and institutional factors associated with the current technology of producing and harvesting feedstocks have cost-saving potentials, if properly considered into a harvesting decision maker's plan. These factors exist in the form of certain interrelationships between the time of harvesting, crop yield, unit area harvesting machinery requirement, annual machinery use, size of machinery inventory, unit cost of machine time and who harvests the crops. Most feedstock cost estimates that currently are available are based on a harvesting system that is common to most agricultural crops where farmers are expected to undertake harvesting operation. Such a system requires farmers to individually maintain, or have access to, the required harvesting machine inventory at the time when it pays them the most to harvest, i.e., when the crop attains the maximum yield. If all farmers in a representative catchment area of a biofuel processing plant decide to harvest the crop at the same time, a huge inventory of harvesting machines will be required to accomplish the harvesting operation. Besides, either farmers or the processing plant has to arrange storage of feedstock at additional costs of storage and storage loss.

This paper shows that there is a tremendous cost advantage in taking into account various techno-economic factors into account in designing a biomass harvesting system. The traditional system of farmer-initiated harvesting operation for biomass crops causes an over investment in agriculture. This over investment is nothing but a *social cost* to the society. Instead, this study develops a least-cost, time-distributed (staggered) harvesting system for switch grass, as an example, that calls for an effective coordination between farmers, processing plant and a single third-party custom harvester. A linear programming model is developed to explicitly account for the trade-off between yield loss and benefit of reduced machinery overhead cost, associated with the staggered harvesting system.

Techno-Economic Relationships Affecting Harvesting Costs

The total cost of harvesting a given quantity of biomass feedstocks is mainly a function of unit machine use time and average or unit harvesting cost (cost per hour). First, the unit harvesting machinery use is expected to increase with biomass crop density or crop yield. The crop yield itself depends on the number of cuttings every year (in the case of switch grass) and the timeliness of cutting. During the harvesting season of a given crop, biomass yield is expected to first increase as we delay the date of cutting and then decline as we further delay the time of cutting. Delays in harvesting could affect the yield and quality of a crop due to moisture loss (gain), damage and foreign matter as well as the increased losses from harvesting (Hunt 1983, p. 257). That is, unit harvesting machine use ultimately is a function of time of harvesting. The time of harvesting depends on the institutional arrangement between producers and processing plant.

This timeliness effect on yield can be formalized by

$$Y(t) = a + bt - ct^2, \tag{1}$$

where $Y(t)$ is crop yield (tonne/hectare) and t is time of harvesting. Following Hunt (1983, p. 4-6), effect of crop yield on unit machine use time (UMT) can be expressed as:

$$\text{UMT} = \overline{\text{IT}} + \frac{\bar{e}}{\overline{M}} Y, \tag{2}$$

where $\overline{\text{IT}}$, $\bar{e}$ and $\overline{\text{M}}$ are known constants of machine idle time per hectare, effective field efficiency and material capacity of the machine, respectively..

Second, the average harvesting cost (AHC) is a function of total stock of machine inventory (NM) to be maintained year-round in order to harvest a desired quantity of biomass, per machine fixed cost (FC), and the actual annual machine hour use (AMH) of that inventory. As the inventory stock increases, the total fixed cost of machines (FC×NM) increases. Further, as the annual number of machinery use hours increases, the average (per hour) fixed capital costs such as annual interest on capital, depreciation, insurance and storage costs will decline. A staggered harvesting plan requires a smaller inventory stock and allows longer utilization of this stock than the conventional harvesting system. Thus, the AHC can be expressed as:

$$\text{AHC} = \frac{\text{FC}*\text{NM}}{\text{AMH}} + \text{AVC} \tag{3}$$

The Model Of Optimal Staggered Harvesting Strategy

A linear programming model is developed for a representative switch grass feedstock region in Tennessee. Switch grass is assumed to be harvested twice a year. The first cutting is assumed to span over a period of three and a half months, beginning June 15 through September 30. The entire harvesting season is split into harvesting periods of 15 days each, with first period ending June 30. The earliest second cutting can occur, after two and half months of first cutting and extend up to another two months. That is, for example, acres harvested as first-cutting during period ending June 30 can be second-cut during any periods beginning September 15 through November 15. But all the second cuttings must be completed by January 15 as field condition then after is not congenial for harvesting. Switch grass harvesting is assumed to be similar to a typical hay harvesting. The crop is harvested using a mover-conditioner; raked with a side-delivery rake; baled as a round bale with the help of a baler; and finally staked by the field side with a hay-staker. All these implements are tractor-drawn.

The objective of the linear programming model developed to simulate staggered harvesting is to minimize the overall farm-gate cost of biomass feedstock that includes pre-harvesting production costs, total fixed and variable harvesting costs, and total harvesting labor costs. The model includes several constraints representing minimum feedstock demand, available periodic machine inventory, yield-related unit machinery use, equality between acres harvested as first and second cuttings.

Erosion-Productivity Impact Calculator (EPIC), a plant growth simulator, is used to estimate yields for different harvesting dates. EPIC has the ability to incorporate specific soil and weather characteristics, crop input levels, and type and dates of management practices as model inputs, and then to estimate crop yields. Running EPIC with 32 different combinations of first and second harvesting dates, switch grass yields are developed. These observations are used to estimate the logistic yield equation in (1), and the predicted yields from this equation are used in the analysis.

Information on pre-harvesting production expenses are adopted from English and Coady (1990). Data on fixed costs, average variable costs, and unit machinery use time are obtained from Johnson (1991). The model is analyzed for an annual feedstock demand of 272,232 metric tonnes (300,000 tons).

Results and Discussion

The optimal staggered harvesting strategy requires a total of 13,398 hectares of biomass to meet the specified feedstock demand. As expected, this strategy requires that first-cutting be done throughout the entire first-cutting season (Table 1). It is important to note that the area harvested during the first-cutting season are almost inversely related to the first-cutting yield. Although the crop yield during the period ending August 15 is the highest (2.12 tonne/hectare), the optimal area harvested as determined by the model is the lowest (1,796 hectares). This is because the crop yields have a direct influence on machine use time, and the machine use time will be restricted by total available machine time in each period. The total available machine time, in turn, is endogenously determined by the model, depending on the overall requirement over the entire harvesting season in a least-cost fashion.

The time-distributed harvesting effect can be observed even during the second harvesting season. Areas harvested during periods ending July 15, July 30, August 40 and September 15 will be harvested over more than one period in their second-cutting. The model does not call for any harvesting during period ending October 15.

The optimal numbers of machines to accomplish the staggered harvesting operation are estimated as: 34 mover-conditioner, 28 rakes, 28 balers, 31 hay-stakers and 121 80 HP tractors. Totals of 169,344 and 126,586 hours of machine time are required for first and second cutting, respectively. As expected machine hours used in the second cutting are less than the first cutting. All the machines are used up to their capacity levels in all but two periods. In period ending October 15, there is no harvesting operation. In period ending November 15, only 23 percent of the machine available time is used.

In order to evaluate the relative advantages of staggered harvesting strategy and the traditional non-staggered strategy, costs and returns of these strategies are analyzed. In the case of non-staggered harvesting strategy, it is assumed that either farmers or a custom harvester will harvest the entire biomass area within a period of 30 days when the crop attains the maximum yield both in both the cuttings. The farm gate price that farmers receive from the plant is assumed at $26.19 per tonne in both the cases. The results show that staggered harvesting strategy has a clear economic advantage over the conventional strategy (Table 2). Total cost of producing and harvesting the target feedstock level will decline from $6,413,686 to $5,263,120 (i.e., by 17.94 percent). Further, net return to farmers will increase from $716,070 to $1,866,636 (i.e., 160.40 percent increase). This increase is due to a sizable decline in machinery cost (by 39.68 percent). Per tonneost of feedstock will decline by 17.94 percent, per hectare production and harvesting cost by 24.78 percent, and per hectare harvesting cost by 37.41 percent. These results lend support to the premise that the traditional harvesting system calls for over investment on agricultural machinery which escalates the feedstock cost. If there is a proper coordination among farmers, processing plant and custom harvesters, this *social cost* can be eliminated. Such a coordination will benefit producers, processing plant and in turn, end users of biofuels.

Concluding Remarks

Harvesting cost is a single largest component of biofuel feedstock cost. The traditional harvesting system in which each farmer individually attempts to harvest the crop at its maximum maturity will require a large machinery system that is prohibitively expensive. This study has developed an integrated, staggered-harvesting strategy that results in a much cheaper harvesting operation. The cost and benefit indicators of staggered harvesting strategy for switch grass is compared with those of non-staggered, single period harvesting plan. The total cost of producing and harvesting is estimated to be 17.94 percent less in staggered harvesting than that of non-staggered harvesting. The harvesting machinery cost alone experiences a significant reduction of 39.68 percent from moving from traditional to staggered harvesting plan. The net return to farmers increases by 160.40 percent. Per tonne and per hectare costs of feedstock production will decline by 17.94 percent and 24.78 percent, respectively. This indicates that the traditional system of single period harvesting causes an over investment on agricultural machinery which escalates the feedstock cost. This *social loss* to the society in the form of escalated harvesting cost can be avoided if there is a proper coordination among farmers, processing plant and custom harvesters. Such an institutional arrangement benefits producers, processing plant and, in turn, end users of biofuels.

Table 1. Biomass Acres Harvested in the Staggered Harvesting Strategy.

Dates of 1st/ 2nd Cutting	Dates of 1st Cutting							Total Acres
	Jun 30	Jul 15	Jul 30	Aug 15	Aug 30	Sep 15	Sep 30	
	Acres							
1st Cutting								
Jun 30	2113							2113
Jul 15		1932						1932
Jul 30			1834					1834
Aug 15				1796				1796
Aug 30					1813			1813
Sep 15						1885		1885
Sep 30							2025	2025
Total Acres	2113	1932	1834	1796	1813	1885	2025	13397
2nd Cutting								
Oct 15								0
Oct 30	2113	455						2568
Nov 15		610						610
Nov 30		867	1757					2624
Dec 15			77	1796	633			2506
Dec 30					1180	1201		2381
Jan 15						684	2025	2709
Total Acres	5218	1932	1834	1796	1813	1885	2025	13397

Table 2. Comparison of Costs and Returns between Non-Staggered and Staggered Harvesting Strategies for Switch Grass Feedstock.

Relative Measures	Unit	Traditional Harvesting	Staggered Harvesting	Percent Change
Total area required	hectare	12,281	13,398	9.10
Total biomass produced	tonne	272,232	272,232	0.0
Total farm-gate cost	$	6,413,686	5,263,120	-17.94
Pre-harvesting cost	$	2,165,217	2,632,178	9.10
Harvesting machine cost	$	3,429,365	2,068,639	-39.68
Harvesting labor cost	$	819,104	832,303	1.61
Gross return	$	7,129,756	7,129,756	0.0
Net return	$	716,070	1,866,636	160.40
Per tonne cost	$/tonne	23.56	19.33	-17.94
Per hectare cost	$/hectare	522.25	392.83	-24.78
Per hectare harvesting cost	$/hectare	345.95	216.52	-37.41

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EVALUATING THE ECONOMICS OF BIOMASS ENERGY PRODUCTION IN THE WATTS BAR REGION

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Abstract

While the commercial potential of biofuel technology is becoming more feasible, it is not clear whether the supply of biomass feedstock will be available in competitive markets. In order to exploit the potential of biomass crops as a reliable source of biofuels, a significant commitment on the part of farmers to convert large amounts of cropland would be required. Dedicated energy crops have to compete with conventional crops which could result in significant interregional shifts in crop production. Those changes could further affect overall agricultural production, food prices, consumer spending, and government spending on farm programs. Evaluating these economic impacts provides important information for the ongoing debate.

This research is a case study incorporating an existing power plant. The objective of this project is to evaluate the potential of short rotation woody crops as a fuel source in the Watts Bar facility located in eastern Tennessee. The appraisal includes estimates of environmental impacts as well as of economic feasibility. This is achieved by estimating the amounts of biomass that would be supplied at a predetermined price. By changing prices of biomass at the plant in an incremental fashion, a regional supply curve for biomass is estimated.

The model incorporates current agricultural production possibilities in the region along with the proposed short rotation woody crop production activities. In order to adequately model the landscape, several variables are considered. These variables include soil type, crop production, government policy, land use conversion to crop land, and distance from the plant. Environmental issues including erosion, chemical usage, and potential leaching are also incorporated within the modeling framework; however, only estimates on erosion are available in this analysis. Output from the model provides insight on where and what types of land should shift from current land use to biomass production.

Four sets of solutions were run from $28.66 to $74.96 per metric ton ($26.00 to $68.00 per ton) delivered biomass, incremented by $2.20 per metric ton ($2.00 per ton). In each of these solutions, the amount of biomass supplied by the regional agricultural sector was plotted against the price of biomass. Biomass production occurred at prices ranging from $33.07 to $46.30 per metric ton ($30.00 to $42.00 per ton) across the alternative solutions. Biomass supply exceeded the target of 272,155 metric tons (300,000 tons) at prices ranging from $46.30 to $66.14 per metric ton ($42.00 to $60.00 per ton). The introduction of biomass resulted in decreased production of corn and wheat, as well as decreased levels of erosion.

Introduction

While the commercial potential of biofuel technology is becoming more feasible, it is not clear whether the supply of biomass feedstock will be available in competitive markets. In order to exploit the potential of biomass crops as a reliable source of biofuels, a significant commitment on the part of farmers to convert large amounts of cropland would be required. Dedicated energy crops have to compete with conventional crops which could result in significant interregional shifts in crop production. Those changes could further affect overall agricultural production, food prices, consumer spending, and government spending on farm programs.

The adoption of biomass crops as part of a national energy strategy occurs during a crucial period in the evolution of U.S. farm programs. Existing cropping practices are subject to reevaluation in terms of sustainability and the impact that traditional agriculture has on the environment and on food safety. The 1990 farm bill has increased the standards of soil conservation compliance. Studies sponsored by the Department of Energy (English and Bhat; Parrish et al.) suggest that certain biomass crops have an advantage over conventional crops, and that adoption of biomass cropping systems may cause less soil erosion and nutrient leaching. Thus, biomass crops might be a promising alternative enterprise for farmers in order to meet environmental quality standards while maintaining farm income.

In the 13 state southeastern region alone, there are 34.7 million hectares (85.8 million acres) of agricultural land, of which 4.3 million hectares (10.5 million acres) are planted in feed grains, 8.2 million hectares (20.3 million acres) in soybeans, 3.5 million hectares (8.7 million acres) in major food grains, and 5.6 million hectares (13.8 million acres) in hay and pasture crops (USDA, ASCS). Most of the region's cropland has the potential to produce selected short rotation woody crops such as poplar, sweet gum, black locust, and sycamore. Given proper incentives, through competitive means or government support, farmers might select short rotation energy crops as a viable alternative crop enterprise.

The Watts Bar supply region consists of 43 counties. Eight are located in northern Georgia, three are located in western North Carolina, and the remainder are located in east and middle Tennessee (Figure 1). The region contains over 2.8 million hectares (7 million acres) of rural and privately owned land within its defined boundaries. According to the National Resources Inventory (USDA, SCS), the major use of land for this area is forest land. Nearly 68 percent of the land in the Watts Bar region is currently in managed and unmanaged forest. Another 20 percent of the land is in pasture and nearly 10 percent, or 280,000 hectares (700,000 acres) of the land, is in

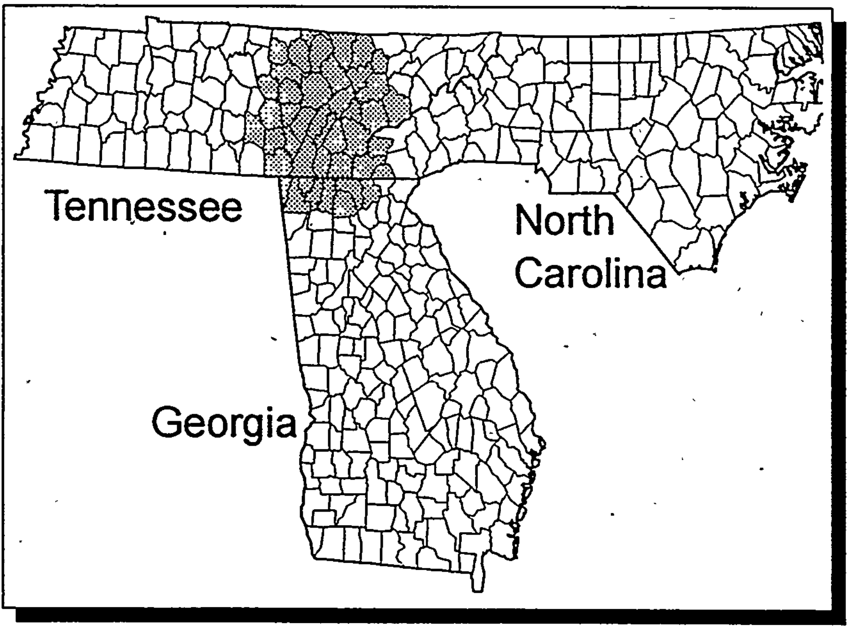


Figure 1. The Watts Bar region

crops. It is possible to convert forest and pasture land to cropland. The Soil Conservation Service in their 1982 National Resources Inventory, developed a measure that evaluates the potential of conversion from forestland or pastureland to cropland. In this comprehensive land survey, the Soil Conservation Service rated land as having high, moderate, low, or no potential for conversion. Applying their findings to the Watts Bar region, there are over 607 thousand hectares (1.5 million acres) of pasture and forest having moderate or high potential for conversion. Of this, 344 thousand hectares (850 thousand acres) are currently in pasture and 267 thousand hectares (660 thousand acres) in forest.

Methodological Approach

This research is a case study incorporating an existing power plant. The objective of this project is to evaluate the potential of short rotation woody crops as a fuel source in the Watts Bar facility located in eastern Tennessee. The appraisal includes estimates of environmental impacts as well as of economic feasibility. This is achieved by estimating the amounts of biomass that would be supplied at predetermined prices. By changing prices of biomass in an incremental fashion, a regional supply curve for biomass is estimated.

The growing of biomass, and therefore its supply to the plant, is restricted by resources available in the region, the price that the plant is willing to pay for the biomass, and the cost of transporting biomass to the plant. The environmental impacts associated with growing energy crops are affected by the cropping practices used, the amount of biomass supplied to the plant, and the land resources available. A regional linear programming model is developed for this study incorporating these environmental parameters. Space restrictions prevent a complete mathematical specification of the model in this paper, however, a detailed description is available from the authors.

The Objective Function

The linear programming model used in the analysis maximizes net returns subject to resource limiting, input purchasing, and output selling constraints. The objective function is specified such that costs of production, excluding land, rent and managerial charges, are subtracted from farm crop income, including biomass, and government deficiency payments. Therefore, gross revenues in the region include the revenue gained from selling crops and biomass commodities produced in the region and deficiency payments resulting in the sale of crops grown on land enrolled in government programs. Costs of production incorporate fertilizer, labor, and energy costs; the costs of machinery, seed, and other inputs; and the costs of converting pasture and forest to cropland.

The Constraints

The objective function is subject to several physical input and output constraints, including land, fertilizers, labor and energy. The land constraints restrain the model as land of a given soil type is finite in quantity within the region. The other input constraints require the purchase of inputs at predetermined prices. The output constraints allow for selling the commodities produced and receiving the benefits of commodity programs through deficiency payments.

There are two types of land constraints in the model. The first restricts production to the level of land available, and the second restricts land conversion activities to the amount of land identified as having a high or moderate potential for conversion. The cropland constraint requires the amount of land used in the production of agricultural commodities, plus the amount set side for government program participation, less the amount that can be converted to cropland from pasture and forest, to be less than the amount currently in cropland. The pasture/forest conversion constraints limit the amount of land converted to the levels available. There are pasture/forest constraints for the combination of type and potential in each region and land group.

The fertilizer constraint requires the quantity of fertilizer needed to produce the agricultural commodities in each region to be equal to the quantity purchased plus the amount supplied through livestock wastes in each region. There are three types of fertilizer included in the model: nitrogen, phosphorus and potassium. Labor in the model is divided into two types: machinery and other. The labor constraint is not region-specific; it requires labor used in the region to equal the labor purchased. All labor, including family labor, is assumed to be purchased. Thus, family labor is assumed to have an opportunity cost equal to the value of labor within the study region.

The energy constraint requires energy to be purchased for farm operations and biomass transportation. There are three types of energy in the model: gasoline, diesel and other. In this model, all farm and transportation energy needs are defined in diesel equivalents. The crop sell constraint requires the amount sold to be less than the amount produced, less that which is consumed within the region by livestock, plus the amount of feed lost when an acre of pasture/forest land is converted to cropland.

The government payment constraint allows a deficiency payment to be paid if the production activity has complied with commodity program provisions. The acreage on which deficiency payments are paid cannot exceed the region's base yield times the acres in production. At present, the erosion constraint does not limit erosion. Rather, it sums the number of tons of sheet and rill erosion that occur in each region as a result of agricultural production.

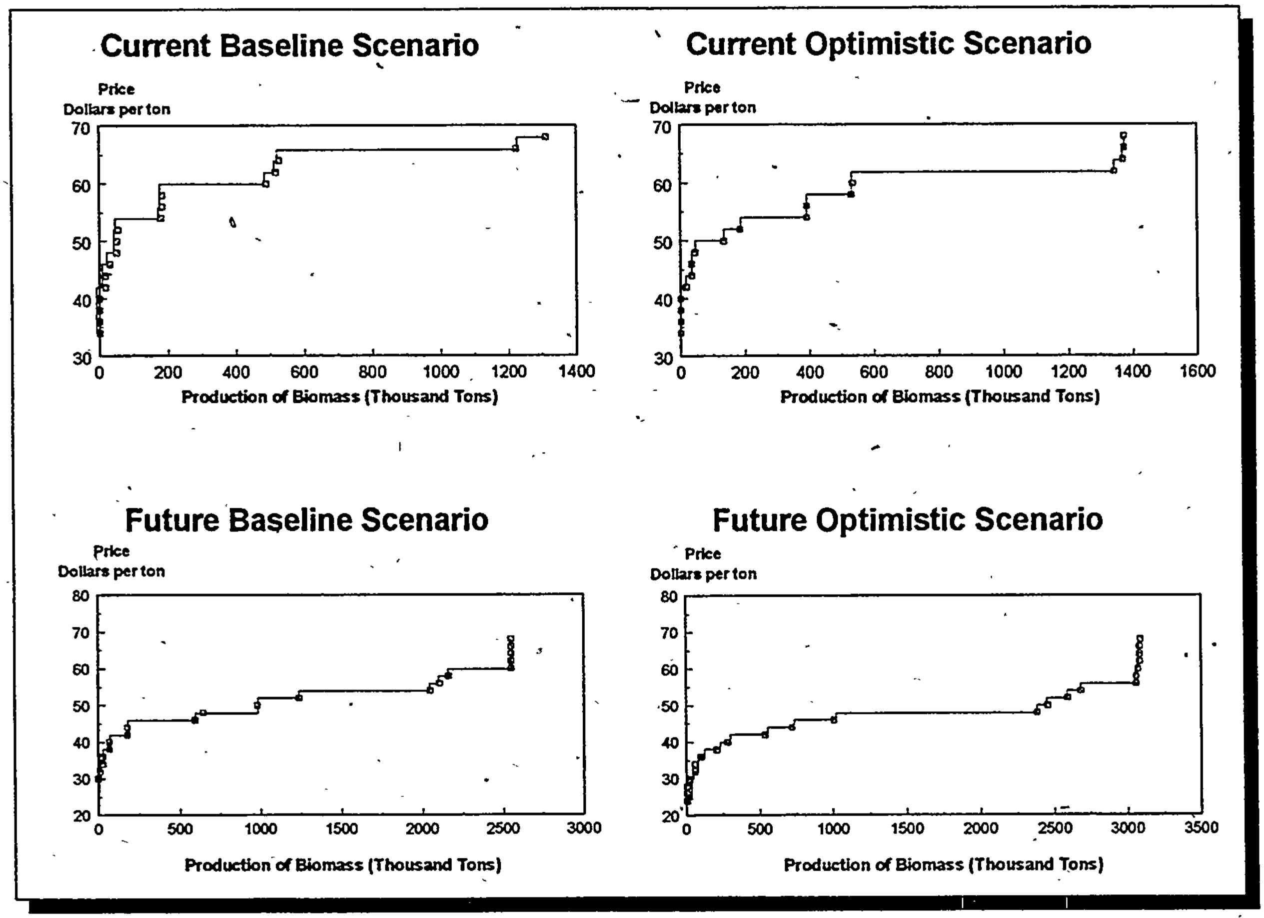
The Supply of Biomass to Watts Bar

Estimating the supply of biomass to the Watts Bar facility requires estimating a solution at various plant gate biomass prices. The quantity of biomass supplied to the plant at a predetermined price can be thought of as the quantity of biomass that would be available if the assumptions incorporated in the model prevail. Since short rotation woody crop trials are not yet sufficient to provide accurate yields, the analysis is conducted using four sets of biomass assumptions: Current Baseline, Future Baseline, Current Optimistic, and Future Optimistic. Once the supply curves are generated under the four sets of assumptions, a 272,155 metric ton (300,000 ton) per day supply is assumed and evaluated in more detail. Finally, three sets of pricing biomass price schemes are assumed with harvest costs doubled, interest rates halved, and commodity subsidies removed. Each of these solutions are designed to test the sensitivity of the initial solution and provide indicators as to critical variables. Only the base solutions for the current and future scenarios are presented here. Detailed comparisons of the four solutions and the sensitivity analysis may be obtained from the authors.

The Supply Curves

Four sets of solutions are run from $28.66 to $74.96 per metric ton ($26.00 to $68.00 per ton) delivered biomass, incremented by $2.20 per metric ton ($2.00 per ton). In each of these solutions, the amount of biomass supplied by the regional agricultural sector is plotted against the price of biomass (Figure 2).

In the Baseline Current alternative, biomass begins arriving at the plant at $46.30 per metric ton ($42.00 per ton). At $63.93 per metric ton ($58.00 per ton), biomass supplied in the current baseline is nearly 172,365 metric tons (190,000 tons). By $66.14 per metric ton ($60.00 per ton), the quantity supplied to the plant exceeds 435,449 metric tons (480,000 tons). When no biomass is produced, the region produces 96,829 metric tons (3,812,000 bushels) of corn, 633,632 metric tons (23,282,000 bushels) of wheat, and 381,925 metric tons (421,000 tons) of hay. No soybeans are produced and all cropland is used in the solution. There are 17,345 cubic meters (4,582,000 gallons), diesel equivalent, of energy used in the agricultural production process. In addition, 4,853 metric tons (10.7 million pounds) of nitrogen are applied along with 8,165 metric tons (18 million pounds) of phosphates and potassium. Over 4.5 million metric tons (5 million tons) of erosion occurs as a result of agricultural production in the region, an average of nearly 15.7 metric tons per hectare (7 tons per acre). At a gate price of $66.14 per metric ton ($60.00 per ton), corn production drops to 73,663 metric tons (2,900,000 bushels), wheat production to 485,770 metric tons (17,849,000 bushels) and erosion to 4,055,116 metric tons (4,470,000) tons. Approximately 48,158 hectares (119,000 acres) of cropland shifts to biomass production.


Current Baseline Scenario

Current Optimistic Scenario

Future Baseline Scenario

Future Optimistic Scenario

Figure 2. Watts Bar biomass supply curves

In the Baseline Future alternative, biomass begins arriving at the plant at $35.27 per metric ton ($32.00 per ton). At $48.50 per metric ton ($44.00 per ton), biomass supplied in the future baseline is nearly 162,749 metric tons (179,400 tons). By $50.71 per metric ton ($46.00 per ton), the quantity supplied to the plant exceeds 539,775 metric tons (595,000 tons). When no biomass is produced, the solution is the same as in the current baseline alternative. In the $50.71 per metric ton ($46.00 per ton) solution, comparison to the current baseline shows little change except in the amount of land required to produce the biomass. The land required to produce 539,775 metric tons (595,000 tons) of biomass in the Watts Bar region is slightly more than 46,134 hectares (114,000 acres). In this alternative, soil erosion declined to 3,719,457 metric tons (4,100,000 tons).

Impact of Yield Assumptions

The impact of changes in the per hectare tonnage of biomass available can be examined by comparing the current baseline and the future baseline alternatives. This comparison is achieved by resolving the two alternatives with a 272,155 metric ton (300,000 ton) biomass constraint and a #37.48 per metric ton ($34.00 per ton) price for biomass. The model is forced to produce the biomass and the shadow value of the constraint represents the additional price for biomass the plant would have pay at the gate. In the current baseline alternative, the price of biomass required to gain a 272,155 metric ton (300,000 ton) supply is $65.37 per metric ton ($59.30 per ton). In the future baseline solution, that price is reduced by $16.54 per metric ton ($15.00 per ton) to $49.10 per metric ton ($44.54 per ton). Other interesting changes occur, especially when examining the regional shifts. In the current baseline, for example, the biomass is produced throughout all four regions. However, the future baseline solution shows the biomass produced in the first three regions, but not in the furthest region.

It should also be noted that the prices calculated in this model represent marginal costs to the biomass producer, but marginal cost is only one way to view the cost to the power plant. The marginal biomass costs such as the ones reported thus far and reflected in the supply curves are costs that will purchase the last unit of biomass. In a perfectly competitive market, the marginal cost will equal the price and those producers capable of producing units below that cost reap producer rent. However, in the system of one demander for a product and multiple suppliers of that product, the demander may be able to capture some of the producer rent resulting in a lower average price paid for biomass.

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Herbaceous Energy Crops in Humid Lower South USA

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Abstract

The humid lower South has the long warm growing season and high rainfall conditions needed for producing high-yielding perennial herbaceous grasses and shrubs. Many potential biomass plants were evaluated during a ten-year period. Perennial tall grasses such as elephantgrass (Pennisetum purpureum), sugarcane and energycane (Saccharum spp.) and the leguminous shrub Leucaena leucocephala were the highest in biomass production. These perennial crops often have top growth killed by winter freezes and regenerate from underground parts. The tall grasses have high yields because of linear crop growth rates of 18 to 27 g m^2 d^{-1} for long periods (140 to 196 d) each season. Tall grasses must be planted vegetatively, which is more costly than seed propagation, however, once established, they may persist for many seasons. Oven dry biomass yields have varied from 20 to 45 Mg ha^{-1} yr^{-1} in colder subtropical to mild temperate locations to over 60 Mg ha^{-1} yr^{-1} in the lower portion of the Florida peninsular. Highest biomass yields have been produced when irrigated with sewage effluent or when grown on phosphatic clay and muck soils in south Florida. The energy content of 1 Mg of oven dry tall grass and leucaena is equivalent to that of about 112 and 123 gallons of number 2 diesel fuel, respectively.

The long warm growing season and high rainfall makes the humid lower South [located in subtropical and warmer temperature climatic zones (See Figure 1)] ideal for the growth of high-biomass-producing perennial herbaceous grasses and shrubs. Only the humid tropics have a longer growing season and as favorable rainfall for high biomass production. This paper will summarize a number of experiments conducted on herbaceous plants as a result of a 10 year agreement between the University of Florida Institute of Food and Agricultural Sciences and Gas Research Institute of Chicago, IL to study the feasibility of producing methane from biomass energy crops. After several years of exploratory research (Smith and Frank, 1988) involving many genera and species of plants, the tall tropical grass elephantgrass or napiergrass (Pennisetum purpureum Schum.) was found to have great potential as an energy crop (Prine et al., 1988). A demonstration plot of PI 300086 elephantgrass planted in 1980 had a 1981 oven dry biomass yield of 44.5 Mg ha^{-1} (19.9 tons/acre). This gave us the first indication of the yield potential of elephantgrass as a biomass crop and started us evaluating this crop for energy use. Later, the tall grasses, energycane and sugarcane (Saccharum spp.) and leucaena [Leucaena leucocephala (Lam.) de Wit] a tropical shrub legume were added to list of the exceptional biomass producing plants. These crops all have the potential of growing for entire warm season with little loss of produced biomass. The accumulated biomass can be harvested during winter and regrowth begins the next spring from underground rootstocks. The elephantgrass, sugarcane, and energycane have C_4 photosynthetic pathway for maximum solar energy efficiency during warm season. All the selected plants have cultivars which are adapted to the humid lower South (Figure 1.)

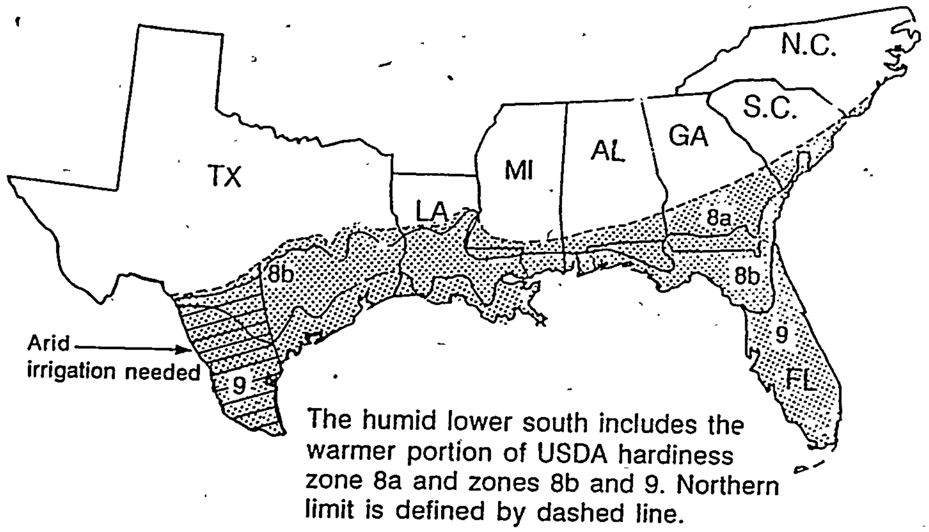

Fig. 1 The Humid Lower South, USA

We planted 11 of the best of 45 collected genotypes in a replicated trial at Dairy Research Unit in September 1982. The dry biomass yields of the best six elephantgrass genotypes for the next five seasons are given in Table 1.

Table 1. The Oven Dry Biomass Yields of Selected Elephantgrass Accessions Grown in Scranton Loamy Fine Sand at Dairy Research Unit Near Gainesville, FL Over the Five Growing Seasons 1983-1987.

	Dry matter yield (mean of 4 replications)					
Entry	1983	1984	1985	1986	1987	5-yr avg
	Mg ha^{-1}					
N51	27.8	42.1	37.5	27.7	24.3	32.1
PI 300086	37.1	35.0	35.0	32.0	21.0	32.0
N43	32.8	32.4	32.5	24.4	19.3	30.5
N13	32.5	27.3	30.4	30.1	20.1	28.1
Merkeron	25.5	41.6	32.9	18.7	18.7	27.5
PP3	27.6	21.4	21.4	17.1	20.5	21.8

Fertilized with 168-42-64 kg ha^{-1} N-P_2O5-K_2O fertilizer annually applied in early spring. To convert Mg ha^{-1} to tons/acre divide by 2.24.

We learned of L79-1002 energycane [developed at LSU (Giamalva et al., 1984)] and received enough planting material to plant an experiment at Green Acres farm near Gainesville, FL comparing elephantgrass, sugarcane and energycane in December of 1983. The biomass yields for the next four years of the different crops are given in Table 2. The elephantgrass, sugarcane, and L79-1002 energycane all had similar yields. In 1987 the stand of CP72-1210 sugarcane begin to thin and it was too sparse to harvest in 1988. The L79-1002 energycane and PI 300086 elephantgrass persisted until the crops were plowed under in 1991.

Table 2. Oven Dry Biomass Yields of Selected Tall Grasses Planted on Arredondo Fine Sand at University of Florida Green Acres Farm Over 4 Growing Seasons, 1984-1987.

	Oven dry biomass yield†				
Accession + crop	1984	1985	1986	1987	4-yr avg
	Mg ha^{-1}				
CP 72-1210 sugarcane	29.3	36.2	31.0	26.5	30.8
PI 300086 elephantgrass	30.7	37.3	29.6	35.7	33.4
L79-1002 energycane	30.2	34.0	31.8	36.5	33.1

Fertilized with 168-42-64 kg ha^{-1} N-P_2O5-K_2O fertilizer applied once in early spring.
† Yields are means of 4 replications.

In 1986, an experiment was planted to compare selected perennial tall grasses with the annual tall grasses, sweet and forage sorghum [Sorghum biocolor (L.) Moench] at 5 locations in the Southeast (Prine et al., 1991). The average annual dry matter yields over the next three years over the five locations are recorded in Table 3. The warmer the environment and longer the growing season the higher was the yield of the elephantgrasses but the L79-1002 energycane gave consistent yields over the 5 locations. The commercial sugarcane CP72-1210 developed for the muck soils south of Lake Okeechobee did not do well at any of the locations but in some of same years excelled on settling pond clays in Central Florida (Table 4). Note several of the tall grass entries in this trial had yields over 60 Mg ha^{-1} during high yielding years. The high yields of the tall grasses are due to long linear growth periods (140-196 d) at growth rates of 18 to 27 g m^{2}d^{-1} [Woodard and Prine (1993)].

Table 3. Average Annual Biomass Yield of Elephantgrass (eg), Energycane (ec), Sugarcane (sc), Sweet Sorghum (ss) and Forage Sorghum (fs) at Five Locations in Southeastern United States Over Three Growing Seasons, 1987-89.

	Oven dry biomass				
	Florida				Alabama
Crops	Ona	Gaines-ville	Quincy	Jay	Auburn
	Mg ha^{-1} yr^{-1}				
N-51 eg	46.7	39.7	33.8	32.1	24.0
PI 300086 eg	41.6	28.6	24.1	24.0	18.6
L79-1002 ec	23.3	32.2	30.1	33.9	24.2
CP72-1210 sc	19.4	10.4	19.2	8.2	6.0
M81E ss†	23.0‡	11.3	10.0	18.5	7.8
Pioneer 931 fs†	23.8‡	11.0	11.7	20.9	5.3

† Two harvests per season at most locations and years.
‡ Average over only two seasons; serious Pythium and nematode problems occurred.
To convert Mg ha^{-1} to tons/acre divide by 2.24. Table derived from Prine et al. (1991).

Fertilization

We began a fertilization study (Table 5) on PI 300086 elephantgrass cut once a season for biomass in 1982. The highest rate of fertilizer was 672 kg ha^{-1} yr^{-1} of N in split applications. The single application of 224 kg ha^{-1} yr^{-1} N in a 4-1-2 ratio with P_2O_5 and K_2O usually gave the best annual yields and was best over the 5 years of the study. We have conducted most of our tall grass genotype trials at a fertilizer level of 168-42-84 kg of N-P_2O_5-K_2O ha^{-1} yr^{-1}.

Table 4. Average Annual and Highest Annual Dry Matter Biomass Yield and Oil Equivalent of Biomass of Tall Grass Crops Produced on Phosphatic Clays in Polk County Southwest of Bartow, FL Over Four Growing Seasons, 1987-1990.

Accession + crop	DM yield 4-yr. average (highest yield in single yr.)		Oil equivalent† from average biomass yield
	$Mg\ ha^{-1}\ yr^{-1}$	Tons/A/yr	Gallons/A/yr
PI 300086 elephantgrass	36.3 (40.5)	16.2 (18.1)	1,650
N51 elephantgrass	45.2 (66.3)	20.2 (29.6)	2,060
L79-1002 energycane	42.5 (45.7)	19.0 (20.4)	1,940
US72-1153 energycane	49.0 (58.2)	21.8 (26.0)	2,200
US78-1009 sugarcane	49.7 (55.1)	22.2 (24.6)	2,260
US56-9 sugarcane	52.2 (68.0)	23.3 (30.4)	2,380
CP72-1210 sugarcane	56.2 (67.2)	25.1 (30.0)	2,560
1K-7647 erianthus	48.8 (47.9)	21.8 (21.4)	2,220

†2.45 gm dry biomass = 1 gm No. 2 oil
19.6 lb dry biomass = 8 lb (1 gallon) No. 2 oil. Table derived from Stricker et al. (1993).

Table 5. Oven Dry Biomass Yield of PI 300086 Elephantgrass Grown on Scranton Loamy Fine Sand at Dairy Research Unit Near Gainesville, FL Fertilized with Single and Split Applications of Various Fertilizer Rates Over the 5 Growing Seasons, 1982-87.

Fertilizer application†	N rate	Oven dry biomass (Mean of 5 replications)					
		1982	1983	1984	1985	1986	5-yr avg.
	$kg\ ha^{-1}\ yr^{-1}$	$Mg\ ha^{-1}$					
Single	0	31.8	21.3	31.4	27.7	34.6	29.4
	56	34.8	33.4	39.3	32.8	29.3	33.9
	112	40.9	38.5	39.9	34.6	35.3	37.8
	224	49.0	46.1	55.9	43.3	44.7	47.8
	448	42.1	36.7	57.2	48.5	42.6	45.4
Split	224	41.6	42.1	38.4	33.7	45.2	40.2
	448	56.8	37.2	50.5	39.6	44.6	45.7
	672	48.5	40.5	47.9	44.5	44.6	45.2

† Fertilizer was applied as a 4-1-2 ratio of $N\text{-}P_2O_5\text{-}K_2O$.

Leucaena

The average oven dry stem yield over 12 selected leucaena accessions selected from a duplicate plot nursery of 373 accessions planted in 1979 at Gainesville FL for four growing seasons are shown in Table 6. In colder subtropics and warm temperate climates leucaena is usually killed to ground each winter by freezes and regenerates from underground root stalks. The dead woody stems can be harvested in winter and made into chips for burning or processing into energy products. Twenty accessions of leucaena out of 373 in the nursery had good vigor and/or stands after 12 growing seasons (Cunilio and Prine 1991).

Table 6. The Average and Highest Oven Dry Stem Biomass Yields of 12 Selected Leucaena Accessions Planted in 1979 at Gainesville, Florida, During Four Growing Seasons.

	Oven dry biomass				
Accession	1982	1983	1986	1987	Mean
	Mg ha^{-1}				
Average over 12 accessions	29.3	24.7	40.2	33.4	31.4
Highest yielding	38.9	30.7	58.9	44.9	43.4

Taken from Cunilio and Prine (1991).

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UNDERSTORY BIOMASS FROM SOUTHERN PINE FORESTS AS A FUEL SOURCE

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Abstract

The energy crisis in the U.S. in the late 1970's led to accelerated research on renewable energy resources. The use of woody biomass, harvested from pine forests in the southern U.S., as a renewable energy source would not only provide an efficient energy alternative to forest industries, but its use would also reduce understory competition and accelerate growth of overstory crop trees. This study was initiated in the early 1980's to investigate the feasibility and applicability of the use of understory vegetation as a possible energy fuel resource.

All woody understory vegetation [<14 cm (<5.5 in) in dbh], on 0.2 ha (0.5 ac) plots that represented a range of stand/site conditions of pine stands located in twelve southern Arkansas counties and two northern Louisiana parishes were characterized, quantified, and harvested. Based on the biomass yield from 720 subplots nested within 40 main plots, the top five dominant species in the understory, based on number and size, were: red maple, red oaks, pines, sweetgum, and winged elm. Some other species occurring, but in smaller proportions, were flowering dogwood, beautyberry, white oaks, black gum, wax myrtle, hickories, persimmon, and ashes. Most of these species are deciduous hardwoods that provide high BTU output upon burning. The average yield of chipped understory biomass was 23.5 T/ha with no difference occurring between summer and winter harvests. A predictive model of understory biomass production was developed using a step-wise multivariate regression analysis. In relation to forest type, high density pine stands produced 53% more understory biomass than high density pine-hardwood stands. The average moisture content of biomass was significantly lower when harvested in winter than when harvested in summer.

Analyses of N, P, K, Ca, and Mg contents in the biomass and the soil indicated that significantly higher nutrient contents were found in biomass harvested in summer than in winter. Ratios of nutrient pool in the soil and nutrient removal from the biomass were calculated to assess the effects of understory biomass harvest on depletion of soil nutrients, a measure of changes in site quality or productivity. The ratios indicate that a shortfall might occur with P, K, and Ca following repeated summer harvests. Winter harvests of understory biomass would reduce soil nutrient depletion and lessen the costs of transporting the wood fuel because of its lower moisture content. For a ten-year harvesting cycle, an understory biomass production of 25 T/ha (2.5T/ha/yr) would provide a commercially operable quantity to harvest as fuel.

Introduction

The energy crisis in the U.S. in the late 1970's led to accelerated research on renewable energy resources, including understory woody biomass from forests. Some forest industries in the southern U.S. were developing mobile harvester-chippers to harvest understory woody vegetation for fuel in their physical plants. Concurrently, considerable effort was being made by forest managers to reduce unwanted, nonmerchantable understory vegetation that was competing with overstory crop trees for moisture and nutrients. In view of these facts, a cooperative project between the School of Forest and Wildlife Resources, University of Arkansas at Monticello, the USDA Forest Service, and the Georgia-Pacific Corporation on the use of understory vegetation as a renewable biomass energy resource was conducted. The project was funded by the Department of Energy.

Objectives

The objectives of the study were to: (1) characterize and quantify the understory woody vegetation across an array of stand/site conditions in southern pine forests, (2) develop a model to predict understory biomass production, and (3) determine the effects of periodic harvests of understory biomass on site quality.

Methods

Forty 0.2-hectare (0.5-acre) main plots--arranged in a factorial design with 5 replications--were established in natural southern pine stands located in an area covering twelve southern Arkansas counties and two northern Louisiana parishes. The following criteria, based on composition and structure of overstory trees larger than 14 cm (5.5 in) in dbh, were used for main plot selection:

Forest types:	Pine -- 75% or more of merchantable basal area (BA) in pine.
	Pine-hardwood -- 40-65% of merchantable BA in pine.
Stand density:	High density -- 20-28 m^2/ha (85-120 ft^2/ac) in BA.
	Low density -- 7-18 m^2/ha (30-80 ft^2/ac) in BA.
Site classes:	Good site -- Loblolly pine site index 26 m (85 ft) and better.
	Poor site -- Loblolly pine site index 24 m (80 ft) and less.

Within each main plot, all woody vegetation less than 14 cm (5.5 in) in dbh was measured on eighteen 3.05 m x 3.05 m (10 ft x 10 ft) randomly located subplots. Preharvest inventories included species, diameter at 15 cm (6 in) above ground, diameter at dbh when applicable, and total height. All vegetation in the subplots was then cut at 15 cm (6 in) above ground to simulate the stump-height left by the mechanical harvester-chippers under development. Nine subplots were harvested and chipped using a portable chipper in late summer during full foliage and nine subplots were harvested and chipped in winter after leaf fall.

Fresh weights of the chipped biomass were determined in the field. Subsamples were obtained and dried at 70°C. After drying and weighing, biomass weights were calculated in metric tons per hectare (T/ha) for each subplot. The dried biomass subsamples were then pulverized in a Wiley mill and used to determine nutrient concentrations. Soil samples were collected at 7.5

and 15 cm (3 and 6 in) depths from each subplot after harvest. The biomass and the soil samples were analyzed for N, P, K, Ca, and Mg concentrations using standard laboratory procedures. A prediction equation was developed for the understory biomass production, and an assessment was made of the effects of biomass removal on site productivity.

Results and Discussion

Understory Composition

The most dominant species (in terms of number and size) found in the understories of the various stand types included red maple, red oaks, pine, sweetgum, and winged elm. These species occurred in the ratio of: 3.0:1.5:1.3:1.2:1.0. Some other understory species occurring, but in relatively smaller proportions, included flowering dogwood, beautyberry, white oaks, black gum, wax myrtle, hickories, persimmon, and ashes. Most of these species are deciduous hardwoods and provide high BTU output upon burning.

Understory Biomass Production

A summary of the ovendry biomass harvested by stand/site condition and by season is presented in Table 1. Plot means represent the averages of nine summer-harvested subplots and nine winter-harvested subplots nested in each of the five replicated main plots.

Table 1. Understory Biomass (T/ha) by Stand/Site Condition, Season, and Season Average.

	Pine				Pine-Hardwood			
	High Density		Low Density		High Density		Low Density	
	Good Site	Poor Site	Good Site	Poor Site	Good Site	Poor Site	Good Site	Poor Site
Summer Harvest								
Plot Mean	22.2	31.4	17.8	30.7	16.1	20.5	31.5	23.4
Site Mean	26.8		24.2		18.3		27.4	
Type Mean	25.5				22.8			
Season Mean	24.2							
Winter Harvest								
Plot Mean	25.4	32.1	16.4	23.7	16.5	19.3	25.2	24.0
Site Mean	28.7		20.0		17.9		24.6	
Type Mean	24.4				21.2			
Season Mean	22.8							
Average								
Plot Mean	23.8	31.7	17.1	27.2	16.3	19.9	28.3	23.7
Site Mean	27.8		22.2		18.1		26.0	
Type Mean	25.0				22.0			
Season Mean	23.5							

The understory biomass yields on individual subplots range from a high of 57.6 T/ha on a summer-harvested, high-density, pine subplot to a low of 2.2 T/ha on a winter-harvested, high 2density, pine-hardwood subplot. The average across all 720 subplots was 23.5 T/ha. For a ten-year harvesting cycle, an understory biomass production of 25 T/ha (or an annual production of 2.5 T/ha/yr) would provide a commercially operable quantity to harvest as fuel. In addition to producing a renewable fuel resource, the harvests would also provide an inexpensive silvicultural treatment, as an alternative to herbicides, for controlling competing vegetation in pine stands.

Optimal time of the year to harvest understory biomass depends on such economic and ecological constraints as available labor, storage space, climatic and site conditions, nutrient drain, and moisture content of the biomass. Thus, in view of the seasonal differences associated with biomass production it becomes imperative to evaluate these production data on the basis of season so that proper harvesting decisions can be made.

Analysis of variance indicated that the only significant difference among the various stand/site conditions was in the forest type x stand density interaction ($p<0.05$). Further analysis revealed this statistical difference occurred for winter-harvested biomass but not for summer-harvested biomass. In winter, high density pine stands produced nearly 11 T/ha (60%) more biomass than did high density pine-hardwood stands (Table 2). This difference is due perhaps to the shading effect of the high density pine-hardwood stands that limits the understory growth.

Table 2. Duncan's Multiple Range Test for Forest Type x Stand Density Interaction on Winter-Harvested Understory Biomass.

Forest Type	Stand Density	Biomass (T/ha)[1]
Pine	High	28.7 a
Pine-Hardwood	Low	24.6 b
Pine	Low	20.0 c
Pine-Hardwood	High	17.9 d

[1] Means with different letters are significantly different at $p<0.05$.

Understory Biomass Prediction

Based on the biomass yields from the 720 subplots, a predictive model was developed using a step-wise multivariate regression analysis on all stand/site variables. The following regression was selected as the predictive model:

$$W = 4.6237 + 7.4846X_1 + 17.1133X_2 + 31.5087X_3 + 56.3872X_4$$

Where: W = predicted dry weight of biomass in T/ha
X_1 = number of stems in the 5 cm (2 in) dbh class
X_2 = number of stems in the 7.5 cm (3 in) dbh class
X_3 = number of stems in the 10 cm (4 in) dbh class
X_4 = number of stems in the 12.5 cm (5 in) dbh class

The regression coefficient for the prediction equation was 0.85, a respectable value considering the wide range of biomass in the diverse stand/site conditions. To implement the model, all woody vegetation in the 4-14 cm (1.6-5.5 in) dbh classes should be inventoried from one "representative" 3.05 m x 3.05 m (10 ft x 10 ft) plot. Entering the number of stems in their respective dbh classes into the equation will give a predicted dry weight of understory biomass in T/ha. Average tonnage values derived from a series of sample plots would improve the prediction, particularly when stands or understory vegetation are not homogeneous.

Understory Biomass Nutrient Content

Nutrient contents in the understory biomass, which are analogous to nutrient removal in later discussions, were calculated from concentration values and corresponding biomass dry weights. A series of analyses of variance were conducted for each element using a split-plot factorial model. All elements were found to be significantly higher in biomass harvested in the summer than in biomass harvested in the winter (Table 3). This was primarily the result of high foliar nutrient contents during summer; the deciduous hardwood foliage had fallen prior to the winter harvest.

Table 3. Seasonal Differences in Nutrient Contents (kg/ha) in Understory Biomass.

Nutrient Element	Summer Biomass	Winter Biomass	Difference (%)
N***	86	67	28
P***	9	6	50
K***	72	38	89
Ca***	161	112	44
Mg**	14	11	27

***Indicates significant difference at $p<0.01$
** Indicates significant difference at $p<0.05$

Soil Nutrient Status

Soil nutrient (N, P, K, Ca, and Mg) concentrations were determined for each plot. The average of these values across all stand/site conditions were then converted to values representing the nutrient pool in Kg/hectare-furrow-slice (Kg/ha.f.s.) by season. These values are shown as "Nutrient Pool" in Table 4, which illustrates possible magnitude of nutrient drain associated with biomass harvesting. The NP/NR ratios indicate that a shortfall would likely occur with P, K, and Ca following repeated harvests. However, natural inputs from atmospheric deposition, mineralization of parent material, and decomposition of organic matter may sufficiently replenish these elements in the nutrient pool. Further, if these elements were in critical supply, the winter harvest would be nearly twice as conservative as the summer harvest.

Table 4. Ratios of Soil Nutrient Pool and Nutrient Removal by Season.

Nutrient Element	Nutrient Pool (Kg/ha.f.s.)	Nutrient Removal (Kg/ha)	Ratio (NP/NR)
	Summer Harvest		
N	1,486	86	17.1
p	10	9	1.1
K	112	72	1.5
Ca	542	161	3.4
Mg	143	14	10.2
	Winter Harvest		
N	1,419	67	21.2
P	9	6	1.5
K	126	38	3.3
Ca	646	112	5.8
Mg	159	11	14.4

Results indicate there is no difference in understory biomass production between summer and winter harvests. Since summer-harvested biomass contains significantly more nutrients and water, it would be logical to recommend a winter harvest of this material to reduce nutrient drain on the site and to lessen the costs of transporting the chipped biomass because of its lower moisture content.

MASSAHAKE WHOLE TREE HARVESTING METHOD FOR PULP RAW-MATERIAL AND FUEL - R&D IN 1993 - 1998

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ABSTRACT

In Finland biofuels and hydropower are the only indigenous fuels available. Peat, wood and wood derived fuels form about 18 % of total primary energy requirement (30 mill. toe in 1991). The largest wood and wood fuel user in Finland is wood processing industry, namely paper- and pulp mills together with sawmills.

Due to silvicultural activities the growth of forests has developed an instant need for first thinnings. This need is about 12 %/a of total stem wood growth. With conventional harvesting methods this would produce about 8 mill. m^3 pulp raw material and 2 mill. m^3 wood fuel. By using integrated harvesting methods about 12 mill. m^3 pulp raw material and 8 mill. m^3 (about 1,3 mill. toe) fuel could be produced.

At the moment, there is no economically profitable method for harvesting first thinning trees for industrial use or energy production. Hence, there are a few ongoing research projects aiming at solving the question of integrated harvesting.

MASSAHAKE chip purification method has been under R&D since 1987. Research with continuous experimental line (capacity 5 - 10 loose-m^3) has been done in 1991 and 1992. The research has concentrated on pine whole tree chip treatment, but preliminary tests with birch whole tree chips has been done. The experiment line will be modified for birch whole tree chips during 1993.

Based on the research results more than 60 % of the whole tree chips can be separated to pulp raw material with < 1 % bark content. This amount is 1.5 - 2 times more than with present technology. The yield of fuel fraction is 2 - 4 times higher compared to present methods. Fuel fraction is homogeneous and could be used in most furnaces for energy production. By replacing fossil fuels with wood fuel in energy production it is possible to reduce CO_2-emissions significantly.

This paper presents the wood fuel research areas in Finland and technical potential of MASSAHAKE-method including the plan for building a demonstration plant based on this technology.

1. INTRODUCTION

Wood fuels are commonly used for energy production both in developing and industrialized countries. Industrialized countries often get their wood derived fuels as by-product from processes. The present harvesting methods are mainly concerning on raw material production, and wood for fuel purposes is harvested separately, if harvested at all.

Concern over global warming is intensifying the search for ways to use more biomass in energy production in industrialized countries. These energy questions are a part of the strategies of the 1990's.

Like in many countries, also in Finland there is a common interest to increase the production and use of wood fuels significantly till the beginning of the year 2000. Also the competitiveness and use of fuel peat are being improved by developing production methods and due to more effective methods also decreasing the production costs. The increase in the use of biofuels is an important part of the energy strategy in Finland. It is also the main goal of the new Bioenergy-Research Program, launched 1/1993.

New technologies for peat production and biomass combustion, primarily various fluidized bed applications have been developed and used during the past few years. Special effort is devoted to make also wood fuels more competitive.

2. FOREST RESOURCES

Forest resources in Finland have increased significantly during the last few decades. At present there are 22 million hectares of forest area in Finland. This is about 72 % of the total land area. The growth and the volume of the stem wood reached their rapid growth speed in the end of the 1960's. This is due to the systematic forestry and silvicultural programme. During the last decades old slowly growing forests have been replaced with fast growing young forests. Also the ditching of bogs in forest areas, systematic thinnings of forests and fertilizing are explaining the increase in growth.

Since the 1970's the yearly growth of forest biomass has exceeded the yearly removal of trees. It has been estimated that during 1985 - 1989 the growth of forests has been about 25 million m^3 greater than removal. This corresponds to about 5 million toe/a or 18 million t_{CO2}. If the ratio of removal and remaining forest biomass remains the same, in Finland the volume of growing stem wood will be doubled in less than 50 years. Annual biomass growth is estimated to be about 13 0million m^3 (20 million toe; 92 million t_{CO2}) of which the portion of stem wood, including bark, is about 79 million m^3.

Wood processing industry uses 60 - 65 % of the biomass of the whole tree. The rest is logging residue and small wood and it is usually left behind in the forests although it could well be used in energy production. The amount of biomass, which is not systemically harvested (forest residues etc.) in Finland is estimated to be about 45 million m^3/a, corresponding to about 9 million toe or 30 million t_{CO2}.

The situation appears to be very similar to Finland in some of the most important pulp and paper producing countries in Europe. There, too, the annual growth of the forests is somewhat greater than the annual cutting, although the ratio between the annual growth and cuttings is remarkably smaller in most countries. There is reason to ask wether we can affort to waste such valuable raw material and fuel by leaving most of the wood biomass into the forests as leftovers from harvesting? Should we instead make use of all the available wood and process it further in order to add its value, rather than just waste it? Table 1 presents the basic information of several pulp producing countries in the world.

TABLE 1. Forests in Various Countries.

(1989 level) Country	U.S.A	Canada	Finland	France	Germany fr	Italy	Japan	Spain	Sweden
Total energy consumption (Mtoe)	1945.5	219.7	29.2	218.1	271.6	153.5	85.4	86.4	47.8
Total electricity consumption (TWh)	2795	474	60	346	412	233	755	139	139
Total Land Area (1000 km2)	9167.0	9921.0	305.0	550.0	244.0	294.0	377.0	499.0	412.0
Forest Area (mill.ha)	294.0	358.0	23.2	14.8	7.4	6.7	25.1	15.7	28.0
Forest Area %	32.1	36.1	76.2	26.9	30.3	22.9	66.7	31.3	68.1
Growing stock (mill.m3)	30000	24000	1880	1623	1062	637	2860	542	2425
Annual Increment of total biomass* (mill.m3)	1100	600	135	104	73	24	n.a.	60	137
Annual increment (stock mill.m3)	635	360	79	61	43	14	n.a.	35	80
of which: coniferous trees	550	260	61045	26500	32500	4560	n.a.	23886	64325
non-coniferous	440	100	17955	34150	10300	9220	n.a.	10584	15141
Annual Use (mill.m3)	498.0	155.0	48.6	42.6	35.0	9.7	30.0	16.1	52.8
Annual Growth - Use (mill.m3)	137.0	205.0	30.4	18.1	7.8	4.1	n.a.	18.4	26.7
Fuelwood + Charcoal production (1000m3)	116268	6834	2984	10436	3656	4177	523	2590	4424
Pulpwood production (1000m3)	140300	45515	22960	10812	12457	878	10901	9149	28307
Pulpwood imports (1000m3)	1806	847	5912	547	1642	2212	n.a.	757	7224
Pulpwood exports (1000m3)	7783	2977	389	3457	3975	2	n.a.	209	840
n a = not available	theoretical								

	World	Asia	N.C. America	Europe	USSR	Others
Fuelwood + Charcoal production (1000m3)	1796164	802780	172139	54942	80700	685603
Pulpwood production (1000m3)	434078	22095	188790	125157	42800	55236
Pulpwood imports (1000m3)	52401	20702	2662	29037	n.a	0
Pulpwood exports (1000m3)	53812	1013	10760	17653	10605	13781

3. ENVIRONMENTAL ASPECTS OF BIOENERGY

Environmental regulations are receiving more attention all the time. Most regulations concern the amount of harmful emissions to the atmosphere. The approach to air pollution control varies among countries, but emission limits based on the best technology available are gaining more general acceptance. The tendency is for more stringent emission requirements, alongside with the advances made in developing new technology.

If we look at the international agreements, there are several topics related to environmental questions:

- SO_x -emissions must decrease from the 1980 level by 80 % during the next ten years.
- NO_x-emissions must decrease from the 1980 level by 30 % until year 1998 (Sofia 1988).
- CO_2- and other greenhouse gases should stabilize to the level of the late 1990's till the beginning of the year 2000 (Rio 1991).

In Finland about 75 % of the total of SO_2-emissions and 40 % of NO_x-emissions was due to energy production in the country. The amounts of SO_2- and NO_x-emissions from over 1 MW wood and bark fired boilers were insignificant compared to other boilers.

The CO_2-emissions from energy production could be restricted by using biofuels in energy production. The increase in the use of biofuels effects also to the silvicultural condition of forests, increases self sufficiency in energy production and creates new facilities for increasing employment and economical growth.

4. R&D - THE WAY TO INCREASE BIOFUEL UTILIZATION

In the 1st of June in 1992 Finnish Ministry of Trade and Industry (KTM) gave an assignment for Technical Research Centre of Finland (VTT) to plan the program of the new Bioenergy Research Program for the years 1993 - 1998. This Research Programme was launched in the beginning of 1993.

The business idea of the Bioenergy Research Programme is by means of technological research and development to increase economically profitable and environmentally safe use of bioenergy to improve competitiveness of present peat and wood fuels and to develop new competitive equipment for bioenergy. One of the main goals for Bioenergy Research Programme is to develop new wood fuel production methods so that the fuel produced is competitive with imported fuels.

The Finnish Ministry of Trade and Industry will fund the Bioenergy Research Programme by about US$ 3.2 million and the Ministry of Agriculture and Forestry with US$ 0.3 M in 1993. The funding from industry and other sources will be about US$ 2.4 M in 1993. The total final target funding for the research programme is US$ 42 M for the years 1993 - 1998.

The following entireties are the main research areas of the Bioenergy-Research Programme:

- the production of wood fuels
- peat production
- the use of bioenergy
- further processing of biomass.

In addition the Bioenergy-programme could include separate projects concerning the production of biofuels on the fields and using the solid wastes and liquids in energy production.

The main goals of Bioenergy-research programme are:

- to develop new production methods for wood fuels in order to decrease the production costs to the level of imported fuels (on site costs about 10 US$/MWh). The total potential of the wood fuel use should be at least 1 million toe/a.
- to increase the competitiveness of peat fuels by decreasing the production costs by 20 % and reducing the waste water load of peat production to the level of natural bog and also by reducing other environmental load significantly.
- To demonstrate 3 - 4 new applications concerning the production and use of biomass.
- The treatment research produces basic research results about the treatment of biomass, evaluates the quality, usability, environmental effects of use and the total economy of different products.

Those production methods that fulfill the targets of research will be demonstrated.

5. THE RESEARCH AND DEVELOPMENT OF WOOD FUELS IN FINLAND

The share of wood fuels in Finland's energy production is significant. About 45 TWh/a of total energy requirement is produced with wood and wood derived fuels. Roughly one half of this amount is waste liquor from industry and the other half mainly waste wood from the wood industry and firewood. The total share of wood derived fuels in energy production in Finland is about 14 %.

During the last few years the common interest in using biomass in energy production has increased significantly. The new Bioenergy-Research Programme is planned to be the driving force in this area. Figure 1 presents the main topics of wood fuel research in Finland for the years 1993 - 1998.

The most important research area within the Bioenergy research programme is the development of production technology of wood fuels, which could be divided into integrated and separated production methods of wood raw-material and wood fuel.

The most promising techniques presented in Table 2 are the MASSAHAKE-method and the chain flail system. These techniques are already in the pilot phase (MASSAHAKE) and in machinery development phase (chain flail system). In the following the research results with MASSAHAKE-experiment line are presented.

TABLE 2. The plan of the Bioenergy-Research Programme - Main Topics for Wood Fuels.

INTEGRATED HARVESTING	93	94	95	96	97	98
THE BASICS OF INTEGRATED HARVESTING	The separation and properties of wood fraction, the basic research of chipping and separation					
THE HARVESTING OF UNLIMBED TREES	Present	Pilot	Demonstration	Commercial		
			New methods			
THE TREATMENT OF WHOLE TREE CHIPS	Pilot, pine		Demo, pine		Commercial	
CHEMICAL PULP	Pilot, birch and spruce		Other species	Demo, birch	Spruce	Commercial
		Industrial raw material, improvement of the quality of the pulp and yield				
MECHANICAL PULP	Preliminary research	Laboratory research	Pilot, spruce, other species			Demo, spruce
CHAIN DELIMBING AND DEBARKING ROAD-SIDE LANDING	Machinery	Pilot	Demo, pine, spruce	Commercial		
TERMINAL	Plant	Pilot	Demo, pine, spruce	Birch	Commercial	
DRUM DELIMBING-DEBARKING	Present	Pilot	Demo, coniferous, birch	Commercial		
WOOD TREATMENT PLANTS	Consepts and preliminary research		Pilot	Demo	Commercial	
SEPARATE HARVESTING						
HARVESTING RESIDUES	Present	Pilot	Demo	Commercial		
			New methods			
SMALL SIZED TREE HARVESTING BY - OWNER	Present	Pilot	Demo	Commercial		
- CONTRACTOR	Present	Pilot	Demo	Commercial		

6. MASSAHAKE-METHOD

The first researches with the continuous MASSAHAKE-experiment line were concluded during the years 1991 and 1992. Suitability of this method in fines and bark separation from whole tree chips was proven during these experiments. The main features in this method are the grinder, which separates the bark from a single wood chip, pneumatic separator, which separates most of the needles and leaves together with fined bark. Mechanical screen secures the separation of fines and finally optical sorter secures the quality of pulp chips (Fig.1).

In the research was found out that < 1% bark content in pulp chips could be achieved with the yield of 60-65%. The yield received for pulp and fuel fractions were significantly higher than those achieved with present methods. The results showed as well that 20-40% of the total tree biomass are achieved as fuel fraction, without losing any of the pulp chip fraction (Fig. 2).

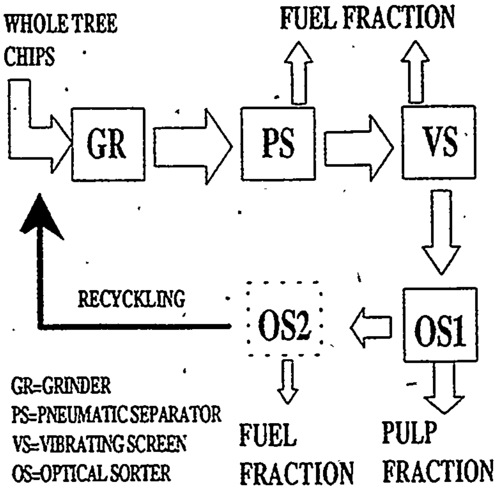

Figure 1. The flowgraph of MASSAHAKE-method.

The heating value of the fuel fraction was defined to be about 20 MJ/kg(dry matter). The average fuel fraction size was found to be 3-4 mm and 90% of it was under 6 mm.

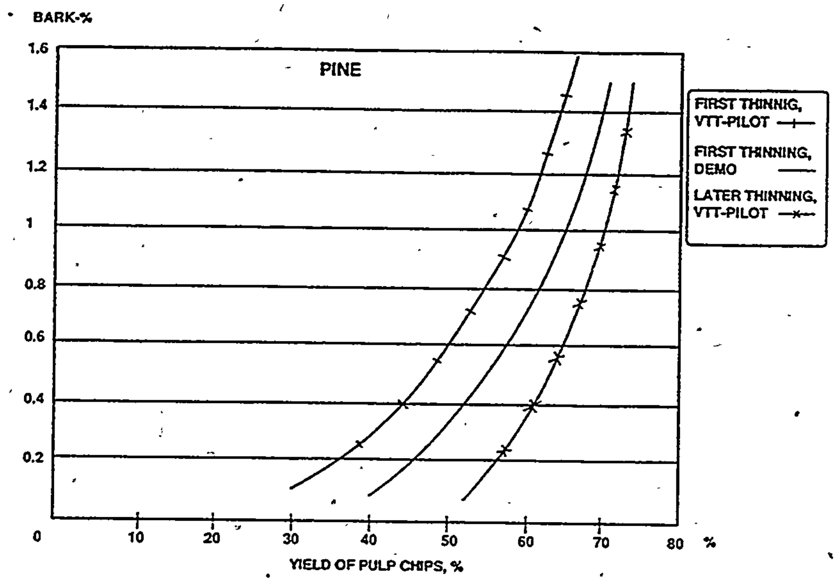

Figure 2. The yield of pulp fraction and fuel.

In the pulp fraction the particle size distribution was found to be longer than 7 mm but thinner than 8 mm (85-90%).

The fuel fraction from the treatment process can be used as fuel in most boiler applications for fossil fuels or new combustion methods. It has been estimated that if all the chemical and paper mills in Finland would use this method the net increase in electricity production in Finland could be with modern combustion methods even about 900 MW_e.

At present the average electricity production in pulp and paper industry is about 670 MW_e. Including the mechanical pulp mills the amount of purchased electricity would decrease from present 11.5 TWh/a to 4 TWh/a if MASSAHAKE-method is used both in raw material production. The potential of integrated harvesting in various sized pulp mills is presented in Table 3.

The decision about constructing the first commercial plant, based on MASSAHAKE-method, will be done during this year. This plant will be in commercial use in the end of 1994.

TABLE 3. Wood Fuel Potential in Various Mill Sizes With Integrated Harvesting

	Pulp mill size (t/a)					
	50000	100000	150000	200000	250000	300000
CONIFEROUS TREES:						
use of wood for pulp (t/a)	104651.2	209302.3	313953.5	418604.7	523255.8	627907.0
bark content (w-%)	9.3	9.3	9.3	9.3	9.3	9.3
bark in used wood (t/a)	9732.6	19465.1	29197.7	38930.2	48662.8	58395.3
WHOLE TREE HARVESTING:						
residues to power plant (t/a)	43113.9	86227.7	129341.6	172455.5	215569.3	258683.2
bark+residues (t/a)	52846.4	105692.8	158539.3	211385.7	264232.1	317078.5
LCV (MJ/kg; w=50%)	8.8	8.8	8.8	8.8	8.8	8.8
energy content in fuel (MWh/a)	258567.0	517133.9	775700.9	1034267.9	1292834.9	1551401.8
NON CONIFEROUS TREES:						
use of wood for pulp (t/a)	97826.1	195652.2	293478.3	391304.3	489130.4	586956.5
bark content (w-%)	15.0	15.0	15.0	15.0	15.0	15.0
bark in used wood (t/a)	14673.9	29347.8	44021.7	58304.3	73369.6	88043.5
WHOLE TREE HARVESTING:						
residues to power plant (t/a)	42403.8	84807.7	127211.5	169467.9	212019.2	254423.1
bark+residues (t/a)	57077.8	114155.5	171233.3	227772.2	285388.8	342466.6
LCV (MJ/kg; w=50%)	10.1	10.1	10.1	10.1	10.1	10.1
energy content in fuel (MWh/a)	320525.9	641051.7	961577.6	1279077.8	1602629.3	1923155.2

NUTRIENT ENHANCED SHORT ROTATION COPPICE FOR BIOMASS IN CENTRAL WALES

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Abstract

Two projects involving short rotation willow coppice are taking place on the eastern side of the Cambrian Mountains in central Wales. One project examines, as an alternative land use, the potential of short rotation willow coppice variously enhanced by combinations of lime, phosphorous and potassium fertilizers and also digested sewage sludge on an acidic upland site at an altitude of 260m. The first year results of this project are described in detail, showing the necessity for limestone additions and also demonstrating that of the four willow varieties established, *Salix dasyclados* is the only possible, profitable fuel crop.

The other project involving willow in a filter bed system is outlined along with an additional project investigating the effect of sewage sludge additions on the *Rubus fruticosus* production in a birch dominated mixed deciduous woodland.

Introduction

Short Rotation Coppice in the United Kingdom

Research in Britain during the early 1980's identified the potential of short rotation coppice as a renewable source of fuel and also as an alternative farm enterprise (Carruthers *et al.*, 1991). The majority of research in the UK has involved the growth of coppiced poplar and willow species at very close spacing (up to 40 000 trees ha^{-1}) on a rotation of 3 to 5 years after initial cut back at the end of the first growing season to initiate coppice growth. Unrooted cuttings are planted into cultivated, weed-free land and application of residual herbicides is carried out immediately afterward. Trees can remain in production for as long as 30 years (Lees, 1991) and by planting areas of available land in successive years, annual harvesting can be achieved, giving a regular fuel source or income. Farmers wishing to establish energy forest can enter into The Forestry Authority Woodland Grant Scheme which has recently been extended to include the establishment of short rotation coppice plantations.

Short rotation coppice is seen as a good option for utilising agricultural land currently in food overproduction and afforestation of Set-Aside land has been proposed as one form of diversification in the lowlands. In order to halt the population drift from upland farming areas, profitable, alternative land uses for marginal hill land must be found. Short rotation coppice may well be one way to supplement existing farm incomes.

From an environmental point of view, coppice has it's advantages. Wood is not only CO_2 neutral, it contains only 10% of the sulphur found in coal, thus producing less acid gas per tonne.

Nutrient Enrichment

Research in Sweden, France and the UK has identified the need for fertilization on certain soils (Sennerby-Forse, 1986.,Parfitt & Stott, 1987). In Sweden a compound application of nitrogen, phosphorous and potassium is recommended the first year after planting, followed by application of nitrogen in the second year (Sennerby-Forse, 1986). French research has concluded that phosphate should be applied prior to planting, nitrogen application following after one year of growth (Touzet, 1988). Limited work has been carried out in Britain with respect to nutrient enhancement, although Parfitt and Stott, 19 have investigated the effects of nitrogen, phosphorous and potassium levels on the productivity of 13 willow clones. Both Taylor (1991) and Ledin (1986) suggest that liming on acid soils and basic fertilization with phosphorous and potassium should be carried out with amounts based on analysis of the soil.

Recent work in the UK has centered on the use of digested sewage sludge as an organic fertiliser . Each year, the UK produces over 1 million tonnes of dry solid sludge (Garvey *et al.*, 1992), approximately 25% of this is currently dumped at sea (Learner, 1990). A recent EC Directive stated that all sea dumping must cease by 1998 (Official Journal of the European Communities, 1991). Several alternative disposal methods are under investigation, these include incineration, landfill, composting and woodland application. The use of sewage sludge as a fertliser may help to replace the commercial fertilizers currently used in energy forestry thus lowering the cost of any nutrient enrichment required and also by increasing the saleable biomass produced.

Short Rotation Coppice in Central Wales

It is likely that the decline in sheep production in the uplands due to decreased EC support will lead to the release of large tracts of land. This will force farmers to diversify their interests and short rotation coppice may well prove a profitable option in upland areas such as central Wales.

Both field trials and glasshouse experiments are underway at the UWCC Llysdinam Field Centre, the purpose of which are to determine the effects of nutrient enhancement during the establishment phase of a short rotation willow coppice plantation.

Materials and Methods

Carnau Field Trial

Carnau consists of 1.5 hectares of marginal sheep grazing land. It is situated at an altitude of 260 metres approximately 1.5 kilometres north-west of Llysdinam Field Centre (SN 995597). It is within the Cambrian Mountains Environmentally Sensitive Area (ESA). Prior to cultivation the field was dominated by *Molinia caerulea* and *Juncus sp*.

Four willow cultivars were planted at Carnau in April 1992; *Salix viminalis* (Bowles hybrid), *S.x dasyclados*, *S.*delamere and *S.cinerea* (McElroy) (Stott,1991). A spacing of 0.5m * 1.0m (20 000 trees ha-*1*) was implemented as suggested by Ken Stott formerly of Long Ashton Research Station. Cultivars were divided into 12 plots of each, plots being 7m * 7m (96 trees in each). Residual herbicide application followed immediately after planting. Fertiliser application took place in June, phosphorous being applied as basic slag giving 60kg P ha^{-1} and potassium as muriate of potash giving 100kg K ha^{-1} (Taylor,1991). Magnesium limestone was applied at a rate of 10 tonnes ha^{-1} to half the fertilised plots as the field site has a very low pH (range 3.15-5.17).

A sample of three trees was taken randomly from each plot at the end of the growing season prior to leaf fall and leaf area indexes calculated. During December, all stems in all plots were cut back and a total biomass for each plot recorded.

Glasshouse Experiment

Using the same four cultivars as at Carnau, a series of pot experiments were set up in triplicate. For each of the cultivars six treatments were implemented:-

(1) 60kg P ha^{-1} & 100kg K ha^{-1}
(2) 60kg P ha^{-1} & 100kg K ha^{-1} & 10 t MgCO$_3$ ha^{-1}
(3) 100 m^3 digested sewage sludge ha^{-1}
(4) 200 m^3 digested sewage sludge ha^{-1}
(5) 300 m^3 digested sewage sludge ha^{-1}
(6) 100 m^3 digested sewage sludge ha^{-1} & 10t MgCO$_3$ ha^{-1}
NB. Fertilizers were applied at the same rates as at Carnau.

The nutrient value of the sewage sludge was as follows:-

% dry solids	3.53
K(% dry solids)	0.05
P(% dry solids)	0.88
N(% dry solids)	4.01

Two sets of controls were also established for each cultivar. Each 28cm diameter pot was filled to a standard with well mixed soil from the Carnau field site and one unrooted cutting planted in each. The resultant 96 pots were arranged randomly in the glasshouse. Soil samples were taken regularly from each pot for nutrient cycling work, those results will not however feature in this paper. Similarly, extension growth measurements were recorded weekly throughout the growing season. At the end of the growing season total cut back took place and aboveground wet biomass was measured. Shoots were then dried at 105^{o}C to constant weight to give the dry weight of each stem.

Results

Carnau Field Trial

The mean Leaf Area Indices and their respective standard deviations in parenthesis for all combinations of willow cultivar and treatment can be seen in table 1.

Table 1 - Leaf Area Indices

	Willow Cultivar			
Treatment	S.viminalis	S.dasyclados	S.Delamere	S.cinerea
Control	0.0144 (0.0100)	0.1659 (0.0904)	0.1372 (0.1678)	0.1078 (0.0492)
P & K	0.0718 (0.0638)	0.2807 (0.0604)	0.1021 (0.0257)	0.1193 (0.1224)
P & K & Lime	0.0557 (0.0245)	1.0220 (0.6260)	0.1908 (0.0595)	0.1407 (0.0136

Analysis of Variance of Leaf Area Index

	DF	F	P
CULTIVAR	3	19.93	0.000
TREATMENT	2	7.21	0.002
CULT*TREAT	6	1.21	0.322

Least significant difference = 0.443

NB. A logarithmic transformation of the data was required in order to meet the assumptions of homogeneity of variance and normality of residuals.

The mean wet biomass calculations, standard deviations and the resultant analysis of variance can be seen below in table 2.

Table 2 - Wet tonnes ha^{-1}

	Willow Cultivar			
Treatment	S.viminalis	S.dasyclados	S.Delamere	S.cinerea
Control	0.119 (0.048)	1.020 (0.647)	0.249 (0.304)	0.386 (0.193)
P & K	0.358 (0.330)	0.859 (0.512)	0.426 (0.170)	0.151 (0.080)
P & K & Lime	0.500 (0.249)	2.580 (1.649)	0.678 (0.172)	0.394 (0.095)

Analysis of Variance of Wet Tonnes ha^{-1}

	DF	F	P
CULTIVAR	3	10.53	0.000
TREATMENT	2	6.84	0.003
CULT*TREAT	6	1.25	0.305

Least significant difference = 0.711

NB. A logarithmic transformation of the data was required in order to meet the assumptions of homogeneity of variance and normality of residuals.

Table 3 shows the percentage establishment success of all plantings at Carnau for each willow cultivar.

Table 3

Establishment Success (%)	
S.viminalis	96.0
S.dasyclados	99.4
S.Delamere	98.7
S.cinerea	98.4

Glasshouse Experiment

The mean dry weights (g) for each cultivar - treatment combination can be seen in Table 4. The analysis of variance follows this.

Table 4

	S.viminalis	S.dasyclados	S.Delamere	S.cinerea
Control	5.71	7.37	1.55	2.17
P&K	15.57	17.93	12.88	8.49
P&K&L	27.85	23.89	20.87	15.48
100m3ha-1	7.51	16.98	6.72	3.36
200m3ha-1	7.91	11.61	10.92	5.63
300m3ha-1	15.15	13.32	13.50	5.99
100m3ha-1 & L	15.33	14.01	18.66	8.87

Analysis of Variance Glasshouse Dry Weights

	DF	F	P
CULTIVAR	3	17.46	0.000
TREATMENT	7	25.48	0.000
CULT*TREAT	21	1.49	0.112

Least significant difference = 6.25

Discussion

Salix .x dasyclados proved to be the most successful cultivar in terms of biomass production at the Carnau field site, the other three cultivars producing extremely low amounts of biomass. Significant differences can be seen between the *S.dasyclados* control plots and those of *S.viminalis* and *S.*Delamere. Similarly, the *S.dasyclados* plots treated with both fertilizers and magnesium carbonate produced a significantly higher biomass than all other plots. For the three low biomass producing varieties, no significant increases in biomass production were seen with either treatment. The same differences were apparent in terms of leaf area index.

In terms of dry weight produced, the glasshouse experiment gave different results from the field, *S.viminalis* being just as succesful as *S.dasyclados*. At Carnau, *S.viminalis* was visibly affected during April and May 1992 when there was very little rainfall. The early leaves yellowed in colour and the establishment success of that cultivar was the lowest of the four. Daily watering took place in the glasshouse and the *S.viminalis* thrived. Although visible and significant differences were seen at Carnau for *S.dasyclados* alone, in the glasshouse, differences were seen for certain treatments for all cultivars (see Table 4), those trees treated with both fertilisers and limestone producing greater biomass in all cultivars.

From work to date it has been concluded that of the four cultivars investigated in central Wales, only *S.dasyclados* is worth pursuing as a possible, profitable biomass crop. The establishment success was almost 100%, for all treatments it produced over twice as much biomass as the other three cultivars and it withstood a period of drought immediately after planting. Research will continue for a further two seasons, it is thought that greater fertilizer effects will be seen the season after application. All further plantings at the field site have been accompanied by limestone additions and a field sewage sludge trial was set up in April 1993. 21 additional willow varieties were also planted at the field site at this time but with no fertilizer additions.

Other Projects Underway at Llysdinam

(1) Willow (*S.purpurea & S.viminalis*) are being utilised as two of a series of filter bed treatments for the effluent from a domestic refuse site. The longer term aim is to use the willow as both part of a filtration system and simutaneously producing a biomass crop.

(2) Application rates of digested sewage sludge of 100, 200 and 400 m3ha-1 were applied in 1991 to plots within a Birch dominated mixed deciduous woodland. The main aim of the project is to look at the effects of sewage sludge on the ground flora. The extension growth of *Rubus fruticosus* stolons was measured in 1991 and 1992. There was no significant increase in stolon length due to sludge application in 1991, but in 1992 sludge treated stolons were significantly longer than the controls.

Acknowledgements

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DEVELOPMENT AND ANALYSIS OF SRIC HARVESTING SYSTEMS

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ABSTRACT

This paper reviews several machine combinations for harvesting short-rotation, intensive-culture (SRIC) plantations. Productivity and cost information for individual machines was obtained from published sources. Three felling and skidding systems were analyzed for two stands, a 7.6-cm (3-in) average d.b.h. sycamore and a 15.2-cm (6-in) average d.b.h. eucalyptus. The analyses assumed that whole trees were chipped at roadside.

Costs and production were summarized for each system. The systems were: (1) Continuous-travel feller-buncher, skidder, and chipper; (2) 3-wheel feller-buncher, skidder, and chipper; (3) chainsaw, skidder, and chipper. In the 7.6-cm stand, system productivities were 9.9, 7.3, and 7.5 BDLT/SMH, and costs were $20.9, $20.8, and $18.0 per BDLT for the three systems, respectively. System production rates for the 15.2-cm stand were 24.3, 10.2, and 12.5 BDLT/SMH, and costs were $8.7, $10.9, and $13.2 for systems 1, 2, and 3, respectively.

INTRODUCTION

Timber harvesting consists of several functions that must balance to assure efficiency. Harvest and transport costs depend in part on tree size, volume removed, transport distance, and type of product. But total cost per unit of product is influenced by machine cost and system efficiency.

This paper reviews several machine combinations for harvesting short-rotation, intensive-culture (SRIC) plantations. Several machine combinations are incorporated into systems and costs are estimated. The analysis is based on studies and simulations conducted in 7.6-cm (3-in) d.b.h. sycamore (*Platanus occidentalis L.*) stands in south Alabama and 10.2-cm (4-in) to 15.2-cm (6-in) d.b.h. eucalyptus (*Eucalyptus camaldulensis*) plantations in central California (Stokes et al. 1986; Woodfin et al. 1987; Hartsough 1990; Hartsough and Nakamura 1990).

MACHINE REVIEW

Harvesting small stems requires highly efficient felling and bunching. Bunching stems facilitates subsequent wood removal. Chainsaw felling may cost less than machine felling but, without bunching, may increase total cost. Also, chainsaw felling is more hazardous and less productive than mechanical felling, making it more difficult to recruit and retain workers. Moreover, mechanical felling and bunching are more commensurate with the other mechanical functions in the system.

For this analysis we used three felling options: chainsaw, 3-wheel feller-buncher with shear, and a continuous-travel feller-buncher with saw. The 3-wheeler has two drive wheels in front and a free castering wheel in the rear. A continuous-travel feller-buncher with a sawhead was represented by a prototype unit tested in 1985 (Stokes et al. 1986) for harvesting SRIC plantations with tree diameters of about 17.8 cm (7 in) at the stump.

A small (77 hp) and a medium (100 hp) grapple skidder were used for skidding. Two farm tractors, approximately 35 hp, were used; one was equipped with a grapple and the other with a winch. Farm tractors may be a low-cost option for seasonal operations where they can be used for other work the rest of the year.

A medium chipper (400 hp) was used for all processing, producing whole-tree chips (wood, bark, and foliage).

METHODS

Productivity and cost information was obtained from published sources. The information was compiled to develop harvesting systems for two representative short-rotation stands: a 7.6-cm (3-in) and a 15.2-cm (6-in) average d.b.h. Various options for felling, extracting, and processing were combined into systems. Then the systems were balanced, by adjusting the number of machines.

The production rate for a system composed of several machines is limited to the least productive function in the system. There are several ways to balance the functions in a system. One way is to increase productivity or increase SMH of the limiting function. Another way is add machines. Balanced systems have lowest costs.

In the analysis, scheduled machine hours (SMH) is the time a machine is scheduled to work - 8 hrs per day. Productive machine hours (PMH) is the time a machine actually does productive work. The ratio of productive time to scheduled time is utilization. Harvesting machines operating year-round generally have utilization rates of 65 to 95 percent. In this analysis units of production were BDLT, bone dry long tons (BDST, bone dry short tons); 50 percent moisture content (wet basis) was used in the conversion.

Machine costs depend on the utilization rate of the machine and how it is utilized in the system. In this analysis, a machine rate is used. Machine rate is the average owning-and operating-cost based on assumed use over the life of the machine (Miyata 1980; Brinker et al. 1989).

COST AND PRODUCTION SUMMARY

In the analyses, some piling time was added for the chainsaw felling when cutting in the 7.6-cm (3-in) trees. All trees were assumed to be taken to the deck whole and chipped with a medium-sized chipper.

Table 1 summarizes the production and cost for each function by machine type and tree size. Costs include labor at $10.00 per SMH. The highest cost machines per SMH were the continuous-travel feller-buncher, medium-sized skidder, and chipper. The lowest were the small tractor and manual felling. These were the individual costs for one machine only, and do not reflect the costs in a balanced system.

The effect of system balancing is demonstrated in Table 2. In this example, for 15.2-cm (6-in) d.b.h. trees, the 3-wheel feller-buncher, small skidder, and chipper are used. When only one machine is used in each function (upper section of table), the system production is 3.7 BDLT/SMH (4.1 BDST/SMH) and the system cost is $27.6/BDLT ($24.6/BDST).

Table 1. Estimated Machine Production and Cost

	Util.		BDLT/SMH (BDST/SMH)				$/BDLT ($/BDST)			
	(%)	$/SMH	7.6 cm (3 in)		15.2 cm (6 in)		7.6 cm (3 in)		15.2 cm (6 in)	
Felling										
Continuous FB	70	39.9	6.0	(6.7)	27.5	(30.8)	6.6	(5.9)	1.5	(1.3)
3-Wheel FB	70	25.3	3.7	(4.1)	10.2	(11.4)	6.9	(6.2)	2.5	(2.2)
Chainsaw	60	11.3	2.8	(3.1)	3.1	(3.5)	4.0	(3.6)	3.6	(3.2)
Extraction										
Small skidder	80	26.0	3.7	(4.1)	-	-	6.9	(6.2)	-	-
Medium skidder	80	36.2	4.8	(5.4)	12.1	(13.6)	7.5	(6.7)	3.0	(2.7)
Small tractor w/grapple	80	14.6	1.2	(1.4)	-	-	11.6	(10.4)	-	-
Small tractor w/winch	80	23.2	2.8	(3.1)	4.6	(5.1)	8.4	(7.5)	5.2	(4.6)
Processing										
Medium chipper	75	49.5	9.9	(11.1)	13.0	(14.6)	5.0	(4.5)	3.8	(3.4)

Note: SMH is scheduled machine hours; BDLT is bone dry long tons and BDST is bone dry short tons; Costs include labor ($10/SMH); Chainsaw felling also includes hand piling. Tractor w/winch includes hook setter.

Table 2. Balancing a Typical System

	Machine			System					
	BDLT /PMH	(BDST (/PMH)	Util. (%)	No. mach.	BDLT /SMH	(BDST /SMH)	$/ SMH	$/ BDLT	($/ BDST)
3-Wheel FB	5.3	(5.9)	70	1	3.7	(4.1)	25.3	6.9	(6.2)
Small skidder	4.7	(5.3)	80	1	3.8	(4.2)	26.0	7.1	(6.4)
Medium chipper	13.2	(14.8)	75	1	9.9	(11.1)	49.5	13.5	(12.1)
System					3.7	(4.1)	100.8	27.6	(24.6)
3-Wheel FB	5.3	(5.9)	70	2	7.3	(8.2)	50.6	6.9	(6.2)
Small skidder	4.7	(5.3)	80	2	7.5	(8.4)	52.0	7.7	(6.4)
Medium chipper	13.2	(14.8)	75	1	9.9	(11.1)	49.5	6.8	(6.0)
System					7.3	8.2	152.2	20.9	(18.6)

Note: BDLT is bone dry long tons; BDST is bone dry short ton; PMH is productive machine hours; SMH is scheduled machine hours; Utilization is PMH/SMH; Costs are rounded to nearest whole numbers and summations may not add.

There is excess chipping capacity and a high chipping cost. By adding two felling and two skidding units, (lower section of table), the balanced system's productivity is 7.3 BDLT/SMH (8.2 BDST/SMH) and the system cost is $20.9/BDLT ($18.6/BDST).

This process was used to develop balanced systems for other options. A summary for the 7.6-cm (3-in) d.b.h. stand is shown in Table 3 for the three felling options and small skidder. The small skidder was used because it was more cost efficient. Other machine combinations from Table 1 can be used to derive costs for other systems.

All the systems in Table 3 were balanced with only one chipper. Two felling units were required when using mechanical felling and bunching. Three chainsaw operators were needed to balance the manual system. Three skidders were needed to balance the continuous-travel feller-buncher system; only two were required to balance the other systems.

The chainsaw system was more cost effective with the medium chipper. It was assumed that the skidding productivity was the same for chainsaw-felled trees as for mechanically-felled trees. The chainsaw option assumed hand piling, although it may be impossible to maintain such productivity using hand piling. Also, there are safety problems associated with chainsaw use.

Table 3. Systems for 7.6-cm (3-in) D.b.h. Stands

	Machine			System					
	BDLT /PMH	(BDST (/PMH)	Util. (%)	No. mach.	BDLT /SMH	(BDST /SMH)	$/ SMH	$/ BDLT	($/ BDST)
Continuous FB	8.5	(9.5)	70	2	12.0	(13.4)	79.7	8.0	(7.2)
Small skidder	4.7	(5.3)	80	3	11.2	(12.6)	78.1	7.9	(7.0)
Medium chipper	13.2	(14.8)	75	1	9.9	(11.1)	49.5	5.0	(4.5)
System					9.9	(11.1)	207.3	20.9	(18.7)
3-Wheel FB	5.3	(5.9)	70	2	7.3	(8.2)	50.6	6.9	(6.2)
Small skidder	4.7	(5.3)	80	2	7.5	(8.4)	52.0	7.1	(6.4)
Medium chipper	13.2	(14.8)	75	1	9.9	(11.1)	49.5	6.8	(6.0)
System					7.3	(8.2)	152.2	20.8	(18.6)
Chainsaw	4.6	(5.2)	60	3	8.3	(9.3)	33.8	4.5	(4.0)
Small skidder	4.7	(5.3)	80	2	7.5	(8.4)	52.0	6.9	(6.2)
Medium chipper	13.2	(14.8)	75	1	9.9	(11.1)	49.5	6.6	(5.9)
System					7.5	(8.4)	135.3	18.0	(16.1)

Note: BDLT is bone dry long tons; BDST is bone dry short tons; PMH is productive machine hours; SMH is scheduled machine hours; Utilization is PMH/SMH; Chainsaw felling also includes hand piling; Costs are rounded and summations may not add.

Table 4 summarizes the options used for the 15.2-cm (6-in) d.b.h. stand. Again, the same three felling options were used with the medium-sized chipper. The chainsaw system was matched with a small tractor using a winch. This combination was used because it is very difficult to hand bunch such large stems, and a winch is more efficient than a grapple for unbunched stems. Two chippers were required to balance the continuous-travel felling option. A larger chipper could probably be used in lieu of the two medium-sized chippers. Only one chipper was needed in the other systems. The high-production, continuous-travel feller-buncher system also required two skidders. The chainsaw system needed three tractors to balance it.

The system costs ranged from a low of $8.7/BDLT for the continuous-travel feller-buncher to a high of $13.2/BDLT for the manual system.

CONCLUSIONS AND COMMENTS

The least expensive harvesting system for the 7.6-cm d.b.h. stand used chainsaw felling. This system was cost effective but not highly productive and is hazardous to chainsaw operators. In the 15.2-cm d.b.h. stand, the lowest cost combination included a specialized continuous-travel feller-buncher. It cost 40-140 percent more to harvest the 7.6-cm d.b.h. stand than the 15.2-cm d.b.h. stand.

This analysis examined only cost to roadside. It did not include overhead for moving equipment, crew transportation, service truck and tools, profit, or transportation to the mill. It was based on several assumptions and limited data on operating systems. The systems were also limited to the production of whole-tree chips.

The analysis was based on year-round logging. It may be necessary to harvest SRIC stands only in the dormant season to ensure good coppice. Reducing the working period or working only part-time would increase costs unless the equipment could be used in other applications.

Table 4. Systems for 15.2-cm (6-in) D.b.h. Stands.

	Machine			System					
	BDLT /PMH	(BDST /PMH)	Util. (%)	No. mach.	BDLT /SMH	(BDST /SMH)	$/ SMH	$/ BDLT	($/ BDST)
Continuous FB	39.4	(44.1)	70	1	27.5	(30.8)	39.9	1.6	(1.5)
Medium skidder	15.3	(17.1)	80	2	24.3	(27.2)	72.3	3.0	(2.7)
Medium chipper	17.3	(19.4)	75	2	26.1	(29.2)	99.0	4.1	(3.6)
System					24.3	(27.2)	211.4	8.7	(7.8)
3-Wheel FB	14.6	(16.3)	70	1	10.2	(11.4)	25.3	2.5	(2.2)
Medium skidder	15.3	(17.1)	80	1	12.1	(13.6)	36.2	3.5	(3.2)
Medium chipper	17.3	(19.4)	75	1	13.0	(14.6)	49.5	4.9	(4.3)
System					10.2	(11.4)	111.1	10.9	(9.7)
Chainsaw	5.2	(5.8)	60	4	12.5	(14.0)	45.0	3.6	(3.2)
Small tractor w/winch	5.7	(6.4)	80	3	13.7	(15.3)	69.8	5.6	(5.0)
Medium chipper	17.3	(19.4)	75	1	13.0	(14.6)	49.5	4.0	(3.5)
System					12.5	(14.0)	164.3	13.2	(11.7)

Note: BDLT is bone dry long tons; BDST is bone dry short tons; PMH is productive machine hours; SMH is scheduled machine hours; Utilization is PMH/SMH; Chainsaw felling also includes hand piling; Tractor w/winch includes hook setter; Costs are rounded and summations may not add.

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CARBON AND NITROGEN DISTRIBUTION IN OAK-HICKORY FORESTS DISTRIBUTED ALONG A PRODUCTIVITY GRADIENT

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Abstract

Biomass, carbon and nitrogen pools were determined for oak-hickory forests of varying productivity. Little information of this type is available for the central hardwood region. Six oak-hickory dominated forests were chosen to represent a range in potential site productivity as influenced by soil type, amount of recyclable nutrients and available water. Biomass, carbon and nitrogen storage were determined for the following components: above ground standing biomass, fine root biomass, forest floor organic layers and litterfall. As site productivity increased, biomass allocation to living trees increased. The total carbon sequestered at each site was dependent more on the amount of living biomass at each site rather than differences in carbon concentrations within the same tissue type at each site. Litterfall, to some extent, increased with increasing site productivity. As potential site productivity decreased, total fine root biomass increased. The data suggest that as site quality decreased fine root production and turnover may become as important in nutrient cycling as annual litterfall.

Introduction

Increases in atmospheric concentrations of carbon dioxide and other greenhouse gases are thought to be a primary cause of global climate change. Mean global temperature is expected to increase over present day levels with shifts in temperature patterns. Changes in rainfall patterns and storm intensities are also expected. The potential impact of climate change on litter quality may result in a direct change in biomass accumulation and carbon and nitrogen sequestration. Changes might also occur in the annual litterfall. Decreases in litter quality ie., increases in C:N ratio, and changes in the afore mentioned abiotic variables may cause a reduction in the rate of N mineralization that can lead to decreases in plant productivity and directly impact annual biomass accumulation and carbon sequestration. Of particular concern are forests growing on nutrient poor sites. The first step in this process of understanding potential forest responses to environmental change, is to quantify the C and N in the various soil/plant pools. Study sites are selected for oak dominated forests in Indiana to represent inherent differences along a soil moisture gradient, and consequently represent forest stands of varying productivity. The objectives are (1) to determine the amount biomass in the above-ground and below-ground components and (2) to quantify the amount of C and N in these components.

Materials and Methods

Site Characteristics

Six forest sites, with a dominant overstory of oak-hickory, are selected for study and represent a productivity gradient throughout the state of Indiana. Low productivity sites are located on the Clark State Forest in Clark Co. (Rarden silty clay loam - Clayey, mixed, mesic Aquic Hapludult) and the Jasper-Pulaski Fish and Wildlife Area in Pulaski Co. (Plainfield fine sand - Mixed, mesic Typic Udipsamment). Medium productivity sites are chosen at the Southeastern Purdue Agricultural Center (SEPAC) in Jennings Co., the Southern Indiana Purdue Agricultural (SIPAC) in DuBois Co. and Feldun Purdue Agricultural Center (Feldun) in Lawrence Co. The dominant soil type at each site, in order, is a Clermont silt loam (Fine-silty, mixed, mesic Typic Ochraqualf), a Wellston silt loam (Fine-silty, mixed, mesic Ultic Hapludalf) and a Chaneyville silt loam (Fine, mixed, mesic Typic Hapludalf). The highest productivity site is located in central Indiana at Nelson-Stokes Forest in Putnam Co. where the dominant soil type is a Russell silt loam (Fine-silty, mixed, mesic Typic Hapludalf). Site indices for oak (base age 50 years) range from 18-20 m at both Jasper-Pulaski and Clark State Forest to 28-30m at Nelson- Stokes. The forest Stands range in age from 80 to 130 years and have not been disturbed for at least 30 years. The forest sites range in basal area from 21 to 36 m^2/Ha, and the stand density ranges from 417 to 721 stems/Ha.

Procedures

Three replicated plots are established at each site. Fifteen 1/20 Ha sub-plots, five from each replicate, are used to sample vegetation. Fine root biomass is determined from 24 cores at each site, 8 in each replication. Each core measured 6.3 cm in diameter and 30 cm in depth..

Fifteen 0.5 m^2 litter traps, five from each replicate, are located in each site to determine litterfall. Standing aboveground biomass is determined from equations developed by Hahn and Hansen (1991) and Smith (1985). A Leco 600 CHN Elemental Analyzer is used to determine carbon and nitrogen concentrations in tree branches, litterfall, fine roots, residual litter, humus layers and tree bole wood.

Results and Discussion

Biomass accumulation, i.e. above ground (living trees >5 cm in diameter), is dependent on site productivity and ranged from 124,260 Kg/Ha at Clark State Forest to 243,367 Kg/Ha at Nelson Stokes (Table 1). Leaf biomass, as determined by leaf-fall, ranged from 3,349 Kg/Ha to 5,186 Kg/Ha, but the relationship to site productivity is less clearly defined than is the relationship for living trees (woody biomass). The litter and humus accumulation are dependent on litterfall and decomposition rate and generally increased with increases in productivity.

Table 1. Biomass (Kg/Ha) for Different Components at Each Site.

Component	Clark	Jasper-Pulaski	SEPAC	SIPAC	Feldun	Nelson-Stokes
Living Trees	124,260	124,765	171,914	204,980	221,483	243,367
Litterfall	4,064	3,349	4,512	5,186	4,297	5,228
Litter	4,686	3,703	5,082	7,674	5,922	6,518
Humus	5,444	7,566	15,132	10,459	9,083	11,573
Fine roots	3,365	3,760	2,541	3,792	2,688	2,133
Total	141,819	143,143	199,181	232,091	243,473	268,819

Carbon and nitrogen pools differed depending upon site conditions. As site productivity increased, total carbon sequestration increased (Table 2). This increase was due primarily to increased C storage in aboveground biomass. Total C sequestration in the living biomass and the forest floor ranged from 65,123 Kg/Ha at Jasper-Pulaski to 122,679 Kg/Ha at Nelson-Stokes. Tissue carbon concentrations appeared to be relatively independent of site quality. The total carbon sequestered at each site was dependent more upon the living biomass supported at each site rather than differences in C concentrations within the same type of tissue at the different sites. As site quality decreased, carbon partitioning to fine roots increased.

Table 2. Carbon (Kg/Ha) for Different Components at Each Site.

Component	Clark	Jasper-Pulaski	SEPAC	SIPAC	Feldun	Nelson-Stokes
Living Trees	61,496	57,180	84,633	97,161	98,737	113,214
Litterfall	2,224	1,531	2,204	2,501	2,365	2,522
Litter	2,213	1,773	2,297	3,614	2,802	2,949
Humus	1,969	2,838	5,103	2,989	2,858	3,006
Fine roots	1,641	1,801	1,206	1,765	1,230	988
Total	69,543	65,123	95,443	108,030	107,992	122,679

The N returned through litterfall ranges from 29 Kg/Ha at Jasper-Pulaski to 52 Kg/Ha at SEPAC (Table 3).

Table 3. Nitrogen (Kg/Ha) for Different Components at Each Site.

Component	Clark	Jasper-Pulaski	SEPAC	SIPAC	Feldun	Nelson-Stokes
Living Trees	882	867	1,485	1,380	2,027	1,923
Leaf-fall	37	29	52	50	46	47
Litter	59	51	85	108	80	100
Humus	86	129	239	156	144	161
Fine-roots	27	45	30	33	25	21
Total	1,091	1,121	1,891	1,727	2,322	2,252

The quality of this litter, i.e. the C:N ratio, appears to differ significantly between sites. The C:N ratio of litter has been found to alter decay rates which controls nutrient cycling. The C:N ratio of freshly fallen leaves at Jasper-Pulaski and Clark is 59:1 and 55:1 respectively. SEPAC has the lowest C:N ratio at 43:1 respectively (Table 4). These differences in C:N ratios are due primarily to different nitrogen concentrations in the freshly fallen leaves rather than to differences in carbon concentrations. As litter decomposition progresses, the C:N ratio decreases at each stage. The C:N ratio of freshly fallen leaves is consistently higher than the C:N ratio of litter, which is higher than the humus layer.

Table 4. Carbon and Nitrogen Concentrations in Litterfall, Litter and Humus from Selected Sites.

Site	Component	% C	% N	C:N Ratio
Clark	Litterfall	54.7	0.92	59
	Litter	47.2	1.25	38
	Humus	36.2	1.58	23
Jasper-Pulaski	Litterfall	49.8	0.90	55
	Litter	47.9	1.38	35
	Humus	37.5	1.71	22
Nelson-Stokes	Litterfall	47.0	1.02	48
	Litter	45.3	1.53	30
	Humus	26.0	1.39	19
SEPAC	Litterfall	48.9	1.15	43
	Litter	45.2	1.68	27
	Humus	33.7	1.58	21

As site quality decreases, fine-root biomass increased. At the lowest productivity sites, Jasper-Pulaski and Clark, total C and N contained in the fine root tissues were comparable to the amounts in the annual litterfall. As site quality increases, annual litterfall becomes increasingly more important in supplying inputs to the C and N pools. At the highest quality site, Nelson-Stokes, the C and N contained in the fine roots was less than 1/2 of that contained in annual litterfall. These results indicate, that as site quality decreases nutrient cycling via fine root production and turnover may become as important as nutrients cycled via annual litterfall.

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COMPATIBILITY OF SWITCHGRASS AS AN ENERGY CROP IN FARMING SYSTEMS OF THE SOUTHEASTERN USA

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Abstract

The objective of this paper is to examine the compatibility of switchgrass as an energy crop in farming systems in the southeastern USA, relative to other regions. In particular, the issues addressed are (1) competition between switchgrass as an energy crop and existing farm enterprises, based primarily on economic returns, (2) complementarity between switchgrass and existing farm enterprises, and (3) environmental benefits. Because projected economic returns for switchgrass as an energy crop are highest in the Southeast, and returns from forestry and beef pastures (the major existing enterprises) are low, there is a very strong economic incentive in this region. In contrast, based on current information, economic viability of switchgrass as an energy crop in other regions appears doubtful. In addition, switchgrass in the southeastern USA would complement forage-livestock production, row crop production and wildlife and would provide several additional environmental benefits. It is concluded that the southeastern USA offers the greatest opportunity for developing switchgrass as an economically viable energy crop.

Introduction

Although isolated commercial plants that convert biomass to energy in the USA are currently in operation, the concept of producing energy from biomass on a commercial scale is still in its infancy, relative to other technologies. In addition, several technologies for producing energy from biomass have not yet proceeded beyond the experimental stage. For example, the U.S. Department of Energy proposes to install commercial scale demonstration plants over the next several years for the conversion of biomass to ethanol by enzyme hydrolysis (Chum *et al*, 1991) while the private sector is investigating similar options for other technologies, such as Biomass Gassification and Fuel Cells (Anonym., 1993). The apparent intention for these demonstration units is to verify commercial viability of the technologies, thereby providing the incentive for large scale commercial development by the private sector. Clearly, the success of this whole process will depend heavily on the commercial success of the demonstration plants. Therefore, it is critically important to maximize the probability of commercial success of these plants.

Since cost of biomass production can account for close to half the total cost of energy production from biomass, this factor should be a major consideration in development of demonstration units. Clearly, cost of biomass production will be strongly related to biomass yield of energy crops, which varies widely among different regions of the United States. In addition, successful commercial development of biomass for energy production will depend on the compatibility of energy crops with existing farming systems, which also vary widely by region. Consequently, the choice of region for location of demonstration plants and initial commercial development will probably be critically important to the success of the whole commercialization process.

The objective of this paper is to examine the compatibility of switchgrass as an energy crop in farming systems in the southeastern USA, relative to other regions. In particular, the issues addressed here are (1) competition between switchgrass as an energy crop and existing farm enterprises, (2) complementarity between switchgrass and existing farm enterprises, and (3) environmental benefits.

Competition from Existing Farm Enterprises

In order for switchgrass to be adopted by producers as an energy crop in place of existing enterprises, it is necessary that it be more profitable than existing enterprises. Therefore, introduction of switchgrass as an energy crop to any particular region is most likely to be successful if (a) profitability of existing enterprises in the region is low, and (b) potential profitability of switchgrass is high.

Profitability of Existing Enterprises

Forestry and pastures for beef production are the two enterprises which occupy most land on which switchgrass is likely to be established in the Southeast. Both of these enterprises currently offer low returns (on average, less than $40/acre/year) when compared to row crops such as corn in the mid-West (mostly $100 to $150/acre/year). Production of the more profitable row crops (as opposed to forestry and beef pastures) in the Southeast is restricted mainly by unproductive soils which are very erosive and often already highly eroded, and a prevalence of diseases and pests compared to the mid-West. This reduces yields and increases production costs, thus diminishing returns. Consequently, even under the most suitable conditions for row crop production in the Southeast, yields and returns for crops such as corn and soybeans are considerably lower than in the mid-West, and are often less than $100/acre/year.

Potential Profitability of Switchgrass

Potential profitability of switchgrass as an energy crop will be highest in regions where biomass yields are highest and where yields vary least from year to year, provided production costs per acre are similar across regions. Clearly, research data on biomass yields of switchgrass throughout the eastern USA indicate that yields in Alabama have been, on average, at least 50% higher than in any other state, and among the least variable from year to year (Table 1; Martin and McLaughlin, 1992).

Table 1. Productivity Ranges for Switchgrass in Several States in the Eastern and Mid-Western USA (Martin and McLaughlin, 1992)

Productivity Ranges			
State	Best cultivar	Year	Yields dry tons/acre (dry Mg ha^{-1})
Alabama	'Alamo'	1990	15.4 to 11.0 (34.6 to 24.7)
Indiana	'Cave-in-Rock'	1989	9.2 to 2.5 (20.7 to 5.7)
Iowa	'Cave-in-Rock'	1988	3.7 to 2.2 (8.3 to 5.0)
Nebraska	'Pathfinder'	1990	2.8 to 1.8 (6.2 to 4.1)
New York	'Cave-in-Rock'	1989	5.8 to 1.8 (13.1 to 4.0)
North Dakota	'Sunburst'	1990	5.6 to 3.3 (12.5 to 7.5)
Ohio	'Cave-in-Rock'	1989	4.6 to 3.6 (10.3 to 8.1)
Virginia	'Cave-in-Rock'	1989	7.2 to 5.3 (16.2 to 7.0)

The reasons for the high yields obtained in the Southeast are (a) a long growing season with a high and well distributed rainfall, (b) adaptation of highly productive varieties such as 'Alamo', which break winter dormancy early (often 4 to 6 weeks earlier than other varieties) and are therefore able to take advantage of the extended period of favorable growing temperatures in the South, (c) relative insensitivity of switchgrass to soil type, and (d) little evidence of serious pest and disease problems, possibly because it is a native grass.

To project potential returns of switchgrass as an energy crop at this stage, without an established switchgrass-to-biofuel industry, is clearly difficult. However, considerable applicable information is available from hay production which can serve as a useful guide. If it is assumed that it costs $60/acre/year to produce switchgrass (fertilization, prorated establishment costs, etc.), $121/acre for producers to cut and bale it themselves (as opposed to $20/ton for custom harvesting and baling) and $5/ton for the producer to haul switchgrass 10 miles to a collection depot (as opposed to $8/ton for custom hauling), and the price received by the producer for switchgrass delivered to the collection depot is $35/ton, then the cost and return figures in Table 2 apply.

Table 2. Effect of Switchgrass Yield on Gross Return, Costs and Net Returns for (a) Self-Operated Production (Production, Harvesting and Hauling Done by the Producer), (b) Custom Harvesting but Hauling and Production Done by Producer, or (c) Custom Harvesting and Hauling, and Only Production Done by Producer

Switchgrass Yield	Gross Return	(a) Self-Operated		(b) Custom Harvest Only		(c) Custom Harvest and Hauling	
		Costs	Net Return	Costs	Net Return	Costs	Net Return
(tons/acre)	$/acre						
4	140	201	- 61	160	- 20	172	- 32
6	210	211	- 1	210	0	228	- 18
8	280	221	59	260	20	284	- 4
10	350	231	119	310	40	340	10
12	420	241	179	360	60	396	24
14	490	251	239	410	80	452	38
16	560	261	299	460	100	508	52

Information in Table 1 and 2 allow several conclusions to be drawn. First, break even yield is around 6 tons/acre for self operated enterprises or where only harvesting is done on a custom basis, but is over 8 tons/acre if both harvesting and hauling are done on a custom basis. Secondly, custom harvesting and/or hauling substantially reduces net returns and makes economic feasibility questionable. This is entirely understandable with a low-value commodity like biomass for ethanol production, priced at $35/ton, as opposed to higher value commodities such as hay, which usually sells for $50 to $75/ton. Thirdly, projected net returns for self operated switchgrass production appear comparable with row crops if yields of 10 tons/acre or more can be achieved. Finally, the only state that has consistently provided profitable yields to date is Alabama (Table 1). Given that these yields were achieved in research plots and do not take into account harvesting and storage losses, economic feasibility of producing switchgrass as an energy crop outside of the Southeast has to be considered extremely doubtful at this point.

Complementarity with Existing Farm Enterprises

The southeastern USA is essentially a mixed farming region. While the acceptance of switchgrass as a new crop in the region will depend largely on its projected returns relative to existing enterprises, its complementarity with existing enterprises will also likely play an important role in its acceptance. In this regard switchgrass has much to offer, especially in association with forage-livestock production, row crops and wildlife.

Forage-Livestock Production

Switchgrass and existing forage-livestock enterprises complement one another in several ways. Switchgrass itself is an excellent forage, although it has not been used for this purpose in the Southeast. It can be used for both hay and grazing, and provides high yields of excellent quality feed. For example, Burns *et al* (1984) obtained average daily weight gains of 2.1 lb per animal and seasonal weight gains of 967 lb/acre for beef steers grazing 'Kanlow' switchgrass in North Carolina over a 3-year period. This is almost double the production commonly achieved from traditional forage species such as bahiagrass and bermudagrass. On the other hand, existence of a large forage industry in the Southeast means that many producers already own hay-making equipment that is required to harvest and bale switchgrass as an energy crop. Therefore, at least initially, large scale purchase of equipment will not be necessary.

Row Crops

Poor soils with low organic matter and impervious plow pans, and pests pose major restrictions on yield and profitability of row crops in the southeastern USA. Nematodes are a particularly devastating pest of soybeans, cotton and peanuts, but recently, many nematicides have been removed from the market because of environmental concerns. Those that remain are expensive and are also under scrutiny by environmental agencies. However, recent research has shown that use of bahiagrass in medium- to long-term rotations with soybeans and peanuts can dramatically increase yields (Rodriguez-Kabana, *et al*, 1991). Bahiagrass provides multiple benefits in the rotation, including nematode control, puncturing of impervious plow pans with a powerful root system, and addition of organic matter to the soil. Ongoing research at Auburn University suggests that switchgrass could provide equivalent benefits, but would have added advantages over bahiagrass as both a forage and an energy crop.

Wildlife

Although not generally recognized as such, wildlife is an economically important enterprise for landowners in the Southeast. For example, Stribling *et al* (1989) estimated that in Alabama alone, more than $600 million are spent annually on hunting and hunting-related activities. This included $30 million for land leases and fees, and $34 million for food plots. Switchgrass is well recognized among wildlife specialists for providing preferred habitat and/or food for deer and quail in particular, but also for many other species of wildlife. Therefore, it is quite possible that fields of switchgrass on a property could elevate hunting leases and fees.

Environmental Benefits

Several environmental benefits of switchgrass as an energy crop have already been mentioned in previous sections. These include improved soil productivity from addition of organic matter and puncturing of impervious plow pans, reduction in nematodes harmful to row crops, reduced use of hazardous nematocides, and therefore reduced contamination of groundwater with chemicals and harmful effects on non-target organisms, and enhanced wildlife. In addition, switchgrass will play a major role in reducing soil erosion, especially if it replaces annual row crops currently grown on marginal land. It could also play an important role in reducing contamination of ground and surface water because it is extremely efficient in assimilating soil nutrients, probably because of a very extensive root system. For example, in Alabama 'Alamo' switchgrass biomass contained over 270 lb of nitrogen per acre, after only 100 lb of nitrogen per acre had been applied as fertilizer (Sladden and Bransby, 1991). This very large excess of accumulated nitrogen over that applied as fertilizer suggests that 'Alamo' switchgrass may even have a nitrogen-fixing association with soil microorganisms.

Conclusions

Evidence in this paper indicates clearly that, based on competition from existing farm enterprises, complementarity with existing enterprises and environmental benefits, the Southeastern USA offers greater opportunity to develop switchgrass as an economically viable energy crop than any other region. In fact, based on current information, economic viability of switchgrass as an energy crop in any other region is indeed questionable. Consequently, this should be the major influencing factor in locating demonstration ethanol plants, even if prospects for cost sharing in these plants may be more promising in other regions.

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FIVE YEARS OF RESEARCH IN ENERGY PLANTATION IN SOUTHERN QUEBEC (CANADA)

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ABSTRACT

Since 1989, short rotation and intensive culture (SRIC) techniques have been experimented to grow various fast growing species of trees and shrubs for energy plantation or environmental purposes. The objectives were to evaluate the biomass productivity with respect to 1) different weed control methods during the establishment phase 2) drainage conditions and soil quality of the plantation site and 3) frequency of coppicing. Native or introduced species of willows and various species of shrubs, such as honeysuckle and cornel, were grown in an experimental design in the nursery of the Montreal Botanical Garden on former agricultural land. Productivity, in tons of dry material per hectare, was evaluated and compared by harvesting shoot and branch samples at the end of each growing season. Weed control is essential to the establishment of trees in SRIC. When weed repression was applied during the two first growing seasons, biomass productivity was 4 to 5 times greater than the biomass produced on the control plot of the well drained site. With good weed control, willows can yield more than 20 tons of dry material on well drained site and near 15 tons on a poorly drained site, only two years after plantation. The growth potential of shrub species is also interesting. Some of them were able to produce up to 10 tons of dry biomass per hectare per year, which is appreciable considering that such species can be used on marginal lands and for the fixation of river banks. Frequency of coppicing also influences productivity. For willows, we determined that a three-year rotation cycle allowed the highest biomass productivity. Shrubs should be coppiced each year to obtain the best results. Fast growing species and SRIC techniques are not only a good way of producing wood and alcohol for energy but they also represent a way of rapidly colonizing degraded or marginal sites and of fixing river banks.

INTRODUCTION

We have been doing research on short-rotation intensive culture (SRIC) of tree and shrub species since 1989. The main objectives of the various studies on these culture systems were to determine how to increase biomass productivity while controlling costs.

We have therefore become convinced that, in the agricultural context of Quebec and Canada in general, these forestry systems could only be established on land with soil characteristics which render them unsuitable for agriculture. Thus, we have seeked ways to increase productivity and approached the principles of SRIC considering the possibility of using it on marginal sites: rocky terrain, poorly drained or clayey sites, river banks, etc. Moreover, our approach is very respectful of the environment and ecological principles. We are preoccupied with maintaining the biodiversity of the species we use for intensive culture and are striving to find culture methods where interventions, notably weed control, are limited.

In the present article, we review the most important results obtained in these five years of research.

SRIC ON MARGINAL SITES

Methods

In order to verify SRIC results on various types of soil, experimental plantations were established in the spring of 1991 on two sites with soil characteristics and drainage conditions which varied as described in Table 1. A randomized block design was used to monitor above-ground biomass growth and productivity of *Salix viminalis* and *Salix discolor* plants during the first two growth seasons after plantation of the cuttings.

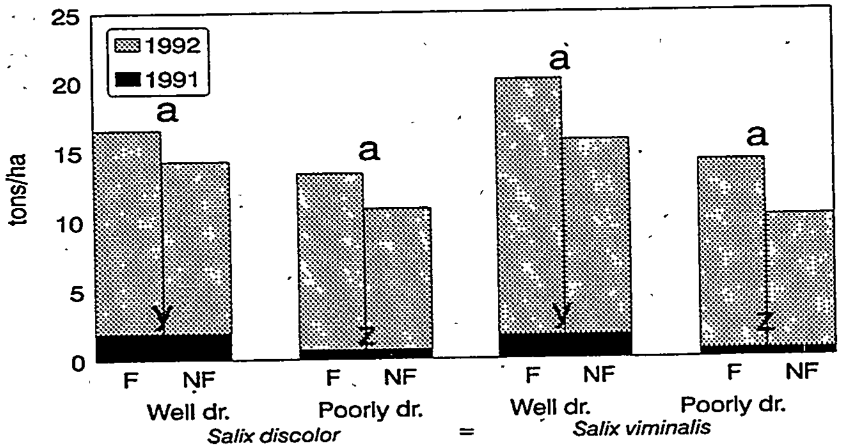
Table 1: Comparison of soil conditions in the two plantation sites.

	SITE	
	Well drained	Poorly drained
Sand (%)	76,4	32,4
Silt (%)	12,0	16,0
Clay (%)	11,6	51,6
Texture	Sandyloam	Clay
pH	6,8	7,3
N/NO^3 (mg/kg)	16,7	15,0
N/NH^4 (mg/kg)	3,4	5,2
P (Kg/ha)	552,0	62,0
K (Kg/ha)	332,0	309,0
Ca (Kg/ha)	5698,0	5653,0
Mg (Kg/ha)	305,0	1372,0
B (ppb)	0,8	0,5
Cu (ppb)	2,4	2,7
Fe (ppb)	228,0	269,0
Mn (ppb)	42,0	60,0

Results and discussion

Figure 1 compares the mean values of above-ground biomass (tons of dry weight/ha) for each species and for each site at the end of the 1991 and 1992 growth seasons. These results show that the above-ground biomass produced during the first season remains rather limited. Both willow species produced similar quantities on each site, but the well-drained site yielded almost twice the biomass produced on the poorly drained site. On the other hand, we observed that the productivity for each set of conditions becomes comparable after two years (Figure 1). Harvested biomass quantities do not differ significantly. This shows an important growth activity by the willows which developed on poorly drained sites. Indeed, their relative growth rates are clearly higher than those of willows grown on the well drained site.

Figure 1. Comparison of the above-ground biomass (in tons of dry weight/hectare) produced by two willow species grown on well drained and poorly drained sites for the first two growth seasons.



Different letters above columns indicate a significant difference at $p<0.05$
F: fertilized NF: non-fertilized (fertilization effect was not considered here)

It is interesting to note that willow plants can take advantage of both cleyey and poorly drained sites. Growth increments and productivity are extremely interesting in the second year. The establishment phase on poorly drained sites seems a determining factor, but once the plants are properly rooted, they seem to be able to cope and develop actively under these conditions. These observations allow us to envision interesting possibilities for cultivating willows under the short-rotation intensive culture on marginal and perturbed sites often found around urban centers.

SRIC AND THE IMPORTANCE OF WEED CONTROL

The establishment phase is the crucial stage for the future productivity of intensive culture systems (Mitchell, 1990). The control of herbaceous plants which compete with the willows for light, water and soil nutrients is essential if we are to ensure the success of future plantations. Weed control measures can be applied in various ways and their efficiency and cost vary according to the intensity and frequency of the treatments (Cogliastro *et al.*, 1990).

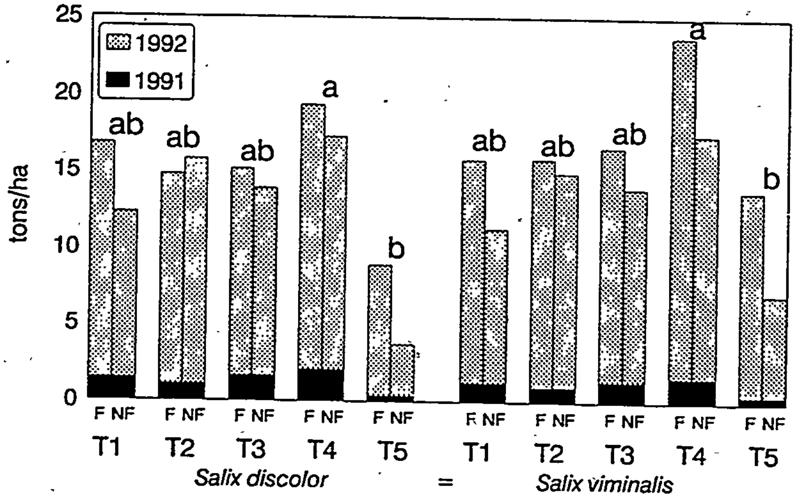
Methods

The experiment consisted in applying various weed control treatments during the first two years of the establishment phase and verifying their impact of the growth and productivity of *S. viminalis* and *S. discolor*.

A randomized block experimental design was established in 1991 on the two sites described above. Dry woody cuttings of both species were planted in rows 1.5 m apart at a spacing of 0.3 m between individual plants for a total density of 20,000 plants per hectare. The experimental design comprised 2 sites, 3 blocks, 2 species and 5 weed control treatments. The following treatments were applied on each block: (1) mechanical weeding, twice the first year, once the second year; (2) chemical weeding, once the first year, mechanical weeding (once) the second year; (3) mechanical weeding (once) and chemical weeding (once) the first year and mechanical weeding (once) the second year; (4) plastic mulch established for three years; (5) control treatment (no intervention).

In order to simplify the presentation of the results, these have been treated without taking the plantation site into consideration (Figure 2). The absence of weed control treatment (treatment 5) has extremely negative impacts on productivity and reduces yields by almost half compared to those obtained when one or the other of the 4 weed control treatments is applied. The plastic mulch is the most efficient treatment to promote plant growth. Under these conditions, both willow species produced almost 20 tons of dry weight per hectare after only two years.

Figure 2. Comparison of the biomass (tons of dry weight per hectare) produced by the two willow species with respect to five weed control treatments.



Different letters above columns indicate a significant difference at $p<0.05$
F: fertilized NF: non-fertilized (fertilization effect was not considered here)

The plastic mulch is very efficient for weed control and promotes the highest yields (notably on poorly drained sites). However, it is costly and relatively complicated to install. We therefore recommend that other means be used to control the development of competing herbaceous plants. All treatments seem to give the similar results, treatment 3 being the most efficient.

THE IMPORTANCE OF COPPICING CYCLES ON SRIC PRODUCTIVITY

What should the rotation frequency of these culture systems be? What impact will the length of the coppicing cycle have on productivity? To answer these questions, we conducted an experiment with the main objective of verifying the yields of *Salix* culture (*S. viminalis* and *S. discolor*) with respect to the frequency of plant coppicing.

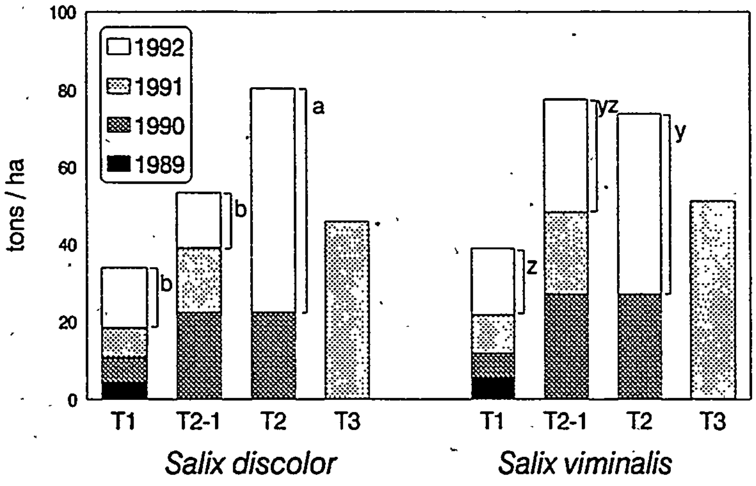
Methods

In a randomized block design, the two willow species were cultivated at a density of 27,000 plants per hectare and 4 treatments were applied: (1) One-year rotation; (2-1) One-year rotation starting the second year after plantation; (2) Two-year rotation; (3) Three-year rotation. At the end of each growth season, part of the experimental blocks were coppiced according to the treatments enumerated above and the biomass obtained from each species was weighed. See figure 3.

Results and discussion

Figure 3 highlights a number of important elements. For each species, we compared cumulative yields until 1992 after various coppicing cycles. First, let us mention that yields are relatively similar for both species. The greatest difference occurs with treatment 2-1 which does not seem to agree with *S. discolor*. For this species, treatment 2 yielded more than 80 tons of dry weight after 4 years of culture, which represents an average of 20 tons of dry weight per hectare per year. Three-year rotation cycles (treatment 3) also allow an impressive productivity. Both species produced around 50 tons per hectare during the first three years of culture. It will be interesting to verify this value for the second coppicing cycle, i.e. six years after the plantation of the cuttings. For *S. discolor*, treatment 2 seems to yield the highest biomass productivity while *S. viminalis* reacts similarly to treatments 2-1 and 2. One-year rotations produced the poorest results although productivity increases a bit each year.

Figure 3. Comparison of above-ground biomass productivity of two species of willows with respect to coppicing cycles.



Different letters above columns indicate a significant difference at $p<0.05$

SHRUB SPECIES UNDER SRIC

In order to increase the diversity of species being exploited under SRIC systems and to intervene in more marginal situations, i.e. near rivers, on steep terrain, etc., we started studying the behavior of shrub species whose very high growth potential was already known (Labrecque *et al.*, 1989).

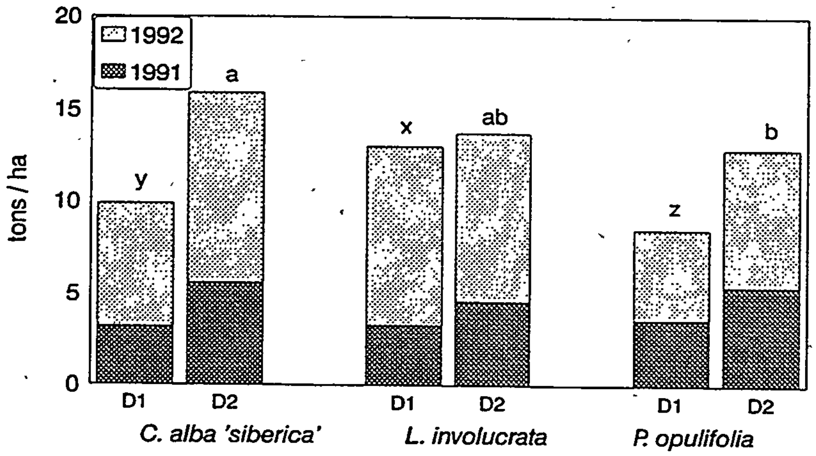
Methods

Three species were studied: *Cornus alba sibirica*, *Lonicera involucrata* and *Physocarpus opulifolius*. Planted in 1990, one-year plants produced from leafy cuttings were distributed in a randomized complete block design under 2 plantation densities: 11,000 and 27,000 plants per hectare. At the end of the 1991 and 1992 seasons, all plants were coppiced and part of them were weighed to evaluate productivity per hectare.

Results and discussion

Figure 4 shows the biomass obtained after coppicing at the end of 1991 and 1992. Yields (in tons of dry weight per hectare) were compared for the three species and for plantation density. Each species reacted differently to density. Thus, when planted at a density of 27,000 plants per hectare, honeysuckle gives the highest yields, producing almost 13 tons of dry weight after three years of culture and two coppicings. On the other hand, dogwood reacts better when it is planted at a higher density and produces up to 16 tons of dry weight during the same period.

Figure 4. Comparison of the productivity of three shrub species with respect to plantation density.



Different letters above columns indicate a significant difference at $p<0.05$

This study allowed us to specify the characteristics of these species for exploitation under SRIC systems and to envision various possible uses.

Acknowledgements. This study was made possible by a grant from Forest Canada and its ENFOR program.

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ACQUISITION OF WOOD FUEL AT THE JOSEPH C. MCNEIL GENERATING STATION

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Introduction

The Joseph C. McNeil Generating Station is the world's largest single boiler, municipally-owned, wood-fired electrical generating plant. The 50 megawatt McNeil Station is located in Burlington, Vermont and is owned by several Vermont public and private electric utilities. The operator and majority owner is the City of Burlington Electric Department (BED).

Discussion

The J.C. McNeil Station began commercial operation June 1, 1984 following an approximately seven year period of planning, design, permit acquisition, financing and construction. In the early 1970's, the City of Burlington recognized a need for new generation to replace an aging coal-oil-natural gas fired plant in Burlington and to replace expiring power contracts with other utilities. The only viable option for new generation apparent in the early to mid 1970's which met Burlington's stringent criteria of capacity, locally available fuel and achievable levels of pollution control was wood.

The city proceeded with initial plans and designs for a wood fueled plant while simultaneously converting two 10 megawatt coal-oil-natural gas fueled generating units at its existing Moran Station to burn either or a combination of wood-oil-natural gas. The strategies behind the conversions were both to locally demonstrate the feasibility of generating electricity using wood fuel and also to establish and gain experience with an expandable wood fuel procurement system. During this successful pilot program, wood chips and bark were purchased directly from suppliers and through a wood chip broker representing several low volume suppliers of sawmill residues. The Department gained experience in wood procurement, storage and combustion and at the same time saw the establishment of several local suppliers.

The licensing process for the McNeil Station spanned 30 months and included 58 days of public hearings. In September of 1981 the State of Vermont Public Service Board granted a Certificate of Public Good authorizing the construction and operation of the facility. The Board's Certificate contained several stipulations regarding the acquisition of wood fuel, including the following:

> 7. Not less than 75% of all wood fuel to be consumed by the facility shall be delivered to the plant site by railway.
> 10. ...the harvester(s of wood fuel) shall (a) advise the Vermont Department of Fish and Game in advance of the location of harvesting operations; (b) adhere to the recommendations of the Vermont Department of Fish and Game regarding cutting near deeryards, wetlands or the habitat of any endangered species; (c) comply with all applicable environmental protection standards...; (d) limit clear cutting to 25 acres or less except in genuine cases of land use conversion...; (e)

comply with all terms and conditions of (the) "Harvesting Policy for Whole Tree Chipping Operations in Vermont"... .

These requirements were directed by the Board in response to public concerns regarding traffic congestion if all the wood were to be delivered to the plant site by truck, and the environmental effects of wood chip harvesting. The rail delivery requirement was complied with by establishing a satellite receiving yard 35 miles north of Burlington. Here wood is received by truck from the forest, temporarily stored, then reloaded into 7,000 cubic foot capacity bottom-dumping railcars. Twenty-one cars, owned by the McNeil Station, carry about 1,600 tons per unit train delivery. Unloading occurs on a trestle and requires two to three hours per train. The unloading of bottom dumping cars is especially difficult in the winter when the wood tends to freeze to the sides of the cars. An electric vibrator on each car aids in dislodging the wood.

The "Harvesting Policy for Whole Tree Chipping Operations in Vermont" referred to in the Certificate of Public Good is a list of forest resource operation and protection activities developed by Burlington Electric with input from the State of Vermont Department of Forests, Parks and Recreation. The policy addresses prescribing and adherence to appropriate silvicultural practices, implementation of soil erosion control practices, protection of scenic, archeological and recreation resources as well as critical wildlife habitats. A staff of four professional foresters and one wood residue broker/forester are required by the Public Service Board to be hired by Burlington Electric to monitor the wood fuel procurement provisions of the Certificate.

Prior to the completion of the McNeil Station construction, the Burlington Electric Department entered into twelve wood supply contracts which ranged in duration from three to five years. The long term nature of these contracts was advised by financial experts who had the job of selling approximately $55 million in revenue bonds to finance the plant and by forestry and engineering experts who foresaw the need to provide a long term commitment to wood suppliers in order for the suppliers to justify the expansion of their businesses to serve BED's increased demand. BED was well familiar with the practices of regional paper companies to issue contracts of six month duration, however, we were also confident of prognostications of high levels of electrical production and consequent fuel consumption at the future McNeil Plant.

In New England, generating stations owned by utilities must abide by the New England Power Pool rules regarding dispatch. All generating units in the Pool are dispatched to operate in order of energy cost, with the least expensive units being called into service first. It was expected that the McNeil Station would be dispatched weekdays equivalent to a 70% capacity factor. During the first ten months of commercial operation, projections of high wood fuel use came true. Mechanical availability of the plant averaged above 90% and capacity factor was 85%. During January and February of 1985, capacity factor was at 96% resulting in wood consumption of nearly 2,000 green tons per day (60,000 tons per month). This was actually 37% in excess of projections. Feeling comfortable in the accuracy of wood usage projections, BED entered the 1985 spring thaw season with an ample fuel inventory in anticipation of the traditional six week harvest shutdowns and rural road closures. A two week scheduled plant shutdown in April stretched to three. When the plant returned to service in May, a low dispatch rate resulted in capacity factors of 50% in May and 38% in June. This trend continued through the summer of 1985: capacity factors for July and August were 46% and 60% respectively. Wood chip purchases were reduced by means of the issuance of delivery quotas but wood inventory continued to climb to a maximum of 100,000 tons on site at McNeil and 70,000 at the rail loading site in Swanton.

In early September of 1985, evidence of a "hot spot" in the outdoor wood storage pile was detected by plant personnel. Deliveries of wood were suspended. Careful investigation led to the discovery that a "hot spot" existed in the interior of the pile near and below the bucket loader access road. The decision was made to excavate the hot spot, expose the hot material, cool the wood with water and consume the fuel as quickly as possible. The plant was placed in "must run" mode not dependant on economic dispatch to run. A tremendous volume of wood had to be moved to reach the "hot spot" and a large backhoe and two bulldozers were placed in service. There were visible flames on only one brief occasion but the exposed material ranged in temperature from 150 - 200 F. Within a week the hot material was isolated but the cure was perhaps worse than the "disease." As machinery removed the upper layers of wood, a sharp odor permeated the neighborhood leading City officials and investigatory groups to demand explanations and raise issues regarding health hazards. Solving the problem while simultaneously keeping the public pacified required the utmost in perseverance and diplomacy. The experience, in addition to being expensive was physically and emotionally draining for the Plant management and employees, and the plant's exceptional operational record was totally overshadowed. Even eight years after the incident, inquiries and references to the "smelly wood chip problem" are all too frequent.

The curtailment of wood fuel purchases for seven weeks in the Fall of 1985 followed by months of purchases on a quota system resulted in a number of suppliers leaving the wood chipping business and others finding alternative markets. Three of the twelve original contractors filed breach of contract suits against the Department in spite of the contract contingency clause allowing for nonperformance in the events of "fire, major mechanical breakdown and lack of electrical generating dispatch." This language was formulated by the Department's legal counsel and included in the contract at the urging of BED's forestry staff. Nonetheless, over the course of the next six years, and after countless hours of depositions, conferences and two mistrials, the three suits were settled out of court. Although the Department felt legally in the right, it became apparent that a jury trial carried the real threat of a miscarriage of justice and financial penalties far in excess of a reasonable settlement.

The long range impact of learning the vulnerability of relying on dispatch projections as a fuel purchasing guide has been the total abandonment of long term wood fuel supply contracts by BED. Today the Department enters into contracts varying from two weeks to three months in length. We rely on "captive sources" of wood to the greatest extent possible including local sawmill residues and urban wood waste. A small inventory of wood in log form is maintained for emergency use due to its long term stability in storage. Most importantly, the Joint Owners of the McNeil Station have recognized and accepted the need to consume minimal amounts of wood even when it results in a financial penalty in order to meet contractual commitments, provide timely turnover of fuel inventory and maintain a regular purchasing schedule with primary suppliers.

Wood Chip Storage

During the wood storage problem, we found considerable information in the journals of forestry research which pertained to wood chip storage in small, loose piles. Very little documented research on the storage of wood chips in large, tightly compacted, uncovered, outdoor piles existed, and we found such piles to have storage characteristics far different from small, loose piles. In reviewing our own experience of eight years storing wood fuel for the pilot study at the Moran Station during which we had never had a storage problem, we found two main factors of wood chip storage that probably led to our problems; the McNeil wood pile was much larger in all dimensions than any we had built before and there was much greater localized compaction of the pile at McNeil than we had ever had before. It was clear that a direct correlation existed between pile dimension and heat buildup. We also witnessed evidence that pile compaction, although beneficial for reducing infiltration of precipitation, also reduces heat dissipation and can allow temperatures to climb to the point of ignition. There are many variables to consider in outdoor wood chip storage but if we assume that the natural and expected generation of heat within the wood pile is unavoidable, it becomes clear that dissipation of that heat is the key to safe storage.

These conclusions led to the development of a wood chip storage system that has served well since 1986. Wood is stored in multiple piles sized to provide adequate surface to volume ratios for heat dissipation. This also enhances the ability to operate the wood inventory on a "first in - first out" basis. Compaction is controlled by the construction of wedge-shaped piles with no single access road; instead, access is made across the entire face of the pile. Finally, a self-imposed limit on storage time of four months has been established, after which old wood is either burned or aerated by restacking it. These storage principles have resulted in no incidents of combustion or adverse odor formation for eight years. It should be clear that a regular and predictable level of wood consumption would be a preferable means for achieving safe wood storage but that is not a possibility for a plant when operation is dependent on pool dispatch as described previously.

Forest Harvesting

The brightest fact regarding the McNeil Station is that despite the enormous public concern during the planning phase over wood chip harvesting impacts, there has been not a single unresolved environmental violation in the woods. BED's dedicated staff of foresters armed with a clear and workable harvesting policy have won the respect of state regulators and environmentalists. The Vermont Department of Forests, Parks and Recreation conducts a program of monitoring wood chipping operations and prepares an annual report for the State Legislature. An excerpt from a recent report stated, "the Burlington Electric Department's ...standards of performance required from their suppliers operating in Vermont positively influences the achievement of acceptable management practices ... and good forest management." (Vt. Dept. Forests, Parks and Recreation, 1987.)

Harvesting operations supplying Burlington Electric over the years have been categorized by type of harvest in Table 1.

Table 1. Summary of Harvest Types and Acreage of BED Harvests in Vermont 1984 - 1991

	Acres	%
Partial Cuts		
Selection Harvest	6,737	39
Thinning/Improvement	3,491	20
1st-2nd Stage Shelterwood	1,849	11
TOTAL PARTIAL CUTS	12,077	70
Clearings		
Farmland Reclamation	2,169	13
Silviculture (less than 25 acres each)	1,470	8
Development	1,285	7
Species Conversion	235	7
Wildlife	197	1
Salvage	60	-
TOTAL CLEARINGS	5,416	30

Partial cuts composed 70% of the acres from which wood chips were harvested for the McNeil Station during 1984-1991. Thinnings (which concentrate site production on fewer and better trees), and improvement cuts (which remove trees of low potential value) accounted for 20% of the acres. Selection and shelterwood harvests (which result in the retention of a partial tree cover on the site) accounted for 50% of the acreage.

Land clearings of various types accounted for 30% of the harvest acres. The bulk of these acres, 13%, were cleared to reclaim crop or pasture land on farms where the land had been allowed to naturally revert to forests. Predevelopment clearing accounted for 7% of the acres and resulted in reduced open burning and landfilling of clearing waste.

Clearcutting can be an appropriate form of silviculture under some circumstances such as where tree species conversions are to be made, where trees are dying from insect or disease attacks, or where tree species requiring full sunlight are to be grown. Clearcuts for such reasons accounted for 16% of the acreage. BED's Harvesting Policy restricts clearcutting to openings of 25 acres or less except in cases of genuine land use conversion.

Harvesting Costs

Wood chip harvesting operations providing fuel to the McNeil Station are of two general types; fully mechanized "hot yarding" systems and partially mechanized "cold decking" systems. Hot yarding involves tree cutting, skidding to the landing and almost immediate chipping. This system requires balance and reliable performance in all phases of the operation in order to produce the high volumes necessary for efficient operations.

Cold decking is becoming more common and usually involves chainsaw felling, cable skidding and the integration of harvested trees into various products at the landing. Wood to be chipped is stockpiled along the road using a hydraulic loader. Chipping occurs later. Wood fuel sold to BED from cold decked operations increased from approximately 10% in 1981 to over 55% today. Benefits of cold decking include lower equipment cost, generally improved merchandising of wood products and accessibility to harvested wood during periods of inclement weather.

A Connecticut study published in 1989 determined that wood chip production costs vary from $13.00 - $15.00 per green ton from clearcuts and from $13.42 - $17.00 per green ton from thinnings excluding stumpage and trucking (Connecticut 1989). Experience at BED indicates costs in Northern Vermont tend to be toward the lower end of these ranges. Trucking costs using 40 foot box type trailers are reported in the Connecticut study to range from $0.083 - $0.11/per green ton per loaded mile. Our experience at BED indicates that trucking costs in Northern Vermont are at the low end of the Connecticut range.

Soil nutrient changes continue to be a concern of foresters regarding intensive harvesting (Brynn 1991). Wood chip harvesting removes about double the biomass of stem only harvests (Pierce et al 1992). Several practices are employed by Burlington Electric wood suppliers to minimize soil nutrient disruptions. These practices include:

A. Tree length only harvesting is employed on some low nutrient sites, leaving branches and foliage to decompose.
B. Harvests after leaf fall and well in advance of chipping allow leaves to remain on site.
C. Short rotations are avoided.
D. Clearcuts are minimized.
E. Soil erosion control practices are used.
F. Rapid regrowth is encouraged.

Wildlife habitat protection is an integral part of Burlington Electric's Harvesting Policy. The wintering habitat of whitetailed deer, and the habitats of endangered species are specifically protected. Vermont is home to over 20 endangered species of animals plus dozens more plants. Means for protecting deer wintering habitat are well documented and consist of reserving adequate softwood crown closure to permit interception of snow by tree crowns thereby reducing snow depths on the ground to facilitate deer movement. This goal is balanced against the degree of windfirmness of the residual trees and tree regeneration requirements. The protection needs of endangered species are poorly documented and therefore consist generally of deliberate avoidance of harvest activity in and near known habitats.

Wood chip harvesting has been considered as a potential factor in declining populations of some species of migrating songbirds. Land clearing associated with wood chip harvesting may be responsible in some measure for the fragmentation of large blocks of forests essential to some bird species. A report by foresters of the Vermont Department of Forests, Parks and Recreation points out that a diversity of vegetative layers in the forest are important to maintaining a variety of breeding bird populations and that wood chip harvesting can be used to create and enhance this diversity (Salmon & White 1991, Johnson et al).

Summary

Wood fuel procurement for the 50 megawatt Joseph C. McNeil Station has been conducted in an environmentally sensitive way. Harvesting is carried out in conformance with a comprehensive wood chip harvesting policy and monitored by professional foresters. Unpredictable levels of Station operation require rigid adherence to a wood storage plan that minimizes the risk of over heating and spontaneous combustion of stockpiled fuel.

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Principles of Commercially Available Pretreatment and Feeding Equipment for Baled Biomass

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Abstract

During the last 15 years, there has been a growing interest in utilizing waste biomass for energy production in Denmark. Since 1990, it has been unlawful to burn surplus straw on open land. Before the year 2000, it is intended to utilize most of the 2-3 million tons of surplus straw as an energy resource.

The type of plants that were built in the beginning were combustion plants for district heating. The feeding equipment for these plants has been developed to an acceptable standard.

Later, combustion plants for combined heat and power production based on a steam turbine were introduced. This type of plant demands a much greater continuity in the fuel flow, and the consequences of minor discontinuities are to be dropped from the grid.

Gasification and pyrolysis demands a high sealing ability of the feeding equipment, because of the explosive and poisonous gas in the plant and a need for a very high continuity in the fuel feed.

The first plants were built with the equipment and experiences from the farming industries, which have a long tradition in working with biomass-handling.

The experiences gained with this type of equipment were not very promising, and in the early eighties, a more industrial type of biomass-handling equipment was developed.

This paper presents the principles of the heavy-duty biomass pretreatment handling and feeding equipment that was commercially available in Denmark in May, 1993.

Dividers and partitioners.

Basically, there are two different principles when biomass in bales has to be divided. One is to break the bales into smaller pieces and leave the structure of the biomass almost intact. The other is to chip the biomassbale into smaller parts.

The biomass dividing device is one of the great firerisks. The risk of causing fire increases dramatically the faster the dividing device rotates. All known fast rotating balechippers have caugth fire several times.

Fast revolving cutters.

Those have a high capacity, and are generally not sensitive to strings. The energy consumption is between 100 and 500 kJ pr. kg biomass, and the capacity is sensitive to moisture in the biomass. The industrial quality cutters are not very sensitive to foreign bodies in the biomass, but the farm quality cutters throw of the knives at a high speed. Fast revolving cutters have been used in energy production plants, but the fire risks and the large energy consumption, have made them less competitive.

Slow revolving cutters.

The energy consumption is between 20 and 60 kJ pr kg of biomass. Due to the low periphery speed and the high torque, the cutter does not create fire and it is able to cut most foreign bodies including the strings. The capacity is not very sensitive to varying moisture content in the biomass. The cutters produce biomass with a texture that is very well suited for screw transport, as the risk of the biomass winding round the screw is minimal.

Balebreakers.

Balebreakers require less energy than cutters, but are generaly more sensitive to moist biomass, and foreign bodies in the bale.

Balebreakers can be rotating, reciprocating or with chains.
Generally small balebreakers are rotating balebreakers. For heating plants up to 10 MW reciprocating balebreakers have been used with succes.

Rotating balebreakers.

The principle of the rotating balebreaker is that the biomass bale is pressed against one or several drums. On the drums are mounted a number of hooks–knives–edges which pull the biomass out of the bale and deliver it into the transport system.

The rotating balebreakers are very sensitive to strings and foreign bodies in the biomass. It is therefore necessary to add a string remover which complicates the machinery a lot.

The energy consumption is about 10–30 kJ pr kg of biomass, but increases when the biomass is wet. The capacity decreases accordingly.

The balebreakers can only operate with straw and grasslike biomasses.

The dosing accuracy can be good with a high and uniform quality of biomass.

Reciprocating balebreakers.

Reciprocating balebreakers have been the most used balebreaker in the straw heating plants build in the 80ties.

The bale is pressed against 8 giant "hacksaw blades", that pull the biomass out of the bale and delivers it into the feeder.

Because of the large dimensions, the short distance to the feeder and the location of the balebreaker above the feeder, it is not sensitive to strings and foreign bodies in the biomass.

The bale breaker has a tendency to pull out slices of the bale, instead of supplying a umiform flow of biomass. Periods of up to 3–4 minutes with no biomass flow has been observed. That causes problems when a constant biomass flow is required.

Transportsystems.

3 systems has been evaluated. Belt conveyers, screw conveyers and air transport.

Airtransport.

Air transport is attractive because of its flexibility in the construction, but to avoid operational problems the pipework must be of a high quality. The airflow must preferably be larger than 5 kg air/kg biomass, and the airspeed above 20–25 m/s to ensure reliably operation of the transport system.

Thus energy consumption will be large. Up to 150 kJ kg biomass has been reported in well operating systems. The airflow can be reduced when using heated air.

Belt conveyers.

Belt conveyers is the most reliably transport method, and the one that consumes least energy.

When using belt conveyers one is restricted by the maximal gradient of the belt. It is recomended to keep the gradient below 20–25 degrees, even with carriers on the belt.

The belt conveyers are the most expensive solution, and is normally used when the demands for reliability are high.

Screw conveyers.

Screw conveyers are attractive because they can be made airtight and very robust. They are generally cheap in construction, the energy consumption is however higher than belts. The screwconveyer must operate with a surplus capacity depending of the texture of the biomass, to avoid blocking of the screw.

Screw conveyers must not be too long. If the conveyer is more than 10 meters it must be open.

Screw conveyers in biomass handlingsystems are generally used in the last part of the transport system, where there is a risk of heat and mechanical influences at the same time.

Densification.

For densification of biomass, pill og briquett presses can be used.

The energy requirements are generally very high, normally 5–10 % of the lower heating value of the biomass. Densification will influence the already very sensitive economy of most biomass to energy plants to the worse. Every possible other alternative must be considered very carefully to avoid going to the extent of densification.

Two principples have been used vith succes, the matrice pillpress, and the hydraulic rampress.

Both principples give a product that is simple and cheap to transport and feed, but these advantages does not justify the energy consumption.

The crankshaft rampress is very sensitive to varying conditions in the biomass, because the density of the briquette is dertermined by the friction between the biomass and the nozele after the piston. This type of briquettepresses requires considerably skil to produce briquettes of an acceptable quality.

Feeders for combustionsystems < 1 MW.

This type of feeders has been made for automatical operation of small heating plants fired with straw and grass. Low price has generally had a higher priority than the demands for a reliably operation. In spite of that the machinery works quite well when it is use for the purpose it was designed for.

Screwfeeders.

Screwfeeders are the most common type of feeders fore small boilers. The feeders are designed to feed into combustion chambers with a pressure that is very close to atmospheric pressure. The sealing in the feeder is obtained by means of a cellsluice which is placed above the entrance of the feederscrew.

The screwfeeders have been made with feedingscrews from 150 to 300 mm in diameter. The smaller screws have shown a tendensy to wind the biomass round the screw instead of conveying it forward.

To obtain a reliable operation of the feeder it is recomended that the diameter of the screw is the same as the avarage lenght of the biomass particles.

The available feeders could with very little effort be improved to meet industrial demands.

Pistonfeeders.

Pistonfeeders for small boilers are only made to feed small bales.

There is only one system available. The operating principle is that a slice is cut of the bale, and pressed into a pipe. A round piston presses this portion of biomass through a feeding pipe into the combustion chamber.

This system operates satisfactorily when it is feeding into combustionchambers at lower pressure than atmospheric, but has difficulties in starting if tars have condensed in the feeding pipe.

Feeders for combustionsystems > 1 MW.

When designing a feeding system for a combustionsystem it is very important to take the demands of the end user of the energy in consideration.

When designing a heating system there are two main demands to the feeding systems. The feeding system must be able to get the fuel into the combustion chamber, and it must not cause unnessecary emisions.

When designing a feeding system for a steamturbine based heat and powerplant, it is also very important that the fuel supply is very constant, so that one can avoid variations in the steam data.

Screwfeeders.

The principle from the small screwfeeders has been upscaled with 3 parallel screws. The system demands divided biomass at a very uniform quality. The expiriences with this system that has now worked for almost a year have been satisfactorily, although there have been considerable problems with the pretreatment and string remover equipment.
The total energy comsumption with pretreatment equipment is 50–100 kJ pr kg biomass.

An other screwfeeder that has recently been marketed but not yet implemented is a twin screwfeeder with conical screws. Because of the very large conical screws the feeder can feed biomass from the bale with no pretreatment, and no string remover is necessary.

The feeder is equipped with a density regulator at the outlet to ensure a constant texture of the biomass supplied to the combustion chamber, and to provide a seal to prevent leak air to flow to the combustion.

When closing down the densityregulator acts as a heat shield to protect fire from burning back in the feed line.

This feeder can feed up to 15–20 tons biomass an hour, and the total energy consumption is 3–20 kJ pr kg biomass. The energyconsumption is dependent on the initial texture of the biomass and the moisture.

Pistonfeeders.

A piston feeder has been use on a number of heating plants with good results. When the principle was implemented on a steambased heat and powerplant problems with the continuity of the fuel flow arose.

The problems were minimized to an acceptable level after a lot of reconstruction.

The principle has not been considered for any new plants.

Wholebalefeeders.

There are two systems to feed whole bales into a combustion chamber.

One is a system where the bale is fed continuosly into the combustionchamber, and the combustion takes place from the front of the bale. This system is in operation in several heatingplants and one heat and power plant.

It is a reliably and well working system with very few components to cause problems.

Because of the restricted combustion area, which is the front of the bale, the maximal capacity for one feeding line is about 5 $MW_{thermal}$. The feeding system has shown a considerably higher emission of NO_x than other conbustionsystems.

The other system is a system where a whole bale is feed into a prefurnace. The system is extremely simple and reliably. This is the most commonly used system for district heating plants.

Because of the discontinuity it can not be used for applications where a continuous energy production is needed. This system can cause some emission when the bale is introduce in the combustionchamber, but there have been no problems in keeping the average emission limits when measured over 15 minutes.

Feeders for gasification and pyrolysisovens.

Several of the above mentioned feeders have been tested on gasifiers and pyrolysis plants, and none have been able too meet the demands, even after extensive reconstruction.

The problems that was encountered were leak problems and problems with upstart–restart.

Several plants is now working with prototype plug feeders, with and with out densityregulators. That seems to be a principple that can meet the demands of a stable and leaktight feeder with a reasonable low energy consumption.

No feeders for gasifier or pyrolysis plants are yet sold with commercial guarantee.

Conclusion.

Most of the available feeding and handling equipment for biomass are far too flimsy.

For combustion plants feeding equipment of an accetable standard is available.

For gasification and pyrolysis plants the feeders still need some commersial development in order to find a reasonable price level.

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INTEGRATED SOLID WASTE MANAGEMENT IN JAPAN

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Abstract

The Japanese, through a combination of public policy, private market conditions, and geographic necessity, practice integrated municipal solid waste management as defined by the U.S. Environmental Protection Agency. The Japanese have not defined a specific hierarchical preference for alternative waste management practices, i.e., waste reduction, reuse and recycling, combustion, composting, and landfill disposal. However, in marked contrast to the U.S. approach, the Japanese system relies heavily on waste combustion, with and without energy recovery.

"Discards", as the term is used in this paper, refers to all materials considered used and spent by residential and commercial generators. That which is discarded (whether recyclable or nonrecyclable) and treated either directly or indirectly (i.e., through municipal-private agreements) by a municipality is referred to as MSW. This paper provides an overview of MSW management practices and private-sector recycling in Japan. Estimates of the total generation of residential and commercial discards and their disposition are also presented. Such an overview of Japanese practices can be used to assess the potential effectiveness of U.S. integrated solid waste management programs.

Of the estimated 61.3 to 72.1 million tons of residential and commercial discards generated in Japan during its 1989 fiscal year (April 1, 1989, through March 31, 1990), an estimated 55 to 64 percent was incinerated; 15 to 28 percent was recycled (only 2 to 3 percent through municipal recycling activities); less than 0.1 percent was composted or used as animal feed; and 17 to 20 percent was landfilled. Including ash disposal, 26 to 30 percent, by weight, of the gross discards were landfilled.

Introduction

CSI Resource Systems, Incorporated (CSI) of Boston, Massachusetts, has recently completed a study of municipal solid waste management practices in Japan for the National Renewable Energy Laboratory. The funds for the study were provided by the U.S. Department of Energy.[1] This paper summarizes the results of this study and presents statistics that describe the integrated municipal solid waste management practices extant in Japan.

The Japanese, through a combination of public policy, private market conditions, and geographic necessity, practice integrated municipal solid waste (MSW) management, defined as follows in the U.S. EPA's *Decision-Makers' Guide to Solid Waste Management*:

> A practice of using several alternative waste management techniques to manage and dispose of specific components of the municipal solid waste stream. Waste management alternatives include source reduction, recycling, composting, energy recovery, and landfilling.[2]

The Japanese Ministry of Health and Welfare (MHW) publishes a number of guidelines to assist municipalities in the implementation of their MSW management programs. The *Guidelines of Solid Waste Management,* published by the MHW in the late 1970s, provides the planning requirements and minimum technical specifications for waste treatment facilities (i.e., facilities to separate, combust, compost, shred, bail, and/or physically, chemically, or biologically change the refuse until it is suited for recycling or landfill disposal).[3] The approach of MSW management in Japan as stated in these guidelines is as follows:

> The basic concept of refuse treatment consists of recycling discharged refuse into usable resources, reusing such resources as much as possible, and then treating or disposing the unusable portion into a sanitary condition. Considering the difficulty of procuring land or seaside areas for such a purpose as a refuse disposal site, it will be necessary to minimize the volume of collected refuse for treatment or disposal.[4]

This approach clearly incorporates waste reduction, reuse and recycling, combustion, and disposal, and thus represents integrated municipal solid waste management.

The Japanese have not defined a specific hierarchical preference for these waste management options. However, in marked contrast to the U.S. approach, the Japanese system relies heavily on waste combustion, with or without energy recovery. Specifically, the MHW's guidelines state:

> Among the various treatment methods, incineration permits the highest reduction of volume while at the same time stabilizing putrefactive organic matter. In general, therefore, combustible refuse will principally be burned and then finally disposed of.[5]

Current policy still emphasizes combustion/waste-to-energy as a primary means of treating MSW. For example, the *Annual Report on Health and Welfare 1990-1991*, states:

> MSW volume can be slashed by crushing [shredding] or compressing to some extent, but reduced substantially by incineration in terms of weight and cubic volume. Therefore, planned construction of or improvements in incineration facilities must be encouraged...[6]

Japan's heavy reliance on combustion/waste-to-energy can be explained partially by the country's severe shortage of landfill space and the Japanese desire to sanitize and sterilize the waste.

National and local governments are now more actively participating in and promoting recycling, as exemplified by the 1991 passage of the Recycling Law and the 1991 amendment to the Waste Disposal Law. This has been due largely to the rapid increase (approximately 3.6 percent annually) in waste generation since 1985. It is also due to the yen's appreciation, which has made imported virgin materials less costly, resulting in a decrease in the relative value of secondary materials.[7]

Municipal Solid Waste Generation and Treatment

"Discards," as the term is used in this report, refers to all materials considered used and spent by residential and commercial generators. That which is discarded (whether recyclable or nonrecyclable) and treated either directly or indirectly (i.e., through municipal-private agreements) by a municipality is referred to as municipal solid waste (MSW). Such treatment can include municipal recycling, landfilling, incineration, and composting. Discards which are diverted from the waste stream (and therefore not considered MSW) are so diverted through private recycling (e.g., "group recycling," recycling dealers, garage sales, flea markets, returns to retail outlets, donations, etc.). Group recycling, considered a private fund-raising activity, is increasingly becoming subsidized by municipalities. However, in cases where such subsidization occurs, group recycling is nevertheless considered private recycling, rather than municipal recycling. Municipal recycling is the recovery of recyclable MSW and can occur through source-separation programs, mixed-waste processing, materials recovery centers, or post-combustion materials recovery. Therefore, when "MSW treatment" is discussed in this paper, it does not include privately recycled discarded materials that have not entered the MSW stream.

Each year, the MHW publishes comprehensive national statistics on Japan's MSW generation the treatment methods. The information in these documents is compiled from data reported by municipalities that together represent 99.9 percent of the national population. The information presented below was obtained from the report published in December 1991 and reflects data from April 1, 1989, through March 31, 1990, i.e., the Japanese fiscal year 1989 (FY89), and deals exclusively with MSW (discards treated by municipal governments).[8]

During FY89, 53.6 million tons (48.7 million metric tonnes) of MSW were generated in Japan. This tonnage does not include discarded materials that were privately diverted from the waste stream for reuse or recycling, nor does it include the approximately 1.4 million tons that were reported to have been disposed of directly by individuals (e.g., disposed of down kitchen sinks, burned, buried, or composted in backyards). This does, however, include materials separated from MSW for reuse or recycling by municipalities after collection.

Of the 53.6 million tons treated by municipalities in FY89, approximately 74 percent was combusted with and without energy recovery, 23 percent was sent directly to landfill, 3 percent was municipally recycled, and approximately 0.1 percent was composted or used as animal feed. This breakdown clearly evidences Japan's national policy of combusting the combustible fraction of the MSW stream, which was begun in the 1970s.

The residues from MSW processing and incineration were eventually sent, along with noncombustible waste, to landfills for disposal. In total, approximately 19 million tons, or 35 percent, of the MSW treated by municipalities was landfilled. Because of incinerating, shredding, and compacting, the MSW volume reduction achieved is significantly greater than its weight reduction.

Bulky, noncombustible, and source-separated MSW is processed to recover reusable and recyclable materials such as ferrous metals, aluminum, glass, newspapers, magazines, corrugated cartons, clothing, furniture, and appliances. Of the 53.6 million tons of MSW treated by municipalities in FY89, only 1.7 million tons, or 3.1 percent of these materials, were recovered from the MSW stream for reuse or recycling. As indicated previously, municipal recycling reflects only a fraction of all the recycling that occurs in Japan.

Private-Sector Recycling

In the U.S., recycling is typically conducted through municipal recycling programs; hence, Americans tend to think of recycling as a municipal function. However, this is not the case in Japan, where the bulk of recycling occurs through private-sector endeavors.

Historically, there has been a strong private market for secondary goods such as old newspapers, magazines (including the telephone-book-sized "comic books" that are very popular in Japan), corrugated cartons, steel, aluminum, textiles (e.g., used clothing for resale in other, less developed Pacific rim countries), and glass. There are many ways by which such materials are privately collected, including return of reusable glass bottles to stores or distributors, group recycling, and private recycling dealers (often referred to in the U.S. as junk dealers or scavengers).

Many products (primarily beer, sake, and liquor, and to a lesser extent milk and soy sauce) are sold in reusable glass bottles. A relatively large number of bottles are recycled each year in Japan. The Clean Japan Center reports that 80.5 percent of the refillable bottles were returned in 1989.[9] The high rate of return of these bottles occurs in part because many of the products sold in these bottles are distributed in large quantities to restaurants, hotels, and bars where the empty bottles are picked up by the distributor. Similarly, many liquor stores and some milk companies make deliveries to households and pick up the empty bottles in the process.

The private market for secondary goods is supported by volunteer organizations that raise money for the community (e.g., local PTA organization raising money for school activities) by establishing collection points, i.e., drop-off centers, for community residents to bring secondary materials for recycling.[10] The volunteer organizations have agreements with private recycling dealers to pick up these materials at predetermined times, and the recycling dealers pay these organizations for the materials received. Often a recycling dealer only collects specific materials; therefore, it is common to have many dealers working with a given volunteer organization. This type of recycling is known in Japan as "group recycling." Recycling dealers also collect recyclable materials directly from households and commercial establishments.

In Japan there are not many resale outlets comparable to those in the U.S. (such as the Salvation Army, Goodwill Industries; thrift, resale, and consignment shops; garage and estate sales; and flea markets) for diverting from the MSW stream used clothing, furniture, appliances, kitchenware, and other household discards. In part, such outlets are not very prevalent in Japan because the Japanese have a greater aversion to using second-hand goods than do Americans. The national government and many municipalities are, however, promoting such ideas as using goods longer; giving usable but unwanted goods to others; and holding garage sales, flea markets, or bazaars as ways to increase the recycling of discards. Japanese officials often cite the success of such U.S. programs in their educational materials promoting these kinds of activities.

Estimated Total Discards and Recycling Rates

Because the mechanisms for recycling previously discussed are carried out by citizens and private businesses, statistics on the total quantity of discards diverted from the MSW stream are not generated by local or national governments. However, a number of studies designed to estimate the total quantity and types of discards (i.e., MSW and privately recycled discards) have been conducted in Japan. Three such studies were conducted in the mid-1980s: one for the Meguro Ward of Tokyo, one for Okayama City, and one for Matsudo City.[11,12,13] Each of these studies estimated the amount of private-sector recycling of discards from both residential and commercial sources.

These studies may overstate the rates of private-sector recycling occurring in these communities because many of the participants in the studies were municipal employees or members of civic groups, and because "in comparison with the average household, many households in the survey are making an effort to reduce and recycle properly."[14] The bias of the survey technique is somewhat counterbalanced by the recent municipal and national government programs to promote recycling. Therefore, the results of these studies provide reasonable estimates of recycling rates in Japan today.

The 1986 percentages, or levels, of private-sector recycling, exclusive of self-disposed waste, estimated in these studies are 18.2 percent in the Meguro Ward, 12.7 percent in Okayama, and 25.7 percent in Matsudo City.

If it is assumed that the above private-sector recycling rates are representative of Japan as a whole, and if the assumed nationwide range of 12.7 to 25.7 percent is applied to the MHW's

FY89 MSW generation figure, then the resultant range of total discards (exclusive of self-disposed waste) generated in Japan during FY89 is 61.3 to 72.1 million tons. Based on this data, the total rate of combined municipal and private-sector recycling of both residential and commercial discards in Japan (exclusive of self-disposed wastes) is estimated to range between 15 and 28 percent.

Of the estimated 61.3 to 72.1 million tons of residential and commercial discards generated in Japan during FY89, an estimated 55 to 64 percent was incinerated; 15 to 28 percent was recycled (only 2 to 3 percent through municipal recycling activities); less than 0.1 percent was composted or used as animal feed; and 17 to 20 percent was landfilled. Including ash disposal, 26 to 30 percent, by weight, of the gross discards were landfilled.

Endnotes

1. The results and opinions expressed in this report are those of CSI and do not necessarily express those of either the National Renewable Energy Laboratory or the Department of Energy.

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BIOMASS COMBUSTION TECHNOLOGIES FOR POWER GENERATION

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Abstract

The state-of-the-art in power production from biomass has been advancing rapidly. Industry has responded to government incentives such as the PURPA legislation in the U.S. and has recognized that there are environmental advantages to using biomass as fuel rather than disposing of it as a waste. The economics of biomass power production hinge on these key factors.

During the decade of the 1980s many new biomass power plants were built. The relatively mature stoker boiler technology was improved by the introduction of water-cooled grates, staged combustion air, larger boiler sizes up to 60 MW, higher steam conditions, and advanced sootblowing systems. Circulating fluidized-bed (CFB) technology achieved full commercial status and is now the leading process for most utility-scale power applications, achieving more complete combustion, lower emissions, and better fuel flexibility than stoker technology at a small premium in cost. Bubbling fluidized-bed (BFB) technology also acquired an important market niche as the best process for difficult fuels such as agricultural wastes, typically in smaller plant sizes.

Development work on several other dedicated biomass power generation technologies is proceeding at a pace that could result in their commercial introduction during the 1990s. Key components of Whole Tree Energy™ technology have been tested, conceptual design studies have been completed with favorable results, and plans are being made for the first integrated process demonstration. Fluidized-bed gasification processes have advanced from pilot to demonstration status, and the world's first integrated wood gasification/combined cycle utility power plant is starting operation in Sweden in early 1993. Several European vendors now offer biomass gasification processes commercially.

U.S. electric utilities are evaluating the cofiring of biomass with fossil fuels in both existing and new plants. Retrofitting existing coal-fired plants gives better overall cost and performance results than any of the dedicated (new plant) biomass technologies; however, retrofit cofiring is essentially a "fuel-switching" strategy that provides no new capacity and is economically attractive only when tipping fees (negative costs for the waste fuels), emissions credits, or government incentives are available to the utility.

Introduction

The objective of this paper, as requested by the Conference organizers, is to "be broad in scope and provide state-of-the-art summaries of advanced biomass and waste combustion systems for power production in the research and scaleup stages".

The major biomass power technologies include:

- Dedicated wood-fired power plants
    - Direct combustion in a stoker or fluidized-bed boiler, driving a steam turbine generator
    - Advanced direct combustion, including Whole Tree Energy™, direct firing of a combustion turbine, and exhaust duct firing in a gas-fired combustion turbine/combined cycle plant
    - Advanced gasification/combined cycle, steam-injected gas turbine (STIG), intercooled STIG (ISTIG), or fuel cell power plant
- Cofiring with coal in a retrofitted utility or industrial boiler, driving a steam-turbine generator

Stoker, fluidized-bed, and cofiring systems are commercial; the other technologies are in development and demonstration stages.

Wood-Fired Power Plants

Stoker and fluidized-bed boiler plants are capable of burning blends of urban wood, mill, in-forest, and agricultural crop residues. The fuel is transported to the plant by truck, processed to remove fines and ferrous material, and stored in an outdoor fuel yard. The fuel is reclaimed and transported to the boiler by conveyor. Stoker boiler plants typically use an ammonia thermal-deNO$_x$ system to control NO$_x$ emissions. Sand is added to the bed in the fluidized-bed boiler to compensate for the low ash content of the wood fuel, and no thermal de-NOx system is required due to the inherent low NO$_x$ emissions of the fluidized-bed technology. The stoker and fluid bed boiler plants plants use fabric filters for particulate control.

Whole Tree Energy™ (WTE) technology is under development with support from EPRI and other organizations for application to large-scale energy crop production and power generation facilities, with generating capacities above 100 MW$_e$. Whole trees are stacked in a drying building, dried, and burned under starved air conditions in a deep bed combustor. A portion of the moisture in the flue gas condenses in the second stage of the air heater and is collected along with fly ash in a wet particulate scrubber.

Advanced wood gasification/combined cycle plants use steam dryers, air-blown fluid bed gasifiers, hot gas cleanup, advanced aeroderivative turbine cycles, catalytic tar and ammonia removal from the product gas, heat recovery steam generators, and steam turbine generators. The long-term technical and economic feasibility of this technology remains to be verified by demonstration projects now getting underway.

Cofiring in Utility Boilers

Several utility boilers have been retrofitted to cofire wood, refuse-derived fuel (RDF), and tire-derived fuel (TDF) with bituminous coal at up to 15% heat input from the alternate fuel. The retrofit involves adding fuel receiving, storage, and boiler injection equipment to the plant and checking the existing electrostatic precipitator and ash handling equipment to ensure they are in good working order.

The method of fuel handling and firing depends on the properties of the alternate fuel and the boiler type. For pulverized coal boiler applications, the fuel may be copulverized with the coal, separately pulverized and fed with the coal, or injected into the boiler without further size reduction and burned partially in suspension and partially on a dump grate, added to the bottom of the furnace. For cyclone and fluidized-bed boilers, some size reduction may be needed, but pulverization and dump grates are not required.

Technology Status and Technical Issues

Stoker Boilers

Stoker boilers have been available since the 1920s with inclined fixed grate designs. This was a major improvement over the older pile burning systems, providing more efficient combustion because of more even distribution of the fuel. The next major improvement to the stoker was the travelling grate, which provided a thinner and better distributed bed of burning fuel and continuous ash removal from the grate. This resulted in faster fuel burnout rates and less sensitivity to load variations.

Typically, grate heat release rates are somewhat lower for coal than for wood because of the slower burning rates of coal. On the other hand, furnace volumetric heat release rates for wood and coal are about the same, resulting in furnace sizes being approximately equal for both fuels for the same steam production in the boiler.

The higher moisture content of the wood and the lower furnace exit temperatures result in larger heat transfer surfaces in the convective sections of wood-fired stokers than those based on coal. Coal's higher ash deformation temperatures allow higher furnace exit temperatures, while wood's higher moisture content leads to higher volumetric flue gas flows.

There have been steady improvements to travelling grate boiler designs for nearly 50 years. The principal areas of development have been in grate and furnace water wall design and, in recent years, combustion control for lower emissions. Various manufacturers evolved different configurations for the boilers to address the needs for grate cooling and water wall design to prevent slagging and fouling. Recent boilers use water-cooled vibrating grates, allowing the use of higher temperature undergrate air and a higher percentage of overfire air.

Early designs used relatively little overfire air to provide maximum cooling to the grates with underfire air. This resulted in high combustion temperatures and high levels of NO_x. Recent designs, with staged combustion, provide for higher levels of overfire air (as high as 50%) to control NO_x formation. The additional advantage of using lower quantities of underfire air is lower unburned particulate carryover. Reduced underfire air resulted in the need to protect the grate via refractories or other means of cooling (e.g., water-cooled grates).

Much experience has been gained in industry with waste wood combustion in stoker boilers during the 1980s. This experience has been translated into new and improved designs. Although most of this commercial experience has been in the paper and pulp industry and among independent power producers (IPPs), significant experience also exists among utility companies. Two examples are the Burlington Electric McNeil plant in Vermont, and the Chapleau cogeneration plant in Ontario. Both of these plants use stokers; the former uses a travelling grate while the latter uses a water-cooled, vibrating, inclined grate design. Both of these facilities have been described in an EPRI report. [Lee et. al. 1990]

Fuel switching capability of stoker boilers is usually limited. Travelling grate stoker boilers are usually designed for a given fuel size distribution and moisture content. The result of introducing more fines than designed for results in more suspension firing and carryover. Proper design allowance for moisture is particularly critical in the case of wood because of its high moisture content. Moisture content should typically be kept within about 10% of the design range. Fluctuations in moisture content outside this range result in significant changes in flue gas flows and in heat transfer rates.

Certain ash constituents, particularly high concentrations of sodium and potassium, can lead to low melting ashes and slagging in stoker boilers. Other constituents, such as high concentrations of chloride, can lead to stress corrosion. Contaminants such as chlorides can be introduced in urban waste wood and in wood that has been in contact with salt water. Some agricultural wastes, particularly rice straw, contain low melting ashes. Because of problems associated with combustion of agricultural wastes, their content is now limited in the total fuel content going to the furnace. Typically, boiler operators try to keep agricultural wastes below approximately 15% (heat input) of the total boiler fuel.

Other wood properties may also have important impacts on stoker design. For example, the low density of wood permits pneumatic injection of fuel into the furnace. Coal, on the other hand, usually requires mechanical means of bringing fuel into the stoker boiler. Variability in fuel density, caused for example by unwanted contaminants in wood, can lead to uneven distribution on the grate or in suspension burning. [Hollenbacher 1992 and Zurn 1986]

The impact of fuel properties on boiler performance shows the need for good fuel preparation.

Fluidized-Bed Combustors

Development of fluidized-bed combustion technology dates back to the 1960s. This development took place primarily for the purpose of reducing SO_2 and NO_x emissions from utility power plants and providing a technology that could burn a wide variety of fuels. Initial efforts concentrated on development of the bubbling bed concept. Several large-scale test and demonstration units were operating in the 1970s. However, significant commercial application of this technology did not take place until circulating fluidized-bed processes were successfully demonstrated during the 1980s. Circulating fluid bed (CFB) boilers gained favor over bubbling beds for larger scale applications mainly because of their greater ease of maintaining bed stability, more efficient and complete fuel burnout, better emissions performance, and the ability to handle larger variations in fuel particle size. (Bubbling beds are generally favored for smaller plant sizes because of their lower capital costs; CFBs have significantly higher auxiliary power requirements due to fan horsepower.) Most of the development work on circulating beds was done in Europe.

There is now wide commercial experience with CFB boilers burning biomass fuels. California projects represent the largest component of this experience in the United States. [Wilhelm and Simbeck 1990] About 165 MW of installed CFB capacity in California is based on wood and other biomass wastes. Additionally, approximately 100 MW of biomass-based capacity in the state is represented by bubbling bed installations. There are several other CFB boilers using biomass fuels in the United States, such as those at West Enfield and Jonesboro in Maine.

While most of the CFB boilers in the United States are owned by non-utility companies, there is important utility experience with such boilers, albeit on coal rather than biomass. Three CFB boilers, each well over 100 MW, are being operated by electric utilities. Tri-State Generation and Transmission Association is operating one 110 MW unit at their Nucla station in Colorado (previously owned by the Colorado-Ute Electric Association), and Texas-New Mexico Power Company is operating two 150 MW units at its TNP-1 station in Texas. An additional 165 MW CFB unit is scheduled for commissioning in 1993 for the Nova Scotia Power Corporation in Canada. Other 100 to 300 MW-class CFBC units are being considered by some U.S. utilities.

Although a significant number of CFB boilers are operating commercially, and much experience has been gained from their operation, several technical issues remain with biomass combustion that need to be considered with every new project. Among these issues, the principal issue is potential variability of fuel composition and quality.

Low heating value, high moisture content, and high reactivity of biomass fuels determine some of the unique design characteristics for CFB boilers. The lower heating value and high moisture content of typical biomass fuels leads to lower heat transfer requirements in the furnace section of the CFB boiler than for coal firing. Thus, biomass-fired boilers require a higher proportion of convective heat transfer surface than similarly-sized coal-fired units. Because of lower heat transfer requirements, furnace solid bed densities are also lower for biomass than for coal. Gas velocity in the furnace is typically in the range of 17-26 ft/s. Its choice depends on the reactivity of the fuel, which in turn determines the required residence time in the furnace. Gas velocity also is controlled to achieve the desired bed density, which sets the heat transfer rate and turndown capability of the boiler.

Because of high residence time in CFB boilers, carbon burnout of highly reactive biomass fuels such as wood is virtually complete, approaching 100%. (Carbon burnout for coal, which is much less reactive than wood, is about 98%.) On the other hand, because of their lower fuel residence time in the furnace, bubbling bed boilers experience lower carbon burnout than CFB boilers. Other principal advantages of

CFB boilers over the bubbling bed ones are fewer fuel feeding problems and less excess air use. The principal disadvantages of CFBs over bubbling beds are higher fan power requirements and greater cost.

CFB boilers can be designed to handle a wide range of fuel quality. However, to keep costs within reason, the boiler is usually designed for an anticipated set of fuels. Variations of fuel quality outside this range can lead to operating problems. Wide variations in particle size and density, as well as moisture content, can lead to boiler instability. Proper maintenance of solids inventory in the boiler is imperative for stable operation and efficient heat transfer. Maintenance of solids inventory requires good control over particle size distribution for both fuel and inert solid materials used in the bed. Wide swings in moisture content can lead to unstable combustion and to imbalances in heat transfer in both the convective and the furnace sections of the boiler.

Operating difficulties have been caused by ash compositioin, and by fuel impurities such as rocks and dirt, in nearly all biomass-fired CFB boilers. The principal problems have been associated with high alkali (principally potassium and sodium) content, which is most pronounced in agricultural wastes and tree trimmings. These low-melting ash constituents can cause fouling of boiler surfaces, deposition in cyclones, and agglomeration of bed materials. The best current solution for this problem is control of feed in the fuel preparation yard by limiting the quantities of undesirable materials and by judicious blending of different fuels for consistent quality of feed to the boiler. CFB boilers must be designed to allow periodic removal of rocks and agglomerates from the bed during operation. [Babcox & Wilcox 1992, Belin et. al. 1988, Hollenbacher 1992, and Howe and Divilio 1992]

Whole Tree Energy™ (WTE)

All of the WTE process operations are based on commercially available equipment; and yet the process concept as a whole is a radical departure from traditional industry practice.

The fuel drying system is an integral feature of WTE. Waste heat, which would otherwise be vented to the atmosphere in the stack gases, is used to preheat ambient air to 130 °F. This hot, dry air is used to dry the wood stacked in a huge air-inflated building (similar to the Metrodome in Minneapolis) for 30 days before it is conveyed to the boiler and burned.

For a nominal 100 MW_e plant, the drying building is approximately 200 feet high by 650 feet in diameter. It has no internal support columns. The dome also encloses the under-pile air distribution system for the drying air, the tower crane for unloading the trucks, and a portion of the drag conveyor to the boiler.

The tower crane operator deposits a load of dry trees from the tree pile onto the conveyor, picks up a full truckload of green trees, and deposits them on the wet side of the pile. Trucks enter and leave the building through two truck doors. The pile of whole trees is arranged in a randomly stacked donut shaped pile.

The air-supported dome is made from a double layer of a strong, translucent plastic/fabric film. Aircraft cables are embedded in seams every 4 feet to provide structural strength while maintaining the shape of the dome. Low pressure air separates the inner and outer layers of the double-wall cover and acts as an insulation layer. The dome material is expected to last about 15 years before needing replacement.

Natural daylight provides light for operations inside the dome during the day. Lights are mounted on outside poles illuminating the cover at night for shadow-free inside light without internal obstructions. At the top of the dome, a large circular vent is designed to exhaust the warm, saturated air from the building to the atmosphere. This vent is adjustable to retain a positive pressure inside the drying building at all times.

An air distribution system circulates hot air from the heat exchangers to a system of large radial ducts under the pile of whole trees. The ducts are below grade so that the bottom of the whole tree pile is flush with ground level. A system of simple automatic baffles at the manifold end of each air channel is used to control the flow of air through various sections of the pile. Less air is required to remove the excess moisture from the drier wood while significantly higher volumes are required for the wettest wood.

The crane/grapple system in the center of the drying building is mounted on a central tower which doubles as a water storage tank for a deluge fire-control system. An air-conditioned cab for the operator is located on the boom at the top of the tower offering a clear view of the entire tree pile and truck unloading area.

The trees are fed into the boiler from the fuel drying building on a first-in first-out basis. The 8-foot wide drag conveyor consists of regularly spaced parallel steel 8" x 12" rectangular tube slats attached at each end to a continuous loop of cable. The drag conveyor rides along the bottom of an 8-foot square channel and delivers whole trees dried to an average moisture content of 20-25% to the furnace charge box.

The ram charger door allows batches of whole trees, sectioned to about the same length as the furnace width, to be pushed onto the deep bed (some utility furnaces are over 90 feet wide). The ram pushes a load of trees approximately 4 feet high and 8 feet wide into the furnace.

In a typical fuel charge cycle, a cut-off saw extending across the fuel feed conveyor cuts the continuous supply of whole trees into batches slightly smaller than the furnace width. The furnace isolation gate closes and the charge pit isolation gate opens to accept a new batch of fuel. The charge pit acts as an airlock. The injection ram is retracted to the back surface of the charge pit and the charge pit ram pushes the load of trees into the charge pit. The charge pit isolation gate closes, the furnace isolation gate opens, and the injection ram pushes the load of fuel into the furnace on top of the deep pile.

A variety of tests have been completed on WTE technology. In 1979, a high efficiency two-stage combustion device using 2-foot long, 9 inch diameter logs was tested. Results were sufficiently encouraging to proceed with larger-scale tests in a modified boiler using unprocessed 4-foot lengths of trees as fuel. A larger-scale test in 1986 successfully handled and fired unprocessed 16-foot tree sections in a retrofitted 10 MW_e coal-fired unit owned by Northern States Power Company. [Ostlie 1992]

EPRI funded an engineering/economic evaluation of the concept in 1991, and cofunded some field tests to evaluate further the fuel stacking, drying, and combustion operations in 1991-1992. EPRI also cofunded a preliminary feasibility study of retrofitting an old coal-fired boiler at the Tennessee Valley Authority. This work increased the confidence in the workability of the process concept and refined some of the process details. At this point, the process is ready for a full-scale integrated demonstration.

The technical issues addressed during the 1991-1992 test program included demonstrations of whole tree harvesting, transportation, stacking, unstacking, drying, and combustion. The full scale tests used commercially available equipment and duplicated procedures and processes which are pertinent to an actual WTE facility.

The harvesting, loading, and transportation tests demonstrated that whole trees could be harvested from natural, declining, "non-merchantable" stands, skidded to a loading area, loaded (whole) onto standard trucks with payloads of over 25 tons, and transported on logging and improved roads with no noticeable fallout and no special transport restrictions. Rates of harvest, loading, and transportation, using only one set of harvesting equipment and two trucks, were sufficient to supply a 50 to 75 MW WTE power station.

To demonstrate stack stability to a height of at least 60 feet, three thousand tons of whole trees were stacked on a base 70 feet square using a conventional tower crane and grapple. An actual stack height of 102 feet was achieved, with no obvious limitations to stacking an additional 50 feet or more. Stack stability was demonstrated by attaching a D6 Caterpillar crawler tractor to an embedded steel beam in the stack at about the 75-foot elevation. Over 45,000 pounds of lateral load were exerted when the 3/4" steel cable connecting the tractor to the stack separated at the splice. No noticeable deflection of the stack occurred. Stacking and unstacking rates, although using relatively small-scale equipment, were sufficient to support a 50 to 75 MW WTE power station.

For drying testing, the stack of trees was trimmed on the side faces to provide a relatively smooth surface and wrapped with a tarp on the four vertical sides. This allowed simulation of a section of whole trees in a WTE drying dome by uniformly channeling drying air through the stack and minimizing wind entry at the sides. The top was left open to ambient atmosphere. Drying air at 130 °F (representing the drying air heated by waste heat in the flue gas of a WTE power plant) was ducted to a distribution manifold below the trees. Over a 30-day drying period, the average moisture content of the tree stack was reduced from an initial 44% to 20%. Over 700 tons of water were removed from the trees in the 30-day drying period.

The combustion tests were conducted in an open-top refractory-lined vessel intended to simulate the devolatilization and primary combustion zone in the bottom of a WTE boiler. Combustion of the volatile gases occured mostly in the open air above the test furnace. An average heat release rate of 3.3 MBtu/hr/ft^2 was demonstrated, and a short duration test produced over 4.2 MBtu/hr/ft^2. In comparison, a typical coal-fired boiler has a heat release rate of approximately 2 MBtu/hr/ft^2, and wood chip-fired boilers are typically below 1 MBtu/hr/ft^2. [Energy Performance Systems 1993]

The developer of the WTE technology considers the following to be the most challenging technical tasks to be accomplished in conjunction with the design, construction, and operation of a 100 MW demonstration plant: [Ostlie 1993]

- Designing the demonstration plant with enough extra capability to ensure success:
  - Wide range of overfire/underfire air capabilities
  - Wide range of gas flow rates
  - Wide range of temperature approach capabilities
  - Range of heat absorption capabilities in the superheat and reheat sections
  - Design for success; optimize later
- Developing the computer controls for the tree stacking/reclaiming system
- Designing the high pressure fire system in the drying dome

Gasification/Combustion Turbine Systems

Small atmospheric pressure biomass gasifiers are commercially available now for use in combustion turbine power generation applications. However, there have not yet been any commercial gas turbine applications. A number of atmospheric pressure units are operating commercially in Europe and others have operated in the U.S., producing low-Btu gas (LBG) to fire kilns, dryers, and boilers. [Bain and Overend 1991, Bain 1991, and Bain 1992] The largest of these units is rated at about 120 MBtu/hr LBG output, which is approximately comparable to the fuel requirement for a 10 MW gas turbine.

A 600 t/d (peat) Rheinbraun 10 atm.-pressure fluidized-bed gasifier (for ammonia synthesis gas production) operated in Finland from 1988 to 1991, when it was shut down because of the low price of natural gas from Russia. [Sipila et. al. 1989] The commercial readiness of pressurized gasification (at pressures above about 20 atm.) will depend on the successful demonstration over the next five years of both the pressurized gasifiers and pressurized biomass feeding systems. While lockhopper feed systems probably will be used in most cases, a screw feeder (plug flow-type) and other feeders are also under development. [Rautalin and Wilen 1992] The plug flow feeder reportedly requires more power, more maintenance, and a wetter fuel for proper pressure sealing. [Miles 1993]

Although many organizations have been investigating biomass gasification, only a select few technologies are expected to be demonstrated in combustion turbine applications in the near term. Presently all of them are fluidized-bed gasifiers (FBGs) and all but one are pressurized FBGs (PFBGs). The demonstration projects that are underway or in planning now include:

- Varnamo, Sweden: approximately 90 t/d of wood (dry basis), 6 MWe combined cycle plus 30 MBtu/hr district heating, using the new Ahlstrom Pyroflow air-blown, circulating PFBG; in collaboration with the Swedish utility Sydkraft (1993 start-up). [Lundkvist 1992]
- Quebec Province, Canada: nominal 192 t/d of wood (dry basis), 15 MWe combined cycle, using the Biosyn-developed air-blown bubbling PFBG, near a remote Quebec Hydro substation (1996 start-up). [Biothermica International 1993]

- Maui, Hawaii (the PICHTR Project): 100 t/d of bagasse IGT air-blown, bubbling PFBG; in Phase 2 (probably 1995 or 1996) will fire a small gas turbine (probably 3-4 MW). Co-funded by U.S. DOE and the state of Hawaii. [Bain and Overend 1991]

- Brazil (the Global Environment Facility Project): partly funded by the World Bank; two systems are being evaluated; one will be selected. The project will probably start up after 1995. The primary candidate technologies are:

    - Bioflow (a joint venture of Ahlstrom and Sydkraft) design using an Ahlstrom Pyroflow air-blown PCFBG with a GE combustion turbine.
    - TPS Termiska Processor (formaerly Studsvik) design using an air-blown atmospheric pressure CFBG and a GE combustion turbine. [Elliott 1993]

Many of the commercial combustion turbines can burn the low-Btu gas and medium-Btu gas produced by air-blown and oxygen-blown gasification, respectively, if the gases meet the turbine vendors' specifications for heating value, H_2 content, contaminant levels, and temperature. These specifications vary from model to model. The maximum contaminant levels are particularly stringent for aeroderivative turbines.

Fuel gas contaminant levels can be reduced and controlled with properly designed conventional wet (water) scrubbing techniques. Hot gas cleanup techniques, which eliminate wet scrubbing and reheating of the fuel gas, are under development. Even with hot gas cleanup, the hot, raw gasifier product gas must first be cooled to a temperature of about 1000 °F.

Numerous technical issues remain for commercial biomass gasification/combustion turbine plant design and operation. They include:

- Variability in fuel type, composition, and quality

- Optimization of gasifier fuel moisture content by drying, and choice of dryer

- Selection of gasifier type and design; i.e.:

    - Bubbling versus circulating FBG
    - Atmospheric pressure versus pressurized gasification
    - Air-blown versus oxygen-blown gasification

- Maximizing fuel carbon conversion to fuel gas, which includes:

    - Minimization of tars/oils and optimization of processing, recovery, or disposal of tars/oils
    - Char minimization or recycle as plant fuel

- Design and optimization of the hot gas cooling and cleanup system, including NH_3 destruction

- Combustion turbine selection

- Optimization of overall process integration and utilization of low-level heat

Fuel type, composition and quality impact the design of the front end of the plant (receiving, handling, storage), the dryers; and the gasifier. It is desirable to reduce gasifier fuel moisture content as much as is practical (down to 10-15 wt% H_2O) and to control it at a constant level.

Rotary drum dryers have been used with wood and other biomass materials for many years. They are reportedly operationally forgiving and safe (low fire/explosion risk). The use of superheated steam for drying, rather than burning some of the plant feedstock, may permit an improvement in overall plant efficiency. The Finnish utility Imatran Voima Oy (IVO) is developing peat and biomass IGCC concepts with integrated steam drying systems. [Hulkkonen et.al. 1993, 1991, and 1991a]

Lockhopper systems have not yet been commercially demonstrated with wood gasifiers above 10 atm. Inert gas (<4 vol% O_2) is required for the lockhoppers, because of the risk of explosive mixtures with air and biomass fines.

Plug-flow-type screw feeders and other types of feeders are under development for pressurized feeding of biomass. [Rautalin and Wilen 1992] However, the plug-flow feeders require higher moisture content for sealing, substantially more power, high maintenance, and they reportedly are limited to pressure boosts of 150 psi per stage. [Miles 1993]

Both atmospheric pressure and pressurized fluidized-bed gasification are commercially available. Scale-up to larger sizes for utility applications, extension of operating pressure to the 20-40 atm. pressure range, and coupling with combustion turbines remain to be demonstrated.

Circulating FBG provides higher residence time than bubbling FBG. Consequently, carbon conversion should be higher and the production of tars/oils should be lower in CFBG. Circulating FBGs also should be less sensitive to fuel moisture swings than bubbling FBGs (by analogy with CFBC boilers and bubbling FBC boilers). However, pressure drop through a CFBG will be higher than that through a comparable bubbling FBG.

The tradeoffs between pressurized and atmospheric pressure gasification are largely economic, resulting from differences in equipment sizes and weights and plant power requirements. At atmospheric pressure the gasification train equipment is larger, but the feedstock and gasifier air do not have to be pressurized. However, the fuel gas must be cooled, cleaned, and compressed to the delivery pressure required by the combustion turbine. The economics of these tradeoffs remain to be quantified in site-specific and gasifier design-specific engineering studies (e.g., the Brazil Global Environment Facility project).

Tampella's and Vattenfall's proprietary joint engineering studies for the 60 MW VEGA project reportedly showed that an IWGCC plant based on air-blown PFBG is more economical than one based on O_2-blown PFBG. [Lindman et. al. 1992]

Increased fuel carbon conversion to fuel gas and reduction of tar/oil production are facilitated by the use of increased residence time as discussed above; higher gasification temperature (e.g., 1800 °F rather than 1600 °F); the use of dolomite as bed material; staged gasification and tar/oil cracking; the use of O_2-blown gasification rather than air-blown gasification; recovery of tars/oils and recycle to extinction in the gasifier, a separate partial oxidation reactor, or process combustor; and use of gasifier char/ash as fuel for drying gasifier feed.

The tar/oil crackers employed in the two-stage processes should be comparable in size and cost to the first stage gasifier. However, if the tars/oils can be effectively destroyed, the added expense of the second stage may partly pay for itself in the reduction of downstream design and operating complications associated with the condensation and removal (or partial recovery) of tars/oils.

Cooling of the hot raw fuel gas can be accomplished in a convective waste heat boiler. Dow has pioneered the use of fire-tube boilers for this application in its coal gasification process. The fire-tube design is considerably cheaper than the water-tube design [SCS 1990], but it has not been demonstrated with biomass gasification. The potential for surface fouling and tube plugging by condensed tars (with entrained solids) is an issue. In the 600 t/d peat gasifier in Finland this problem was alleviated by the recycle of benzene (one of the oil components). [Bain and Overend 1991]

Further gas quenching and wet scrubbing produces a clean, low-NO_x fuel gas for combustion turbine applications. The actual efficiency of scrubbing for the removal of very fine ash/bed solids and tar particulates to combustion turbine specifications in a utility-scale operation requires demonstration.

A simple partial recovery of a portion of the water-insoluble tar/oil hydrocarbons may be possible if the phases separate cleanly by gravity or centrifuging. This would enable recycle of the recovered material to extinction in the gasifier or other use as process fuel and would improve the overall process efficiency. However, waste treatment of the entire tar/oil-water condensate mixture may be more practical than attempts at recovery. Further process-specific R&D is required on this subject.

Hot gas cleanup is being promoted and developed by a number of organizations, because of the improved thermal efficiency and equipment and capital savings that it would permit. Current throttling valve materials technology and volumetric fuel delivery to gas turbines limit the gas temperature to about 1000 °F maximum. At this temperature level, tar/oil vapors should remain in the vapor phase and contribute to the heating value of the fuel gas and overall thermal efficiency. The impact of this vapor component on CO and smoke emissions is unknown.

No hot gas filters have been proven for this service with coal or biomass gasification. Filter effectiveness and plugging of the filters (possibly irreversibly) by tars and very fine solids are issues.

An environmental disadvantage of hot gas cleanup is that any fuel-bound nitrogen that is converted to NH_3 or HCN in the gasifier passes through the cleanup system and is converted to NO_x in the combustion turbine. To meet stringent NO_x emission limits, either a catalytic NH_3 destruction reactor must be developed, or a selective catalytic reduction unit will have to be installed at the turbine exhaust. The Technical Research Center of Finland, VTT, is conducting laboratory-scale development work on a nickel catalyst system that would operate at gasifier outlet temperature. [Leppalahti 1992]

Given the status of biomass gasification technology, heavy duty combustion turbines are more readily applicable than aeroderivative turbines, for two main technical reasons:

- The heavy duty turbines of interest (15 MW and higher ratings) operate at lower pressure ratios (11-16), thus simplifying gasification train design relative to the higher pressure ratio (18-32) aeroderivative engines of interest

- Aeroderivative turbines require cleaner fuel gas than heavy duty turbines, because of the small clearances in the high-tech aero engines

Aeroderivative engines are more efficient and produce lower-temperature exhaust gas than heavy duty turbines. This means that for the combined cycle based on an aeroderivative engine, a smaller amount of exhaust heat will be available for the steam cycle. This can impact the steam turbine efficiency, which drops off for smaller steam turbines. Consequently, the overall combined cycle efficiency may be lower when an aeroderivative turbine is used, unless the HRSG design is based on close approaches to the pinch points.

An economic consideration is the higher capital cost ($/kW) of aeroderivative turbines. [Gas Turbine World 1991] However, in a baseload operation, the high availability afforded by the rapid replacement engine lease or exchange policies of the aeroderivative turbine vendors could be an important consideration. In simple cycle or cogeneration applications in which a steam turbine is not employed, the higher efficiency of the aeroderivative turbines could be an advantage.

Various turbine models with nominally similar ratings may have different fuel quality specifications for CO, H_2 content, HHV, temperature and contaminant levels. While a fuel LHV of about 150 Btu/scf or higher is desirable, some turbines may be operable with an LHV as low as 100 Btu/scf. A minimal hydrogen content may also be specified for very low heating value fuels. The alkali metal (K and Na) content of the fuel gas must be very low to prevent corrosion of the turbine. (Biomass ash typically contains more K and Na than coal ash.)

Other factors that vary among turbine models are the compressor surge margin and the flexibility for control and design modifications that may be required to fire LBG. The potential for compressor surge (stall) problems due to the potentially higher expansion turbine mass flow with LBG firing can probably be alleviated by extracting air from the compressor or by reducing the expansion turbine inlet temperature and thus derating the turbine. [Johnson 1992]

There is little evident advantage for a biomass gasification/STIG system over a combined cycle system. There is a distinct efficiency penalty for the STIG system relative to the combined cycle. For example, the heat rate for a natural gas-fired 51.4 MW LM5000 STIG system is 9.6% higher than the heat rate for a 56.5 MW GE Frame 6B combined cycle system.

Another issue with STIG is the limit on the amount of steam a specific STIG engine can ingest. Fluidized-bed gasification requires hot gas cooling and produces a substantial amount of steam in the gas cooler (waste heat boiler). The STIG turbine may not be able to ingest this additional steam, unless the added mass flow can be compensated by air extraction from the combustion turbine air compressor. This may be more of a problem for the GE LM1600 (13.4 MW ISO) than the LM 5000 (33.8 MW ISO).

Although STIG offers capital cost savings in the elimination of the steam turbine, condenser and the cooling tower that are required in the combined cycle, the natural gas-fired STIG plant costs in $/kW are higher than combined cycle plant costs. EPRI's 1989 TAG shows estimated capital costs for natural gas-fired STIG plants in a utility setting that are 60-100% higher than costs of combined cycle plants. One primary niche for STIG is in cogeneration applications with cyclical steam demand and in which all of the electric power generated can be used or sold, such as pulp and paper mills and food processors with favorable electric power sales contracts.

Cofiring

Cofiring of biomass with fossil fuels is a well-established technology. Between 1972 and 1984, nine U.S. electric utilities cofired more than 600,000 tons of RDF in existing utility boilers. [EPRI 1988] In 1987, Power Magazine listed 182 companies who had cofired boilers, including 31 electric utilities. [Power, July 1987] Most of the cofiring was biomass and coal in existing coal boilers. Wood waste is commonly cofired with coal in the pulp and paper industry. In 1987, the U.S. pulp and paper industry consumed 46.5 million tons of wood waste (at 50% moisture) and 13.4 million tons of coal. [National Coal Council 1990] On an energy basis this is about 55% wood waste and 45% coal.

Since the Public Utility Regulatory Policies Act (PURPA) of 1987, there has been a great increase in biomass-based power generation. A significant portion of this biomass-based power is generated via cofiring, especially by the pulp and paper industry. Many of the new boilers specifically designed for cofiring have been FBC boilers.

Electric utilities have been responsible for much of the recent activity in cofiring. [Power, August 1991] This cofiring experience is varied. Some utilities continue to cofire RDF with coal. Some have cofired TDF with coal. One utility has cofired whole tires with coal. Another utility has cofired large amounts of hurricane-generated waste wood with coal (this cofiring involved essentially no modifications of the existing PC power plant as the wood chips were directly mixed with the coal before the pulverizers).

There is currently increased interest in the cofiring of biomass fuel with coal in existing utility boilers for the following reasons:

- Lower SO_2 and NO_x emissions than for 100% coal-firing. This is an important advantage for existing coal-fired utility boilers affected by the Clean Air Act Amendments (CAAA) of 1990.
- Higher thermal efficiency than for a dedicated 100% biomass-fired boiler.
- Lower capital cost than for a dedicated 100% biomass-fired boiler. The capital cost savings are significant for cofiring in an existing coal power plant relative to a new dedicated 100% biomass-fired power plant.
- Lower cost of some biomass fuels than for coal.
- Lower impact of the varying quality and quantity of biomass fuel, due to blending with coal.
- Helps ease the growing solid-waste disposal problem.
- Potential of generating ash waste in a better form, such as slag (in a cyclone furnace) and the mixing of biomass ash with coal ash. (On the other hand, adding waste components to an existing facility's coal ash might impact the utility's ability to sell the ash.)

Although cofiring biomass fuels in existing coal boilers has significant capital cost advantages over construction of a new boiler, it does create problems that could be avoided with a new boiler. Cofiring can have significant effects on the performance of existing utility coal fired boilers. [EPRI 1988] This is principally due to the high moisture content of most biomass fuels and the high ash content of some waste fuels, such as RDF.

The key technical issue for cofiring is the negative impact on the existing boiler performance. Cofiring usually results in reduced power plant capacity and efficiency. The capacity derating can be significant depending on the original boiler design and the properties of the biomass. Specifically, the fouling and slagging index of some biomass and waste fuel ash can be severe and can increase capacity derating as well as boiler maintenance. Most biomass fuels contain high moisture content and require large amounts of excess combustion air. This can cause capacity derating due to the higher flue gas flow in addition to the inherent efficiency penalties.

Another technical issue in cofiring is the solid waste. Specifically, solid waste ash from coal-fired boilers is normally considered non-hazardous and, for electric utilities, is exempt from the rigorous Resource Conservation and Recovery Act (RCRA). However, cofiring of waste fuels such as RDF could lead to loss of the RCRA exemption which would increase disposal costs because of the possibility that mixed coal/RDF ash would require disposal in expensive hazardous waste landfills.

Process Considerations for Biomass Fuels -- Present and Future

Tables 1 and 2 summarize some key fuel/process considerations for near -term options by examining size, moisture, and alkali ranges encountered with four major classes of fuel (in-forest fuel, urban wood waste, wood products manufacturing fuel, and agricultural wastes) and preferred by four major process options (stoker or bubbling bed boiler, CFB boiler, Whole Tree Energy™; and cofiring in a coal-fired boiler).

Table 1
Size, Moisture, and Alkali Ranges of Present-Day Biomass Fuels

Fuel Class	Size	Moisture	Alkali
In-forest fuel	Whole trees Logs Branches Hog fuel	30-60% (45% typical) Seasonal	Stem wood: low to medium Branches, leaves: high Hog fuel: medium
Urban wood waste	Construction or demolition debris Prunings, branches Lawn clippings Hog fuel	12-32% (15% typical)	Construction or demo debris: low Prunings: high Clippings: high Hog fuel: medium
Wood products manufacturing fuel	Pieces (ends, edges) Hog fuel Shavings Sawdust	41-46% (45% typical) Shavings, sawdust can be very wet or very dry	Low
Agricultural waste	Prunings, branches Stalks, straw, bagasse Hog fuel Pits, shells, hulls	10-40% (no "typical") Seasonal availability	Very high

Table 2
Process Considerations for Present-Day Biomass Fuels

Process	Fuel Size	Fuel Moisture	Fuel Alkali
Stoker grate or bubbling bed boiler	- Hog fuel OK - Max. ~2 inches - Minimize fines	- OK as long as variability is controlled	- Least sensitive to high alkali - Blend ag fuels to low % of total (<~10%)
CFB boiler	- Hog fuel OK - Max. ~2 inches - Fines OK	- OK as long as variability is controlled	- Very sensitive to high alkali -- avoid ag fuels
Whole Tree Energy™	- Whole trees - Large pieces - Avoid small pieces and fines?	- OK -- has dryer	- Not likely to use high-alkali fuels - Tolerance to alkali unknown.
Cofiring in existing coal-fired boiler	- Smaller the better - Max. ~1/4 inch - With PC boiler, must pulverize or add dump grate	- Less the better	- Avoid high-alkali fuels (ag fuels) completely

These summary tables indicate some likely fuel preferences, given a process (or likely process preferences, given a fuel):

- Stokers and bubbling bed combustors are designed to handle fuel in the "hog fuel" (<2") size range. Fines cause problems and should be minimized. High or low moisture content is not a particular problem as long as the moisture level in the fuel fed to the boiler is consistent. (Fuel blending is key.) All of the three wood waste fuel categories are acceptable, including prunings and clippings. High alkali fuels (agricultural fuels) can be tolerated, but must be kept to a low percentage (~10% is given as an example, but each unit should determine its own operating limits). Of all of the combustion systems, bubbling bed combustors appear to have the most capability for handling very difficult fuels.

- CFB boilers are also designed to handle fuel in the hog fuel size range. However, fines are acceptable because of the gas recirculation system. Moisture content must be consistent. (Again, fuel blending is key.) All of the three wood waste fuel categories are acceptable, as long as prunings and clippings are minimized. CFBs are very sensitive to high alkali fuels, so agricultural wastes should be avoided.

- Whole Tree Energy™ plants are designed to be fed whole trees or large pieces of trees or wood. The ability of the system to handle small pieces and fines has not been demonstrated. High moisture is not a problem because the process has a fuel drying system. Ash deposition is expected to be no problem when whole trees or clean wood wastes are used as fuel.

- The biomass fuel for cofiring with coal is preferably as fine in size as possible, as dry as possible, and low in alkali. Introducing ash deposition problems into a large coal-fired boiler is very costly. Wood product manufacturing waste and urban wood waste (excluding prunings and clippings) are good candidates, and in-forest wastes are acceptable. Agricultural wastes should be avoided.

Tables 3 and 4 are analagous to Tables 1 and 2, except that they look ahead to the future commercial development of dedicated biomass feedstock systems and advanced processing technologies. The future fuel types are classified as wood wastes, wood energy plantation products, and herbaceous crop energy plantation products. The major future process options considered are advanced CFB boilers (with fuel dryers and integrated with natural gas-fired combined cycle systems); advanced WTE; advanced gasification/combustion turbine or fuel cell systems; cofiring in advanced PC boilers; and direct-fired combustion turbine systems.

Table 3
Size, Moisture, and Alkali Ranges of Future Biomass Fuels

Fuel Class	Size	Moisture	Alkali
Wood wastes	Construction or demolition debris	Debris: 12-32% (15% typical)	Construction or demolition debris: low
	Hog fuel Prunings, branches Lawn clippings Shavings, sawdust	Hog fuel, prunings, clippings: 41-46% (45% typical) High or low	Hog fuel: medium Prunings: high Clippings: high Low
Wood energy plantation products	Whole trees Logs Branches Mixed fuel	30-60% (45% typical) Seasonal	Stem wood: low to medium Branches, leaves: high Mixed fuel: medium
Herbaceous crop energy plantation products	Mixed fuel	30-60% Seasonal	Very high

Again, these summary tables indicate some likely fuel preferences, given a process (or likely process preferences, given a fuel). These "future" preferences are somewhat speculative, as there are many unknowns associated with both the future fuels and the advanced technologies:

- Advanced CFB boilers, cofiring in advanced PC boilers, and advanced gasification systems all use processed fuel. Thus they are most likely to be applied to the conversion of biomass waste materials to electricity.
- WTE, which requires no fuel size reduction, appears to be ideal for use with short rotation woody crop plantations. It is possible that WTE could also be adapted to feed baled herbaceous crops (as well as baled residues such as orchard prunings). However, the very high alkali content of herbaceous crops means that ash fouling and slagging would be big potential problems. It is possible that gasification systems can be developed to be more tolerant of high-alkali fuels than combustion systems, although gas turbines are extremely sensitive to alkali.
- If successfully developed, the direct combustion turbine is most likely to be used in small cogeneration applications, feeding very clean and dry wood fines from wood products manufacturing facilities.

Several recent evaluations sponsored by EPRI, as well as work being done by Scandinavian utility companies, indicate that biomass power plants will operate more efficiently and cleanly if they have fuel drying systems, with heat recovery, integrated into their process flowsheets. Although some existing U.S. plants have retroactively installed fuel dryers, there are no existing plants (and no published designs for boilers other than WTE) that take advantage of the capital, operating, and fuel cost savings that can be obtained from fuel drying. This represents an important area of future process development work.

Table 4
Process Considerations for Future Biomass Fuels

Process	Fuel Size	Fuel Moisture	Fuel Alkali
Advanced CFB boiler	- Hog fuel OK - Max. ~2 inches - Fines OK	- OK -- has dryer	- Prefer low-alkali fuels
Advanced Whole Tree Energy™	- Whole trees - Plantation harvest	- OK -- has dryer	- No problem
Gasification/ gas turbine or fuel cell	- Hog fuel OK - Max. ~2 inches - Fines OK	- OK -- has dryer	- Prefer low-alkali fuels
Cofiring in advanced PC boiler	- Pulverized	- Dried: ~15%	- Prefer low-alkali fuels
Direct combustion turbine	- Micronized fuel - Fines (shavings, sawdust)	- Dried (~15%)	- Avoid high alkali fuels

(SOURCE: Wiltsee 1993)

Power Technology Performance and Cost

Table 5 summarizes technology performance and cost estimates for selected biomass and waste fuels and power technologies. Table 6 presents the key design and economic assumptions used in the analysis. The estimates were prepared using the BIOPOWER model of biomass and waste fuel power plant performance and cost, developed by the EPRI strategic analysis project. [EPRI 1993] The BIOPOWER model generates material and energy balances, performance, and capital, O&M, and and levelized cost of electricity estimates for a range of fuels and power technologies. [EPRI 1993a]

Wood-Fired Power Plants

In Table 5, levelized cost of electricity estimates for a reference 120 MW_e natural gas fired-combined cycle plant are compared with those for 50 MW_e and 100 MW_e wood-fired power plants, using a range of technologies. They include the wood-fired stoker and CFB boilers (50 MW_e), WTE boilers (50 and 100 MW_e), and both current- and advanced-technology wood gasification/combined cycle power plants (100 MW_e). The estimates for the advanced wood gasification/combined cycle technology were prepared by adjusting the current technology estimates for anticipated reductions in capital cost and net heat rate, resulting from steam drying of wood, hot gas cleanup, and other enhancements.

The net plant heat rate estimates in Table 5 are based on the higher heating values of the fuels (HHV). The total capital requirement estimates assume plant startup in January 1992. The levelized cost of electricity estimates are presented in constant 1991 dollars, and show the contributions of capital, O&M, and fuel. In addition, the impacts of SO_2, NO_x, and fossil fuel-derived CO_2 emission charges are shown, assuming \$250/ton SO_2, \$2500/ton NO_2, and \$10/ton CO_2.

The comparison shows that the natural gas/combined cycle technology is generally superior to all of the wood-fired technologies with regard to thermal efficiency, capital cost, and levelized cost of electricity, even when the \$10/ton CO_2 emissions charge is assessed for the natural gas-fired plant. With levelized

Table 5
Selected Performance and Cost Estimates for Biomass and Waste Fuel Power Technologies

(End-of-Year 1991 \$)

Power Technology	Net Capacity MW	Net Heat Rate Btu/kWh	Thermal Efficiency %	Total Capital Requirement \$/kW Net	Levelized COE ¢/kWh
Cofiring with coal in retrofitted utility boilers:					
Reference coal plant	200	10,117	33.7	-	2.3
Tire-derived fuel	200	10,127	33.7	38	2.5
Wood	200	10,284	33.2	105	2.8
RDF	200	10,289	33.2	128	2.9
Natural gas combined cycle	120	7,900	43.2	770	4.5
Scrap-tire-fired mass burn boiler	50	12,359	27.6	2,738	5.2
Whole Tree Energy™ boiler	100 50	10,654 10,661	32.0 32.0	1,341 1,722	5.3 6.4
New coal/FGD	200	10,020	34.1	1,900	6.0
Wood-fired stoker boiler	50	13,883	24.6	1,780	7.8
Advanced wood/GCC	100	9,796	34.8	2,130	7.8
Wood-fired fluid bed boiler	50	13,854	24.6	2,085	8.5
MSW-fired mass burn boiler	50	16,373	20.8	4,230	8.6
RDF-fired stoker boiler	50	16,460	20.7	4,350	8.9
Current wood/GCC	50	12,369	27.6	2,466	9.2

Note: See Table 6 for fuel prices and other key design and economic parameters.
(SOURCES: EPRI 1993; McGowin and Wiltsee 1993)

Table 6
Key Design and Economic Assumptions

Reference Date: End-of-Year 1991

	Constant $	Current $
Inflation rate:	0%/year	5%/year
Discount rate:	6.2%/year	9.8%/year
Book life:	30 years	30 years
Levelization period:	10 years 1992-2001	10 years 1992-2001

Real price escalation - fuel and O&M: 0.0 %/year

Unit costs:

Operating labor:	$20.40/hour
Land	$6500/acre
Chemicals	$588/ton
Water	$0.60/1000 gallons
Limestone:	$15.00/ton
Lime:	$55.00/ton
Ash/solids disposal:	$8.00/ton
Gypsum disposal:	$4.75/ton
MSW tipping fee:	$30.00/ton
MSW net recycling cost:	$4.00/ton
RDF residue disposal:	$30.00/ton
Ammonia:	$145.00/ton

Fuel costs:	% Moisture	Btu/lb	$/ton	$/million Btu
Natural gas:				2.50
Coal:	12.0	10,100	25.00	1.24
Wood:	33.2	5554	24.80	2.22
Whole trees	45.0	4840	17.40	1.80
RDF:	24.0	5852	25.00	2.14
TDF:	8.0	12,420	25.00	1.01
Tipping fees:				
MSW:	24.8	4896	30.00	3.06
Scrap tires:	8.0	11,902	30.00	1.26

electricity costs for the wood-fired plants ranging from $0.05 to $0.10/kWh, none of the wood technologies is competitive with the natural gas-fired combined cycle plants ($0.04/kWh), at the $2.50/million Btu natural gas price assumed in the analysis.

The most significant parameters affecting generation cost are capital cost, fuel cost, and capacity factor. Relatively small improvements in thermal efficiency are also possible by using higher steam pressures and temperatures and other enhancements. For example, reducing the capital cost of the plant by 20% and increasing the capacity factor from 80 to 90% would reduce the levelized cost of electricity to about $0.065/kWh, which is closer to, but still higher than the generation cost of gas-fired combined cycle technology. This could be accomplished by building larger plants and by improving plant reliability to allow operation at higher capacity factors.

Dedicated Waste-to-Energy vs. Utility Boiler Cofiring

Table 5 also compares levelized cost of electricity estimates for dedicated 50 MW_e power plants, fired by wood, refuse-derived fuel, and scrap tires, and for existing 200 MW_e utility power plants, cofired by Illinois bituminous coal and each of the three fuels. The cofired plants are retrofitted for cofiring the alternate fuels and coal at 15%/85% heat input ratio, and it is assumed that the retrofit does not include flue gas desulfurization.

The cofiring retrofit plants exhibit higher thermal efficiencies and lower incremental total capital requirements and levelized costs of electricity than the corresponding dedicated plants. Addition of emission charges for SO_2, NO_x, and fossil fuel derived emissions further increases the benefits of cofiring.

Breakeven Fuel Value

For utility boiler cofiring applications, the value of the alternate fuel is limited by the breakeven value of the fuel, i.e., the price a utility can afford to pay for the fuel without changing the cost of power generation. The breakeven value is determined by the net difference between the fuel savings from coal and the incremental capital, O&M, and emissions charges costs/credits resulting from cofiring:

$$\text{(Breakeven Fuel Value)} = \text{(Coal Savings)} - (\Delta \text{ Capital Charge}) - (\Delta \text{ O\&M Cost}) - (\Delta \text{ Emissions Charge})$$

Without emission charges, credits, and and other subsidies, the breakeven fuel value is always less than the delivered cost of the coal. It can also be negative, i.e., the utility must be paid to take the fuel in order to break even. Consequently, even though utility boiler cofiring is superior to building dedicated plants with regard to thermal efficiency, capital investment, and financial risk, cofiring is economically feasible only when the utility receives a large discount on the delivered fuel cost, receives a tipping fee or subsidy for taking the fuel, or there is a credit for reducing fossil fuel emissions.

Conclusions

- Under current conditions, it is difficult for biomass power technology to compete economically with natural gas-fired combined cycle technology.
- Cofiring biomass and waste fuels with coal in utility and industrial boilers is currently the most efficient, lowest cost, and lowest risk method of energy recovery from residual materials. However, retrofit cofiring adds no new capacity and typically is not economically attractive.
- To become competitive with natural gas, improved biomass and waste fuel energy crop and power technology must be developed with high efficiency and reliability. Fuel drying, integrated into process flowsheets to achieve maximum energy recovery, will be one key element.
- The combination of Whole Tree Energy™ and short-rotation woody crop growing and harvesting technology appears to have the highest probability of meeting these goals. Integrated, commercial-scale process demonstrations in various regions of the U.S. are needed.
- Biomass gasification systems also could be competitive, if process simplifications and major cost reductions can be demonstrated during scale-up efforts.
- Other advanced biomass-fueled power generation systems will have important niche market applications.

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COFIRING OF BIOFUELS IN COAL FIRED BOILERS: RESULTS OF CASE STUDY ANALYSIS

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Abstract

Ebasco Environmental and Reaction Engineering, under contract to the Electric Power Research Institute (EPRI), performed a case study analysis of cofiring biomass in coal-fired boilers of the Tennessee Valley Authority (TVA). The study was sponsored by EPRI, TVA, and the U.S. Department of Energy (DOE). This analysis included evaluating wood fuel receiving, preparation, and combustion in pulverized coal (PC) boilers and cyclone furnaces. Additionally it included an assessment of converting wood into pyrolysis oil or low Btu gas for use in a new combined cycle combustion turbine (CCCT) installation. Cofiring wood in existing coal-fired boilers has the most immediate potential for increasing the utilization of biofuels in electricity generation. Cofiring biofuels with coal can potentially generate significant benefits for utilities including: 1) reducing emissions of SO_2 and NO_x by reducing the concentrations of sulfur and nitrogen in the fuel to the boiler; 2) reducing the net emissions of CO_2 generated from combustion of fossil fuels; 3) potentially reducing the fuel cost to the utility depending upon local conditions, particularly in light of the fact that biomass is potentially exempt from the proposed Btu tax and can probably obtain a 1.5 cent/kWh credit for energy generated by wood combustion; 4) supporting local industrial forest industry customers of the utility by providing a market for residues as fuel; and 5) providing a long term market for the development of a biofuel supply and delivery industry. This paper reviews these potential benefits in the context of cofiring biofuel at a rate of 15 percent heat input to the boiler, and presents a comparison between this cofiring strategy and others previously tested or developed by other utilities. It then considers the following issues: 1) wood fuel specifications as a function of firing method, 2) wood fuel receiving and preparation system requirements, 3) combustion system requirements for cofiring biofuels with coal, 4) combustion impacts of firing biofuels with coal, 5) system engineering issues, and 6) the economics of cofiring biofuel with coal. The Allen, TN 330 MW_e cyclone boiler and Kingston, TN 135 MW_e Boiler #1, a tangentially fired PC unit case studies are then summarized in the paper, highlighting the cofiring opportunities.

Introduction

Cofiring refers to the combustion of biomass or a biomass-derived fuel along with another fuel such as coal, oil, or natural gas. For purposes of the EPRI/DOE/TVA project being reported here, the other fuel is a fossil fuel providing well over half of the input of heat into the thermal conversion process. Such cofiring operations offer a method for generating electricity from renewable biomass fuels without incurring the expense and delay associated with designing and building a new power plant capable of using the biomass fuel. However this cofiring, replacing some fossil fuel by biomass fuel, does not provide for any new generating capacity. Therefore the costs of installing the equipment needed for cofiring must be amortized by savings produced from the cofiring operation rather than by the full value of the electricity produced. These savings can be in the areas of fuel cost, emission control costs, operating costs, or credits/offsets for reduced emissions.

The benefits of cofiring to a utility, its customers, and its service territory lie in the following areas: (1) accomplishing convenient or low cost disposal of wood wastes from customer industries, thereby solving economic and community problems; (2) establishing early market for biomass, thereby stimulating local industry or agriculture to produce new supplies of these renewable fuels; (3) SO_2 and potentially NO_x emission reductions; (4) low capital investments, relative to building new power plants; and (5) conversion of wood (or other biomass fuels) to electricity at high thermal efficiencies when compared to existing wood fired power plants. The overall, long-term environmental benefit of cofiring biofuels with coal lies in replacing some fossil fuel combustion. Fossil fuel combustion adds to the increase in carbon dioxide to the global atmosphere while biofuel utilization recycles CO_2 through the atmosphere. If incentives directed at encouraging renewable fuels such as the $0.015//kWh production tax credit for "closed loop biomass" are implemented, or if incentives directed at reducing CO_2 emissions such as a carbon tax are implemented, then there could be an additional immediate benefit to cofiring biofuels with fossil fuels. An incentive of $0.015/kWh, or $50/ton of carbon not emitted from fossil fuel combustion, would be the largest financial benefit to utilities and such an incentive could pay for the investment required to establish the cofiring operation.

Previous EPRI Analyses

EPRI performed a major assessment of cofiring in the mid 1980's, in cooperation with DOE and the Argonne National Laboratory. This assessment focused upon municipal solid waste rather than wood as the renewable fuel. Recent analyses using the RDFCOAL computer spreadsheet model developed by the earlier EPRI project (McGowin and Hughes, 1992; McGowin and Gold, 1993) led EPRI, DOE, and TVA to cofund the present project, which is an analysis of the prospects for cofiring wood with coal in TVA power plants being performed by Ebasco and its subconsultant, Reaction Engineering International (Gold and Tillman, 1993). The new project addresses wood, rather than RDF, because the intent is to evaluate cofiring as a possible first step towards large-scale use of biomass in electricity generation. Wood is today's biomass fuel of choice. Today some 6,000 MW_e are generated from wood. This biomass resource is relatively clean and homogeneous, without the complications that occur when utilizing the more heterogeneous municipal waste fuels. Such complications include management of significant fuel variability, metals content, and chlorine content.

The EPRI Program Approach to Biomass Utilization

Cofiring is being analyzed within the framework of this EPRI/DOE/TVA assessment. In addition to the cofiring of wood with coal, EPRI is also supporting the testing and development of one technology for dedicated (not cofired) power generation with wood. This is the Whole-Tree-Energy^{TM} technology owned by Energy Performance Systems of Minneapolis, MN. The design for a Whole-Tree-Energy™ plant at the 100 MW_e size has a heat rate comparable to those expected in cofiring, i.e. in the 10,000 Btu/kWh range. In the WTE™ case, this heat rate is to be achieved by using dried wood (25% moisture) and an efficient steam cycle (2,400 psig, 1000°F, 1,000°F). The other major thrusts of EPRI's biomass/waste fuel program are completion of a major analysis of the strategic benefits of biomass and waste fuels for electric power generation (McGowin, 1993; Wiltsee, 1993) and the beginning of a new focus on energy crops as the potential source of a major role for biomass in electric power generation (Turnbull, 1993). EPRI plans to work with DOE and its two key biomass laboratories (NREL and ORNL) in cofunded assessments of integrated power systems that include energy crops coupled to electric power generation technologies.

Organization of This Presentation

This paper is the first presentation of the results from the EPRI/DOE/TVA project assessing cofiring of wood with coal in existing TVA power plants. This analysis has been performed by Ebasco (the prime contractor selected for the engineering analysis) and by TVA staff working with and through the University of Tennessee and the Oak Ridge National Laboratory. The TVA/UT/ORNL analysis addresses the issues of wood supply for the cofiring options evaluated by Ebasco. In the next section of this paper, the wood supply assessment is summarized. The full project also includes an evaluation of gaseous and liquid fuels that could be derived from wood and cofired in power systems involving a combined cycle combustion turbine (CCCT) system with natural gas and/or fuel oil as the primary fuels. However the CCCT approaches are not addressed in this paper. Rather, subsequent sections address the following topics: (1) the fuel supply and price considerations; (2) cofiring wood handling and process engineering issues; (3) combustion issues including fuel characteristics, boiler efficiency, flame temperatures, and airborne emissions; and (4) economic factors and considerations.

Availability of Biofuels in the TVA Service Region

TVA is located in a major forest region of the U.S., with significant resources available in eastern Tennessee, northern Alabama and Mississippi, southern Kentucky, and within reach of significant resources in Arkansas. As such, the TVA service area provides a significant opportunity for biofuel utilization in a cofiring application.

Overview of Wood Fuels in TVA Region

TVA owns and operates 59 coal-fired steam generators at 11 point plant sites spread throughout a 90,000 square mile service region. Power generated from TVA's plants serve all of Tennessee and portions of six of the eight neighboring states. Each state has significant forest resources, forest-based industries, and associated mill residue for power generation.

In an effort to understand the extent of the various types of wood fuel available, TVA, EPRI, and DOE/NREL are currently cofunding a TVA regional biomass resource assessment. The assessment is limited to mill residues, logging residues, and energy crops (no native forest harvesting for energy is being pursued). The assessment generates cost/supply curves for the various types of biomass resource delivered to TVA coal-fired plants and will identify resource concentration areas. At the heart of the resource assessment is a geographic information system (GIS) called "BRAVO" - Biomass Resource Assessment Version One, developed by the University of Tennessee. The GIS-based portion of the assessment allows a user to examine the effects of competing demand points, changes in market conditions, and the impact of other variables on the delivered fuel costs to locations throughout the service region. Additionally, the GIS aspect of the resource assessment model will facilitate its usefulness and exportability to other areas of the United States. The first phase of the resource assessment is expected to be complete in August 1993.

Unused Mill Residues

There are over 5,000 forest product manufacturing sites in the TVA region. On an annual basis they collectively produce about 11 million green tons (about 5.5 oven dry tons) of residue, containing over 90 x 10^{12} Btu. Much of this by-product is used on site as a fuel. However, a regional survey indicates that 2 - 3 million green tons (1 - 2 oven dry tons) are left unused and present a disposal problem for mill owners and operators, and a potential fuel supply of 16 - 35x 10^{12} Btu for power generation. This unused wood could fuel 200 - 400 MW_e of baseload capacity (as a rule of thumb, 1 million green tons is enough wood to fuel a base loaded 100 MW_e conventionally-fired pulverized coal boiler).

Logging Residuals

The size of the logging residual overshadows the amount of the unused mill residue resource base. In the eastern United States, its estimated that over 100 million green tons (over 50 million oven dry tons) of logging residues are left behind in the forest after harvesting each year in the form of tree crowns and limbs. These unmarketable portions of the trees (typically 40 - 60 percent of a tree's volume) could be chipped and used for power generation. These logging residuals contain 800 - 900 x 10^{12} Btu, or 0.8-0 1 quad of fuel. In the TVA region, logging residue and cull-trees could supply about 2,500 MW_e of baseload capacity on an annual basis if fully recovered.

Short-Rotation Wood Crops (SRWC)

Short-rotation woody crop trees are the biomass resource of the future. In the SRWC approach, specially selected fast growing trees are cultivated using conventional agricultural techniques - regular weed and pest control, and the addition of fertilizer. The extra care given to SRWC trees increases their juvenile growth rate to the point that they reach a harvestable size in as little as five years compared to a twenty-five year harvesting cycle for standard commercial forests.

The TVA regional resource assessment indicates the ceiling of SRWC production in the TVA service region, with an average yield of 3.5 dry tons per acre per year, would be about 150 million green tons annually! That wood fuel would contain enough energy to completely displace all of TVA's coal-fired capacity - an enormous potential. Actual energy market penetration by SRWC in the TVA region will likely be tied to future environmental and agricultural legislation. The effect of such legislation could create a scenario in which SRWC wood fuel would be competitive with utility coal costs.

Regional Wood Fuel Costs

The least expensive wood fuel in the TVA region is unused mill residues, followed by logging residuals; the most expensive biomass resource will be SRWC wood. TVA's level of interest in tapping the different woodsheds will be dictated by relative fuel prices, environmental credits, and biomass fuel incentives. Regional wood fuel costs, availability and cumulative baseload capacities that could be served by the different fuel types are summarized in Table 1.

Unused mill residues, were targeted as the most important resource to gather data on in support of the wood/coal cofiring case studies that are the subject of this paper. At the time of this writing most of the wood residue data for the TVA region is complete. Comparison of cost/supply curves for unused mill

Table 1. TVA Regional Wood Resource

Resource Type	Estimated Cost, FOB Wood Source [$/green ton]	Annual Quantity [green tons]	Cumulative Baseload Capacity Served [MW_e]
Mill Residues	\$2.00/ton [\$0.23/10^6 Btu]	$2 - 4 \times 10^6$	200 - 400 MW_e
Logging Residuals	\$7.50/ton [\$0.86/10^6 Btu]	14.6×10^6	1,860 MW_e
Short Rotation	\$14.50/ton [\$1.66/10^6 Btu]	14×10^6	3,260 MW_e

residues reveals a wide variation in the amount and cost of resource from one area of the region to another (see Fig. 1). Geographically, these plants represent three distinct regions within the TVA service territory and reflect the importance of site-specific resource analyses. For comparison purposes, it is useful to consider the amount of residues that are available for under \$1.00/MBtu delivered to the different plant sites. Of the three plants, the Allen Plant in Memphis, Tennessee has access to the least expensive and most abundant unused mill residue resource base (270,000 dry tons for $\leq$ \$1.00/MBtu). At the Kingston Plant near Knoxville, Tennessee (on the eastern side of the TVA service region) mill residues are less abundant (100,000 dry tons for $\leq$ \$1.00/MBtu), yet more than adequate to supply a long-term 15 percent cofiring demonstration for one unit at the plant. Unused mill residues are in short supply in the northwest corner of TVA's region around the Shawnee Plant in Paducah, Kentucky. In fact, the supply (50,000 dry tons for < \$1.00/MBtu) would be inadequate to economically sustain the level of energy input from wood set for the cofiring case studies.

Overview of Wood Cofiring Technical Strategies

The cofiring potential in the TVA region is significant, given both the resource available and the substantial coal-fired electricity generating capacity operated by that utility. This combination can be exploited by several strategies, each with its own technical requirements and limitations.

Alternative Cofiring Fuel Feed Rates

Cofiring strategies applicable to large scale utility boilers relate largely to pulverized coal (PC) and cyclone combustion systems, and can be categorized by alternative fuel feed rates as shown in Table II. Note that wood can be fed at 2 - 5% of heat input by putting the wood on the coal pile. With additional wood fuel preparation and handling, wood cofiring can be accomplished at 10 - 15% of the heat input to the boiler. All cofiring strategies where wood contributes <15% of the heat input to the power generating station afford the utility the opportunity to utilize existing boilers, turbine generators, air pollution control systems (APCS), and related investments. Cofiring at 2 - 5% of heat input has been tested or demonstrated by numerous utilities including Santee-Cooper, Delmarva, Georgia Power, Northern States Power, and others. The EPRI/DOE/TVA cofiring evaluation, however, targeted 10 - 15% wood feed (heat input basis) as a goal to advance the utilization of biofuels. Beyond 15% wood in the feed, pulverized biofuel can be used potentially as a reburning fuel, at heat input ratios of 15 - 35 percent. In such cases extensive feed preparation is required. Further, the boiler must be modified for reburn fuel burners and overfire air ports. Reburning was briefly investigated by Ebasco and REI.

Table 2. Alternative Cofiring Strategies and Their Requirements

Wood Firing Percentage [heat input]	Material Preparation Strategy Required	Firing Strategy Required	Boiler Investment Required
2 - 5	copulverize with coal (PC or cyclone)	fire with coal	use existing boiler
	separate receiving and handling (cyclone)	fire in secondary air system (cyclone)	use existing boiler
10 - 15	separate receiving and handling (PC)	separate burners (PC)	use existing boiler
	separate receiving, common storage (cyclone)	fire with coal (cyclone)	use existing boiler
15 - 35	Reburning strategy; separate receiving and preparation, modified	fire above coal burners or cyclone barrels	use existing boiler heavily modified with additional boiler penetrations for fuel feed, overfire air
25 - 50	separate receiving and handling of alternative fuels (coal, biofuels)	fire separately in common, multifuel boiler	new boiler designed with biomass parameters (e.g. fluidized bed)

Cofiring in PC and Cyclone Boilers

Cofiring wood and coal in cyclone boilers

Cyclone boilers are inherently attractive as candidates for cofiring, because they can accept a large size fuel particle (e.g. 1/2") with a high moisture content (e.g. 50%). Further, they can accept fuels with ash compositions high in calcium and potassium oxide. Combustion in a cyclone barrel depends upon formation of a slag layer; this slag entraps large fuel particles. This mechanism is used to enhance residence time and complete combustion of the solid fuel particle. The slag, once formed, then slowly flows from the barrel into the slag discharge system. Only about 25% of the noncombustible material from cyclone combustion exits the boiler as flyash, while 80% of the inert material in PC combustion ends up as flyash. At the same time, however, cyclone boilers are fired with significantly higher combustion temperatures than PC boilers, increasing the formation of thermal NO_x at such installations. For bin-fed cyclones without the lignite predry retrofit, the total fuel must have 6 - 25% ash (dry basis), <20% moisture (total fuel blend), >15% volatile matter in the coal (dry basis), and must have the proper coal ash chemistry (Babcock & Wilcox, 1991). The critical ratio is defined by equation (1):

$$\text{Coal Ash Ratio} = Fe_2O_3/(CaO+Mg) \qquad [1]$$

This ratio must be less than 25 for fuels with sulfur contents <3% (dry basis), and must be less than 10 for fuels with sulfur contents <6% (Babcock & Wilcox, 1991).

Because cyclone boilers have a broader tolerance for fuel than PC boilers, the biomass can be chipped to <1/2" and then stored outside. Further, the wood fuel can be transported to the existing bunkers and fed with the coal. This storage and feeding system is facilitated by gravimetric feeders. This simplification of the biofuel processing has significant economic consequences for wood cofiring in coal-fired boilers. Alternatively, dry and pulverized wood can be fed through the secondary air system of the cyclone as is done at the King Station of Northern States Power, using sanderdust from an adjacent plant of Anderson Windows.

Cofiring Wood and Coal in PC Boilers

Pulverized coal boilers are the dominant fossil fired systems employed by utilities today. Such boilers include both wall fired units and tangentially fired units. For both types of PC boilers, fuel preparation requirements or boiler modification requirements are more significant than for cyclone units. If extensive fuel preparation (versus extensive boiler modification) is the preferred strategy, then cofiring can have minimum impacts on the boiler in terms of specific system modifications. However, in order to cofire 10 - 15% of the heat input to the boiler with wood, the fuel must be prepared to <1/16" particle size, and dried to <20% moisture (at the burner tip). Pulverizing as-received material to <1/16" may require 2-stage grinding of the wood. Further, drying may be required between the stages in order to facilitate the final wood pulverization. Once the wood fuel is dried, it must be stored in covered live-bottom bins or storage bunkers in order to prevent fuel moisture uptake. Given this level of wood fuel preparation, the wood can be fired directly through PC or multi-solid burners into the PC furnace.

Determinants for Successful Cofiring Applications

Cofiring wood in coal-fired boilers at 10 - 15 percent ratios (heat input basis) necessarily requires recognition of the quantities of wood to be fed hourly. For each 100 MW_e fired at a net station heat rate of 10,000 Btu/kWh, 10 - 15 MW_e is fired with wood. This is equivalent to 5.7 - 9.4 oven dry (O.D.) tons of wood/hr, depending upon wood quality. For coal-fired power plants in the 150 - 200 MW_e range, this translates into 9.4 - 12.6 O.D. ton/hr of wood at a minimum. At the burner tip, the wood feed rate is 11.8 - 15.8 ton/hr of 20% moisture wood. Given these fuel feed rates, the cofiring strategies in general, and specifically those strategies designed to achieve 10 - 15% wood heat input into PC and coal cyclone boilers, rely upon the following determinants:

- Site-specific conditions with emphasis on facility layout, availability of space in locations convenient to the boiler house, availability of space convenient for fuel receiving and management, and related critical logistical concerns;
- Coal, wood, and blended fuel chemistry including proximate and ultimate analysis, elemental analysis of the ash, and specific issues associated with ash chemistry;
- Boiler characteristics including firebox dimensions, burner configurations, heat release rates, and air distribution systems (e.g. overfire air provisions); and
- Relative fuel economics, emission credits, and related cost-saving opportunities.

All of these determinants were brought to bear in the evaluation of cofiring opportunities at TVA boilers. The entire population of TVA boilers surveyed by Ebasco as candidates for cofiring evaluation. Three boilers were chosen for case study evaluation: Allen #3 (cyclone), Kingston #1 (tangentially fired PC boiler) and Shawnee #8 (wall fired PC boiler) as shown in Table 3. The Allen and Kingston cases are summarized below.

Table 3. Summary of Conditions at TVA Coal-Fired Boilers Considered as Cofiring Candidates

Boiler	Peak MW_e	Steam Data		Dimensions	Heat Release		Fuel Feed
		psig	°F	W x D x L	Vol. (*)	Plan (**)	(ton/h)
Allen (cyc) (7 cyclone burners)	330	2400	1050	45x28x160.5	---	---	128
Kingston (PC) 1-4	135	1800	1000	38.2x28.1x108	14.47	1.25	55
Shawnee (PC) 1-9	175	1800	1000	46x24x95	18.6	1.21	68

Notes: (*) Volumetric heat release, 10^3 Btu/ft^3-hr
(**) Plan area heat release, 106 Btu/ft^2-hr

THE ALLEN CASE STUDY

The Allen fossil fired station consists of three 330 MW_e cyclone boilers, of which unit #3 was evaluated for cofiring. This generating station, located outside of Memphis, TN, utilizes seven cyclone barrels, each firing about 18 ton/hr of >2% sulfur coal. The unit can receive fuel by a truck or barge, and has the capability to receive significant quantities of low cost biofuel (see Fig. 1). In addition to the mill residues, there is also a significant stockpile of railroad ties potentially available to the Allen facility, and these are high in calorific value and low in moisture.

The Process and System Designs for Allen

Existing Conditions at the Allen Facility

Coal is delivered by barge to the site, where it is unloaded by a twin boom clamshell unloading crane, placed on one of two 1,100 ton/hr conveyors that transfer the coal to a transfer house. From there it is sent directly to the crusher building or to the coal pile for storage. Coal sent to storage is stocked out by one 2,200 ton/hr stationary stacker and one 2,200 ton/hr revolving stacker. Coal is reclaimed from the coal yard storage pile by mobile equipment pushing coal into two reclaim hoppers. From there coal is conveyed to the transfer house by two 1,100 ton/hr conveyors. From there the coal is conveyed to the Crusher Building and crushed to 1/4 x 0" size. From there it is transported to 24-hr bunkers, and then fed to the unit. The day storage bunker operating capacity for each generating unit is approximately 3,000 tons or a 22-hour supply at the maximum burn rate. From the bunkers, the crushed coal flows vertically through gates to scales to the current feeders, which discharge coal at controlled rates to a horizontal cyclone furnace. The current feed systems are being replaced with gravimetric feeders.

Each boiler at Allen is a parallel backpass, reheat, cyclone-fired unit with a rated steam capacity of 2,000,000 lb/hr. Each cyclone is designed to accept a maximum heat input of 425 MM Btu/h. The cyclones are of radial design and are nine feet in diameter. Each unit was originally designed as a pressurized unit, but Unit 3 is now being converted to balanced draft. Each boiler is equipped with two vertical-shaft Ljungström regenerative air heaters. At full load designed to receive air at 110°F and preheat it to 600°F for use in the cyclones. The combustion products enter the air heater at 693°F and are discharged at 275 - 305°F.

Each unit is equipped with one ESP which is divided into four collecting fields. The ESPs were designed to operate at a removal efficiency of 99.0% with flue gas at 290°F. Bottom ash from the slag tanks and fly ash from the precipitator hoppers are disposed to a pond by a sluice-type system. Typical bottom and fly ash splits are 75/25 percent, respectively; with consequent typical flow rates as follows: bottom ash, 9 ton/hr; flyash, 3 ton/hr.

Operating statistics for this facility include a net station heat rate of 9,833 Btu/kWh, a plant capacity factor of 41.7%, a plant availability factor of 67.3% and a plant utilization factor of 63.4%. The typical calculated heat and material balance calculated for the Allen unit results in an estimated boiler thermal efficiency of 88.6%

Conceptual Design Modifications Developed for the Allen Station

The conceptual design for the Allen station consisted of a few basic modifications. Provisions were made for truck receiving of "green" wood at 50% moisture. Trucks would be unloaded, wood would be stocked out, and stored for up to 15 days. Wood is then reclaimed, hogged to 1/2 x 0", and then blended with crushed coal on the main belts feeding the bunkers. Wood and coal are stored simultaneously in the bunkers. The facility is designed such that wood can supply up to 10% of the heat input to the boiler, due to the capacities of each boiler.

The wood is not predried before storage or combustion. The Allen system does not require any predrying or covered storage capability. Converting a cyclone boiler to cofiring involves the simplest of design modifications, particularly when compared to retrofitting PC boilers for cofiring. The capital cost of this system is on the order of $5.0 - $6.0 million depending upon specific layout configuration. The capital cost can be reduced significantly by procurement of prepared fuel to avoid wood fuel chipping, and utilization of a storage silo rather than utilizing a stockout and reclaim system.

Expected Performance Characteristics and Economic Benefits of Allen with 10% Cofiring

Table 4 presents the summary of coal, "typical" fuel wood, and the blend of fuels utilized in analyzing the Allen cofiring case. Given this typical fuel, the cyclone will "see" a blend which has an improved $Fe_2O_3/(CaO + MgO)$ ratio with respect to sulfur content. Further, the base/acid ratio increase associated with blending wood into the coal indicates an improvement in slagging characteristics of the feed.

Based upon the projected wood/coal cofiring blend, a heat and mass balance about the boiler has been developed, comparable to that for coal only shown previously in Fig. 2, is shown in Fig. 2. The expected performance characteristics in terms of flame temperature and gas composition are as follows: flame temperature, 3,492°F (2,196°K); flue gas molecular weight, 29.70. The calculated boiler thermal efficiency is 86.7 percent. These values are very close to the performance characteristics of the boiler when firing only coal. The expected boiler efficiency degradation is on the order of 1.9 % when firing the blend vs firing only coal. Further, by firing the wood/coal blend vs. only coal and achieving the same steaming rate, the Allen boiler experiences a reduction in SO_2 formation of 0.45 ton/hr, an estimated reduction in NO_x formation of 0.9 ton/hr, and an estimated reduction in CO_2 emissions from fossil fuel combustion of 26.7 ton/hr.

Table 4. **Ultimate Analysis of Coal, Wood, and Fuel Blend at the Allen, TN Cyclone-Fired Boiler #3**

	Fuel		
Parameter	Coal	Wood	Blend(*)
Ultimate Analysis [wt %]			
Carbon	65.0	25.0	55.45
Hydrogen	4.5	3.1	4.17
Oxygen	7.8	18.8	10.43
Nitrogen	1.4	0.07	1.08
Sulfur	2.1	0.02	1.60
Chlorine	0.20	0.0	0.15
Moisture	9.0	50.0(**)	18.79
Ash	10.0	3.0	8.33
HHV [Btu/lb]	11,600	4,110	9,682
Ash Slagging/Fouling Analysis [lb alkali/10^6 Btu]			
CaO	0.26	1.86	0.71
MgO	0.09	0.47	0.20
Na_2O	0.03	0.09	0.05
K_2O	0.21	0.44	0.28
Fe_2O_3	1.72	0.22	1.35
Base/Acid Ratio	0.38	0.8	0.46

Notes: (*) Blend is 74.4% coal, 25.6%.

(**) Wood shown as 50% moisture because it is not dried.

The Kingston Case Study

The Kingston case represents a significant departure from the Allen case. The boiler, Kingston #1, is a 135 MW_e tangentially-fired PC unit installed in 1954. As such it is one of the early designs without benefit of overfire air capability.

The Process and Systems Designs for Kingston

Existing Conditions at Kingston

Coal is received at Kingston by rail and truck. There are two rotary car dumpers. In addition one of the hopper buildings contains a through track for unloading coal from hopper bottom cars and dump trucks. Coal from the hopper buildings is conveyed to yard stock out or to the crusher building by parallel 1000 ton/hr belt conveyors. After, crushing, coal may be sent to stockout or directed to the powerhouse by two

1,000 ton/hr conveyors. Ample space exists at this coal stockout area to support wood storage and initial preparation activities. Coal is retrieved from the stockout pile by mobile equipment into two reclaim hoppers which feed the crusher building discharge belts.

Initial coal size reduction is performed in the crusher building prior to conveyance to the powerhouse. Two 1000 ton/hr tripper conveyors deliver coal to the bunkers inside the power house. Crushed coal then flows vertically from the bunkers through gates to four weigh-belt feeders. Each feeder has a capacity of 30 tons per hour and discharges coal at a controlled rate to its companion pulverizer. Each unit has four CE Raymond Bowl Mills rated at 18 tons per hour. The coal is fired by 16 tangential burners at four elevations on each of the four corners. The boilers are reheat units of radiant-type, natural circulation, dry bottom furnaces with a continuous rating of 1,020,000 pounds per hour steam. Each unit is equipped with two Ljungstrom regenerative air heaters to preheat combustion air. At full load, a typical gas outlet temperature is 310°F. Design combustion air temperature influent to the air heaters is 80°F and design air temperature exiting the air heaters is 512°F.

Each unit is equipped with one ESP. The ESPs were designed to operate at a removal efficiency of 99.2 percent with flue gas at 325°F. Bottom ash is removed from the hoppers beneath the furnace and sluiced to a disposal area. The fly ash is pneumatically conveyed to the disposal area. There is no sale of flyash from the Kingston facility. The performance characteristics for Kingston include a net station heat rate of 9,852 Btu/kWh, a capacity factor of 67.1%, an availability factor of 86.6%, and a utilization factor of 84.3%. The boiler has a calculated thermal efficiency of 89.2% when firing on coal.

Conceptual Design Modifications for the Kingston Facility

Two concepts were developed for the Kingston facility: (1) a concept including fuel receiving, stock-out, reclaim, chip to 1/2 x 0", dry to 25% moisture, pulverize to 1/16 x 0", and then transport the wood to the boiler in a stream of flue gas and fire the wood in the third row of burners; and (2) receive prepared wood at 1/2 x 0" and <25% moisture for bin storage, pulverize the wood to 1/16 x 0", and transport the wood to the third row of burners in the boiler in a stream of flue gas. The differences between the two systems revolve around fuel preparation requirements and costs; in the first case the utility (TVA) assumes responsibility for all wood preparation on-site, while the second case involves purchase of prepared wood and more careful handling of that material. The differences between the two cases are largely in capital investment at the power plant. The second case represents conditions which would involve a non-regulated subsidiary of the utility producing the fuel. Capital costs in the first case are on the order of $8.5 - $12.5 million, while capital costs in the second case are on the order of $5 - $7 million.

Expected Performance Characteristics and Economic Impacts of Cofiring at the Kingston Facility

Table 5 presents the summary of coal, fuel wood, and the blend of fuels utilized in analyzing the Kingston cofiring case. The same wood fuel analysis used at Allen was used at Kingston, except for the moisture content. Based upon the projected 15% wood/85% coal cofiring blend (heat input basis), Ebasco evaluated the expected performance characteristics of the Kingston PC boiler #1. The heat and mass balance about the boiler, based upon 15% wood cofiring (heat input basis) is shown in Fig. 3. The expected performance characteristics in terms of flame temperature and gas composition are as follows when cofiring wood and coal: adiabatic flame temperature, 3,498°F (2,199°K); molecular weight of the flue gas, 29.78. The calculated thermal efficiency of the boiler is 87.8%. The calculated impact upon the firing system is shown in Fig. 4. These are very similar to performance characteristics when firing only on coal. The firing of wood/coal blends as opposed to only coal produces a calculated reduction in SO_2 of 0.23 ton/hr, a calculated reduction in NO_x of 0.07 ton/hr, and a calculated reduction in CO_2 from fossil fuel

Table 5. Ultimate Analysis of Coal, Wood, and Fuel Blend at the Kingston, TN Pulverized Coal Boiler #1

Parameter	Fuel		
	Coal	Wood	Blend(*)
Ultimate Analysis [wt %]			
Carbon	68.7	37.4	60.0
Hydrogen	4.7	4.6	4.67
Oxygen	6.4	29.9	12.93
Nitrogen	1.7	0.1	1.26
Sulfur	1.4	0.02	1.16
Chlorine	0.02	0.0	0.01
Moisture	8.1	25.0(**)	12.79
Ash	8.8	3.0	7.19
HHV [Btu/lb]	13,438	6,165	11,418

Notes: (*) Blend is 72.2% coal, 27.8% wood by wgt (15% Btu content in wood).

(**) Wood shown as 25% moisture because H_2O evaporated in final pulverizing and transport enters the boiler.

combustion of 18.4 ton/hr when the boiler is generating the same quantity of steam firing on the blend that id does when firing on coal alone. An assessment of the impact of cofiring on flyash chemistry at Kingston also demonstrated that the wood/coal blend would not be unfavorable to the operation.

Conclusion

Cofiring wood fuels with coal for electricity generation, then, has significant potential for the electric utility industry for managing fuel costs and environmental impacts. Its economics are very site-specific, and depend upon such factors as the availability of processed fuel, site layout, and combustion system design. Conditions at numerous electricity generating stations may be quite favorable to the application of this technology.

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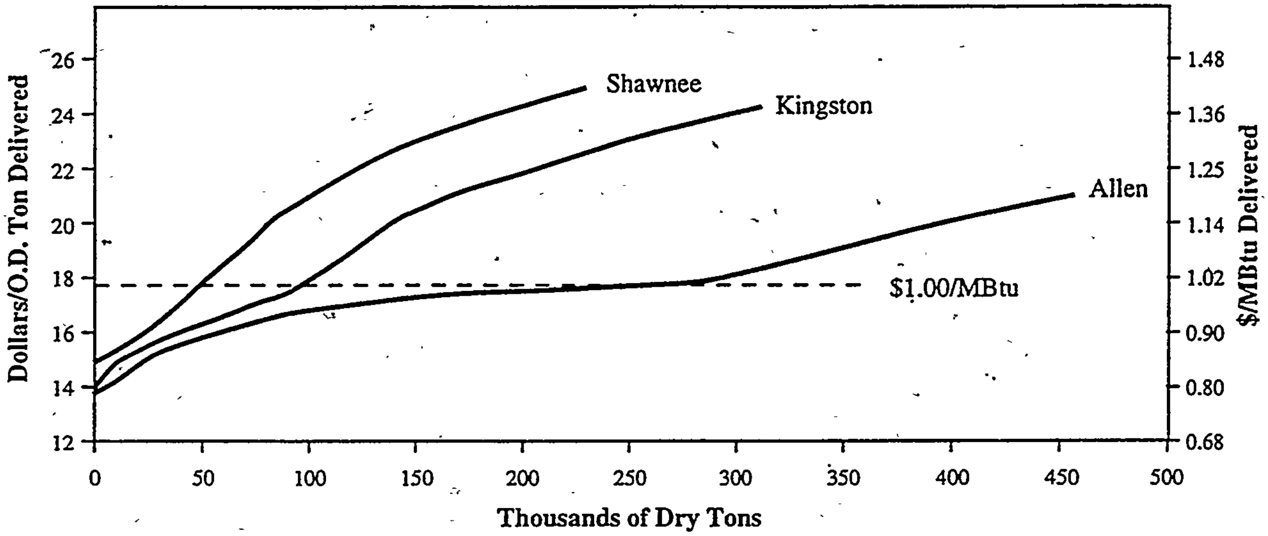
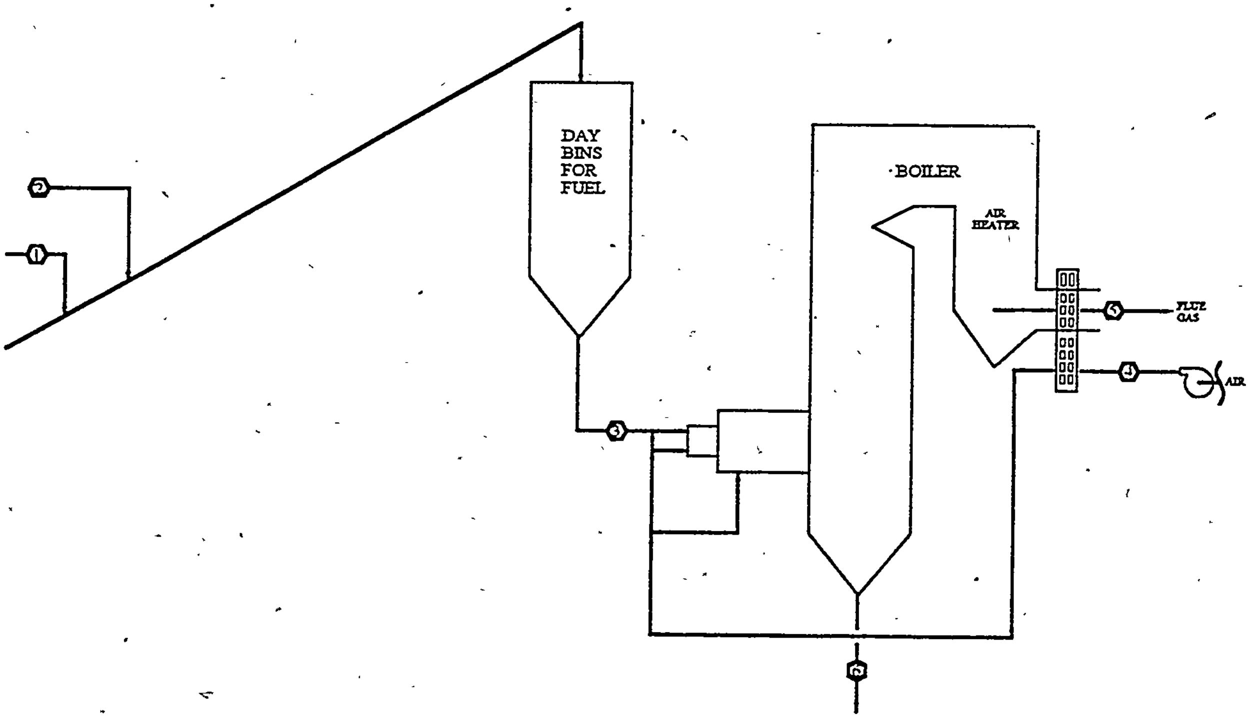
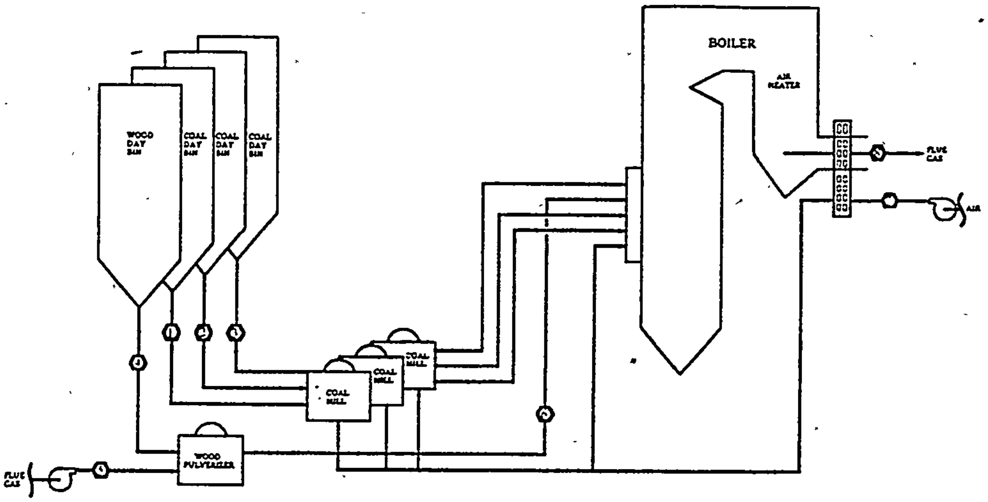


Figure 1. Average cost/supply curves for unused mill residues to TVA coal-fired plants (within 100 mile radius).



PROCESS FLOW TABLE: ALLEN, TN CYCLONE BOILER						
			Stream			
Parameter	1	2	3	4	5	6
	Coal	Wood	Fuel	Combustion Air	Gaseous Combustion Products	Slag
Mass (lb)	233640.0	73269.1	306909.1	2662228.3	2943540.1	25562.1
Temp (F)	77.0	77.0	77	77.0	330.0	N/C
Enthalpy (Btu/lb)	11600.0	4110.0	9811.895	0.0	64.0	N/C
Heat Flow (10^6Btu)	2710.0	301.1	3032.6		188.4	

Fig. 2 Heat and Mass Balances for Cofiring at Allen



PROCESS FLOW TABLE: KINGSTON BOILER #1								
				Stream				
Parameter	1	2	3	4	5	6	7	8
	Coal	Coal	Coal	Wood	Recirc	Wood & FGR	Combustion	Products of
					Flue Gas	to Boiler	Air	Combustion
Mass (lb)	31790.0	31790.0	31790.0	36684.8	58636.4	95321.2	1320789.4	1511295.1
Temp (F)	77.0	77.0	77.0	77.0	300.0	N/A	77.0	330.0
Enthalpy (Btu/lb)	13438.0	13438.0	13438.0	6165.0	56.0	N/A	0.0	63.6
Heat Flow (10^6 Btu)	427.2	427.2	427.2	237.2	3.3		0.0	96.1

Fig. 3 Heat and Mass Balances for Cofiring at Kingston

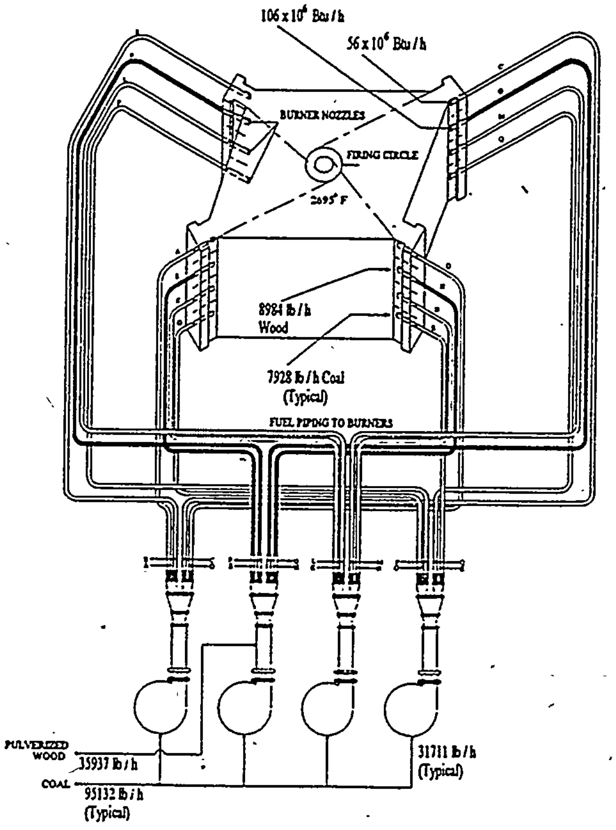


Fig. 4 Impact of Wood Cofiring on PC Combination at Kingston

SUCCESSFUL EXPERIENCE WITH LIMESTONE AND OTHER SORBENTS FOR COMBUSTION OF BIOMASS IN FLUID BED POWER BOILERS

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Abstract

This paper presents the theoretical and practical advantages of utilizing limestone and other sorbents during the combustion of various biomass fuels for the reduction of corrosion and erosion of boiler fireside tubing and refractory. Successful experiences using a small amount of limestone, dolomite, kaolin, or custom blends of aluminum and magnesium compounds in fluid bed boilers fired with biomass fuels will be discussed. Electric power boiler firing experience includes bubbling bed boilers as well as circulating fluid bed boilers in commercial service on biomass fuels. Forest sources of biomass fuels fired include wood chips, brush chips, sawmill waste wood, bark, and hog fuel. Agricultural sources of biomass fuels fired include grape vine prunings, bean straw, almond tree chips, walnut tree chips, and a variety of other agricultural waste fuels. Additionally, some urban sources of wood fuels have been commercially burned with the addition of limestone. Data presented includes qualitative and quantitative analyses of fuel, sorbent, and ash.

EXPERIENCE

LG&E Power Systems has designed, engineered, and constructed eight biomass fueled electric power plants in the last 10 years. The operations and maintenance subsidiary, UC Operating Services, operates 19 electric power plants, including six biomass fired plants. UC Operating Services provides long term operations, maintenance, and fuel procurement. Additionally, LG&E maintains an equity ownership position in two of the plants. These plants embrace a range of biomass combustion technologies including travelling grate stoker boilers, bubbling fluid bed boilers, and circulating fluid bed boilers. The plants range in size from 11 megawatts to 50 megawatts. The plants burn a range of biomass fuel types including forest products, agricultural based fuels, and urban dunnage or waste fuels.

SPECIFIC EXPERIENCE FEEDING SORBENTS TO FLUID BED BOILERS BURNING BIOMASS

Sorbents have been used for a number of years in the following boilers:

- 22 Megawatt Bubbling Bed -- Burning whole tree wood chips, sawmill residues, and agricultural waste fuels.
- 25 Megawatt Circulating Fluid Bed -- Burning whole tree wood chips, agricultural waste fuels, and urban wood waste fuels.
- 25 Megawatt Circulating Fluid Bed -- Burning whole tree wood chips, sawmill residue, and urban wood waste fuels.
- 25 Megawatt Circulating Fluid Bed -- Burning whole tree wood chips.
- 25 Megawatt Circulating Fluid Bed -- Burning whole tree wood chips, and sawmill residue.
- Two 25 Megawatt Circulating Fluid Beds -- Burning urban wood waste fuels, and agricultural waste fuels.

BIOMASS FUELS EXPERIENCE

Biomass fuels experience includes forest products wood waste, agricultural derived fuels, and urban dunnage or wood waste fuels. The forest products include: whole tree wood chips, brush chips, sawmill mill waste wood, bark, and hog fuel. The agricultural based fuels include: grape vine prunings, bean straw, almond tree chips, walnut tree chips, walnut shells, straw hay, almond shells, and numerous other agricultural by-products. The urban fuel sources include: wood pallets, housing demolition debris, cabinet shop wastes, furniture manufacturing wastes, and urban tree prunings.

WHY ADD LIMESTONE TO LOW SULFUR FUELS

Limestone as a fluid bed boiler additive is utilized primarily for its sulfur capture ability with high sulfur coal fuels. Limestone and other sorbents are often overlooked as effective tool in the reduction of boiler corrosion and erosion. When firing any solid fuel, whether it be a premium coal or a biomass fuel, there are always small amounts of chlorine and sulfur present in the fuel. The chlorine and sulfur become concentrated in the bed during combustion. Many fluid bed boilers burning biomass utilize quarry sand or river bed sand as bed media to supplement the very small percentages of ash present in the fuel. The sand functions very well thermodynamically but makes little contribution chemically to the combustion process. The alkalies and salts present in the bed and in the boiler flue gases can cause significant corrosion to the boiler. At the elevated temperatures in the boiler, these compounds become very corrosive and attack boiler tubing and refractory. Even at relatively small levels of concentration over 25 to 30 years of boiler firing during the life of the plant, the corrosion damage to any boiler is significant.

The addition of small amounts of sorbents such as limestone, dolomite, kaolin, or custom blends of aluminum and magnesium compounds can modify and reduce the corrosive nature of the compounds present in the boiler combustor.

FUEL ANALYSIS

Proper fuel sampling and analysis is key to understanding the fuel to be burned and to ultimately being able to reduce corrosion and erosion in the combustor and boiler. Fuel sampling should include samples of each type or species of fuel to be burned. Additionally, agricultural fuels should be sampled from specific fields in case there is a difference in soil type that influences the alkalies present in the harvested fuel. If random grab samples are used, sample and analyze as frequently as budgets will allow. Samples should be sent to an experienced biomass fuels laboratory for preparation and analysis.

Analysis should include proximate, ultimate, higher heating value, and elemental analysis of the ash. Special care must be taken in combusting the sample to ash to assure that all of the moisture present is driven off so that it does not affect higher heating value results. This involves heating the sample for longer periods of time than normally required by the ASTM procedures for solid fuels.

By performing simple calculations utilizing the results of the fuel analysis, one can determine the correct amount of limestone or dolomite to feed to the combustor (see Diagram 1). The basic chemical reaction equations will predict the amount of sorbent required for a balanced reaction. A small additional amount of sorbent should be added to assure complete reaction and result in a combustor slightly saturated with limestone or dolomite to deal with any inconsistencies of mixing during the combustion process.

DIAGNOSIS OF BOILER TUBE METAL AND REFRACTORY CORROSION AND EROSION DAMAGE

The best means of diagnosing boiler tube metal corrosion and erosion involves both non-destructive and destructive tube testing. The non-destructive tube metal thickness testing utilizes long used ultrasonic tube metal thickness tests. The ultrasonic testing should be rigorous and comprehensive testing done on all exposed combustor tubes in a tightly spaced frequently repeated pattern. Then the results should be computer modeled to show any developing patterns of corrosion or erosion. This is expensive but necessary testing that should be done annually prior to major scheduled maintenance outages so that corrective action may be taken during the outage.

Destructive boiler combustor tube testing involves removing several sample coupons (complete tube sections approximately 12 inches in length) during each annual scheduled maintenance outage. The sample should be analyzed by experienced boiler metallurgists to determine the extent of external corrosion and erosion.

Samples of boiler combustor and cyclone refractory and tile should be removed during each annual scheduled maintenance outage. The refractory and tile should be sent to the refractory manufacturer for testing and analysis to determine the extent of corrosion and erosion.

THEORETICAL CAUSE OF CORROSION

The theoretical cause of corrosion in fluid bed combustors firing biomass fuels is due primarily to the presence of sodium, potassium, calcium, sulfur and chlorine in the fuels burned. These elements become concentrated in the bubbling bed or in the circulating bed media with time. Sodium, potassium, and calcium combine with sulfur and chlorine to form molten alkalies and salts in the combustor bed media. The molten salts act together as eutectics, having lower boiling points than their individual elemental forms (see Diagram 2 and Diagram 3). Typical compounds formed include: Na_2SO_4, K_2SO_4, $CaSO_4$, and NaCl. These compounds attach themselves to fly ash and travel throughout the combustor and boiler. In doing so, these compounds come into direct contact with heated tubing metal and heated refractory. Additionally, some of these compounds volatilize or vaporize in the bed or circulating bed media at 1600 degrees fahrenheit or higher and travel throughout the combustor, cyclone, and boiler as corrosive flue gases. When these gaseous compounds come in contact with relatively cooler boiler tubing below 1000 degrees fahrenheit, the gaseous compounds condense as a liquid on the surface of the steel tubing and remain until removed.

These corrosive compounds (Na_2SO_4, K_2SO_4, $CaSO_4$, and NaCl) become even more aggressive at tube metal temperatures as high as 1000 degrees fahrenheit. External pitting and loss of boiler tubing outside diameter base metal thickness are common. Boiler tube metal exfoliation may occur.

As these compounds cool, they become hard solids that adhere to boiler tube metal. This can result in long term deposition if the compounds are not removed mechanically by boiler soot blowing while on-line or periodically by high pressure water blasting during scheduled maintenance outages.

Cleaning is important not only for returning to design heat transfer performance of the boiler, it also removes the corrosive deposit from the boiler tube metal thus stopping corrosion.

Both temperature and time are significant factors in boiler tube metal deposition and corrosion. Both should be limited as much as possible through proper boiler operation and maintenance.

BOILER FUEL, SORBENT, AND ASH MATERIAL BALANCE

By analyzing and weighing the boiler fuel feed, limestone or dolomite feed, and ash production a solid material balance can be calculated for the combustion process. This will indicate the theoretically correct feed rate for the limestone or dolomite. In the combustor, when as little as 350 pounds per hour of limestone or dolomite is added with the fuel to a 22 megawatt boiler, chlorides and sulfides present within the bed or circulating bed combustion process are captured by calcium and magnesium carbonates in the sorbent. These modified and harmless compounds then exit the boiler as non-corrosive fly ash. Please see Diagram 1 Solid Material Balance of a typical bubbling bed boiler.

SOLUTIONS

Boiler combustor corrosion and erosion can be managed best through proper boiler operations and maintenance, and the addition of sorbents. Proper operations involves minimizing boiler combustion temperatures, performing timely soot blowing, procuring the best possible fuel, and properly blending the various fuels procured. Proper maintenance involves the diligent repair of damaged soot blowers to provide the best possible on-line mechanical cleaning of the boiler tubes. Maintenance also involves off-line high pressure water blast cleaning of the boiler tubes.

On-line boiler combustor neutralization of boiler tube and refractory corrosion can best be accomplished through the addition of limestone, dolomite or other sorbents. The sorbent of choice can be fed to the boiler combustor with the existing boiler fuel feed system or possibly by the existing boiler bed media makeup system. For boilers in the 11 megawatt to 25 megawatt size range, the addition of 300 to 400 lbs per hour of limestone should be sufficient to obtain the maximum modification of the corrosive nature of most biomass fuels possible through the use of sorbents. At an average sorbent cost of two cents per pound, this amounts to approximately 200 dollars per day. Not a significant expense.

DECREASED EROSION WHEN FEEDING SORBENTS

All of the sorbents used (limestone, dolomite, kaolin, and custom blends of aluminum and magnesium oxide) are orders of magnitude softer than the quarry sand or river bed sand typically specified by the boiler manufacturers for bed media when burning biomass. Therefore, the use of softer, less abrasive bed media must result in less erosion. It is extremely difficult to quantify tube metal erosion loss and refractory erosion loss and relate that loss to specific bed medias. Such testing could take years to complete.

BOILER THERMAL ENERGY LOSS DUE TO CALCINING LIMESTONE IN THE COMBUSTOR

There should be little concern about the boiler combustor heat lost to calcining the limestone in the combustor. Calculations show this heat loss to be less than one tenth of one percent of the total heat present.

PROBLEMS ENCOUNTERED WHEN OVERFEEDING SORBENTS

If sorbents such as limestone are fed in larger quantities than required for chemical reaction in the boiler combustor, then some undesirable side affects may occur. These side effects are usually not serious enough to require boiler steam flow reductions. Typically during an overfeed condition, unreacted limestone leaves the boiler mixed in with the normal fly ash and is clearly visible as small white colored specs in the fly ash. If sufficient limestone is present in the fly ash it may cause the fly ash to become sticky and difficult to convey to the fly ash storage silo, trucks or containers. In the one occurrence when this happened it was solved by one man, manually assisting the flow of fly ash from the storage silo to the waiting truck.

If the fly ash is marketed for a specific use after it leaves the power plant then the fly ash should be tested periodically to insure that any unreacted limestone is not modifying the fly ash chemistry enough to make the fly ash undesirable for its intended use. This has not been a significant problem.

CONCLUSIONS

The addition of relatively small quantities of sorbents to fluid bed boilers burning biomass fuels has long term corrosion and erosion reduction advantages. The sorbent will tie up corrosive sulfur and chlorine alkalies and salts that concentrate in the bed media during combustion. The resulting compounds containing sulfur and chlorine alkalies and salts which have been rendered harmless can then exit the boiler with the ash. Corrosion of boiler combustor tube metal and refractory is reduced.

Erosion is reduced to the extent that softer, less abrasive sorbents are substituted for some of the harder, abrasive quarry sand or river bed sand as bed media.

REFERENCES

Diagram 2: J.J. Rowe, G.W. Morey, and C.Z. Zen, Geol. Surv., Prof. Pap. (U.S.), 1972, No. 741, 37 pp.

Diagram 3: R. Nacken, News Jahrb. Mineral., Geol., Palaontol., Beil. Band 24, 1 (1907).

DIAGRAM 1. SOLID MATERIAL BALANCE 22 MW BUBBLING FLUID BED BOILER

CALCULATED FUEL MIX:

INFOREST	25%
SAWMILL	30%
URBAN	35%
AGRICULTURAL	+ 10%
	100%

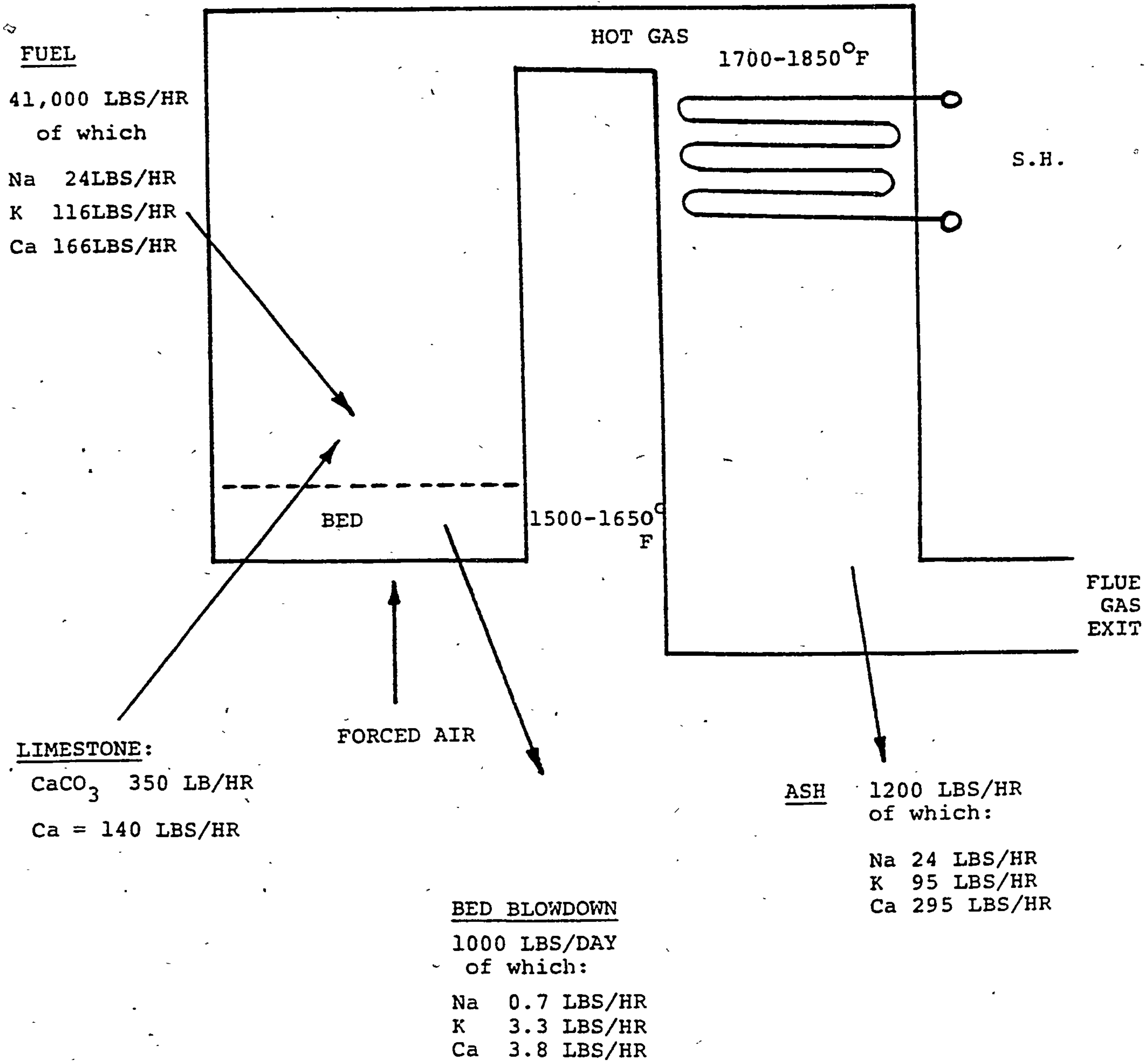
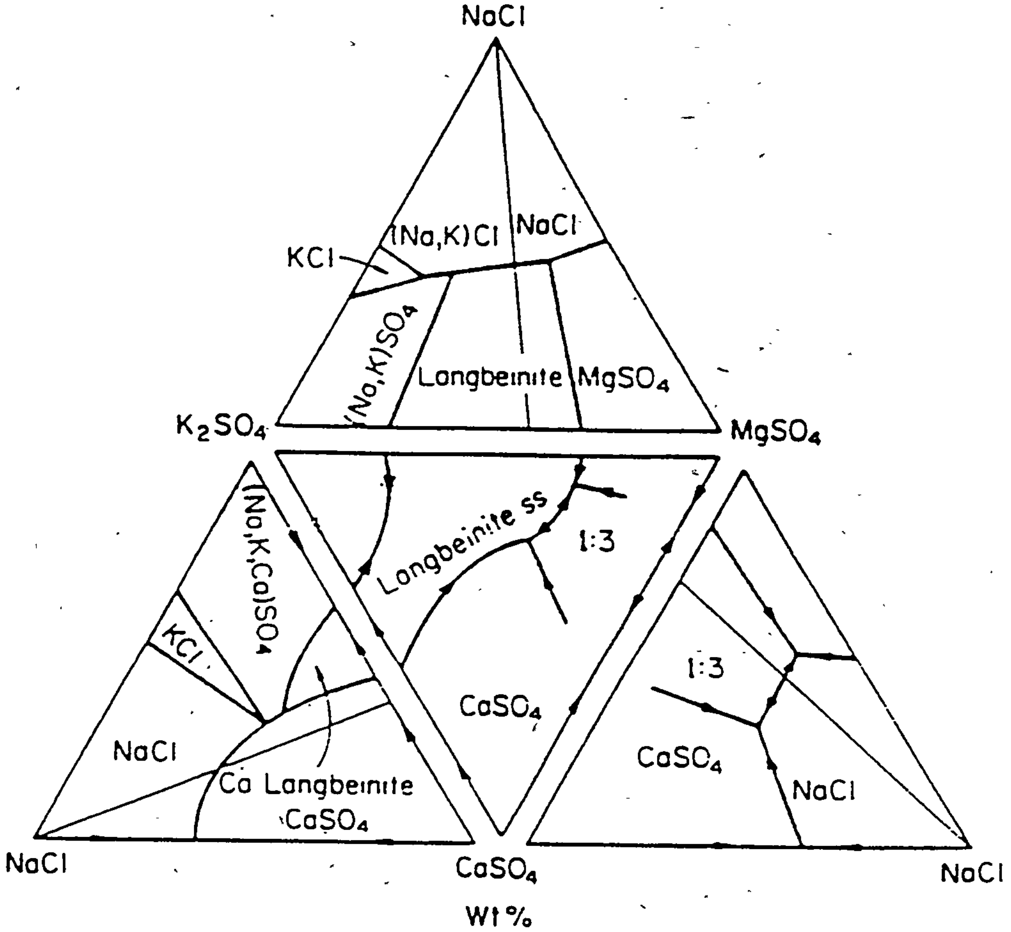
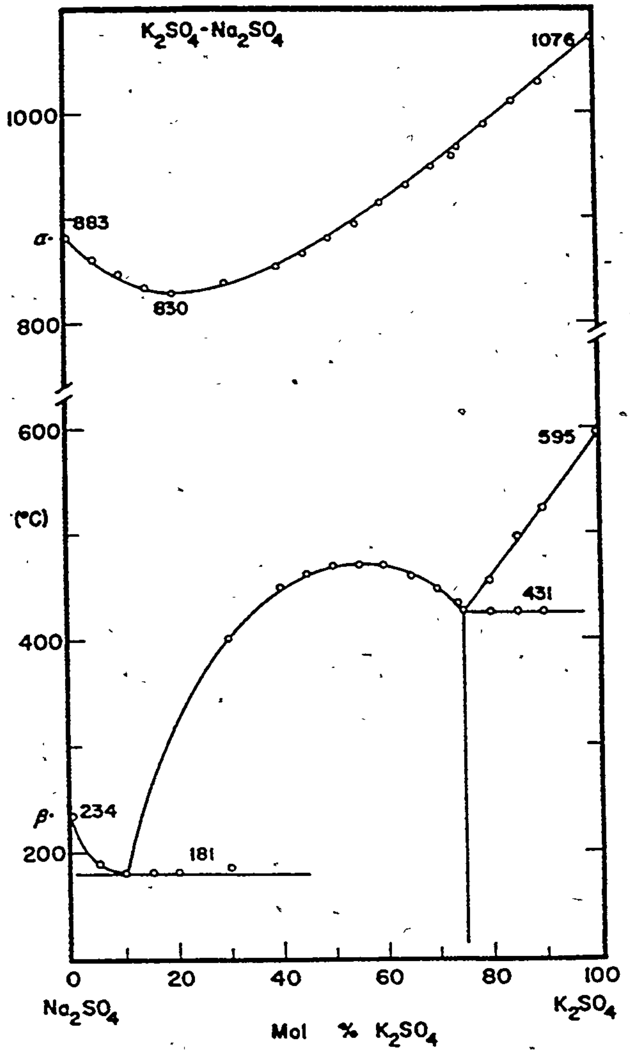


DIAGRAM 2. TYPICAL BOILER COMBUSTOR ALKALIE/SALT EUTECTIC



Data from: J.J. Rowe

DIAGRAM 3. EUTECTIC PHASE DIAGRAM



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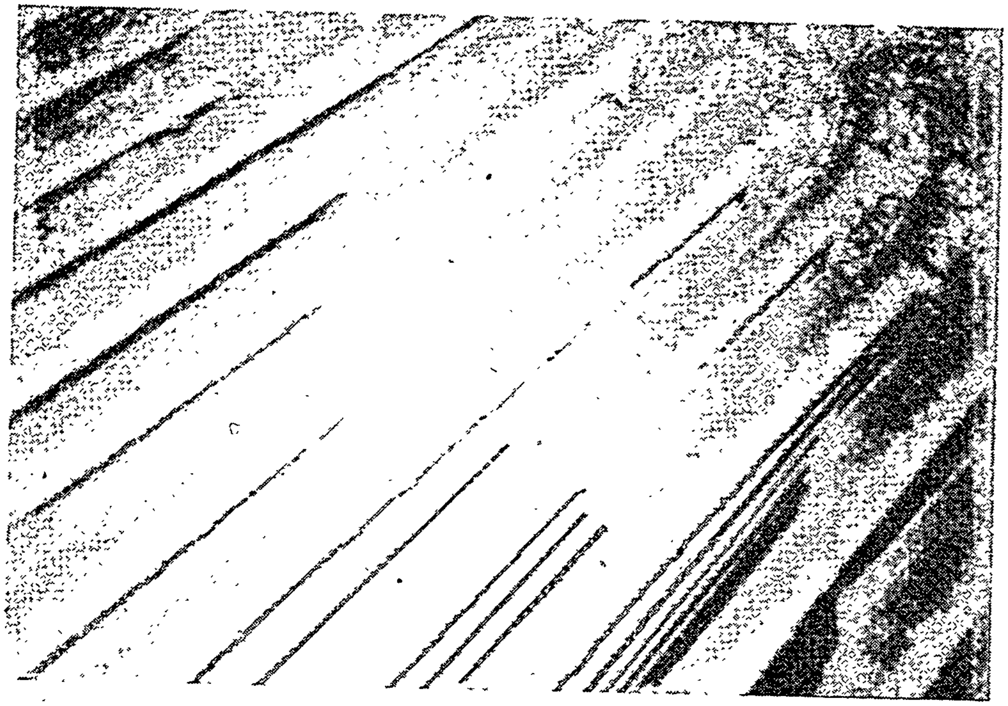
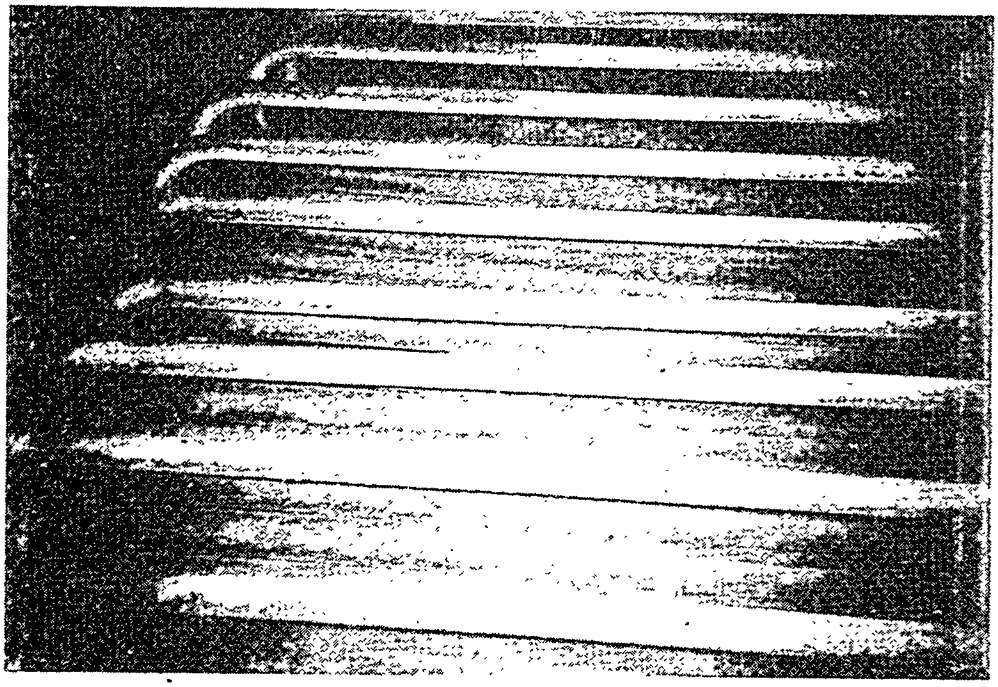
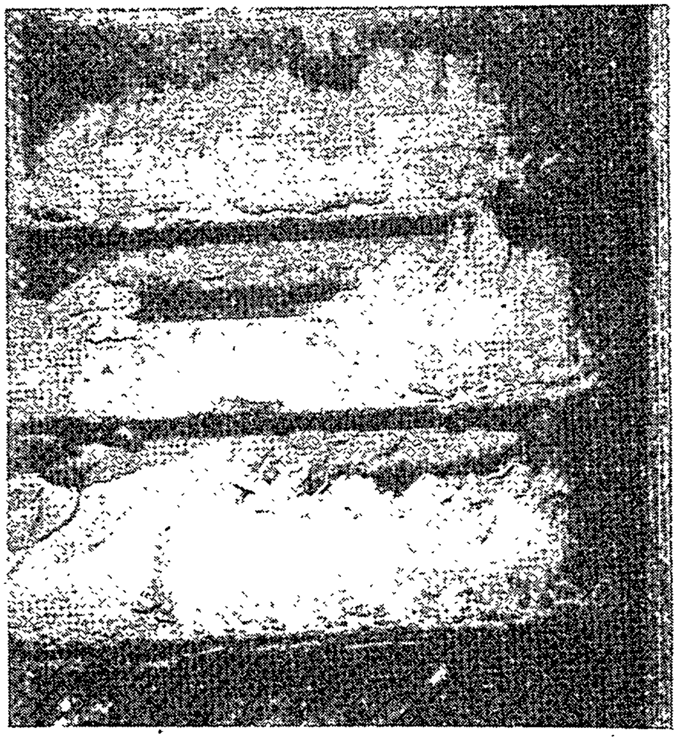


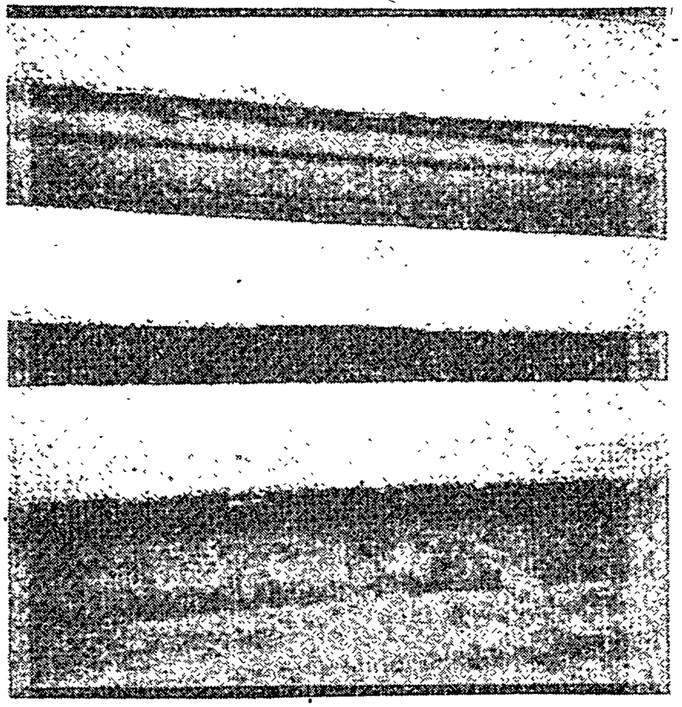
BOILER SUPERHEATER AFTER FIRING WITHOUT LIMESTONE



SAME BOILER SUPER HEATER AFTER FIRING WITH LIMESTONE



BOILER SUPERHEATER AFTER FIRING WITHOUT LIMESTONE



SAME BOILER SUPER HEATER AFTER FIRING WITH LIMESTONE

W B P
The Wood Brazilian Big-GT Demonstration Project

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ABSTRACT

Brazil is one of the leading countries in the use of renewable energy. Most of its electricity comes from hydro power, about 200.000 barrels a day of ethanol from sugar cane is used as fuel, around 38% of the pig iron, and 20% of the steel production, uses charcoal as a reducing medium.

Located in the tropics, with the sun shining all year round, and with its vast territory, the Country may be regarded as having all the basic conditions to develop a modern Biomass for Electricity industry.

The conjunction of those characteristics with, the necessity of developing new energy resources for electricity production in the Northeast of the Country, the results of the studies made by Princeton University, Shell and Chesf, the progress achieved by the BIG-GT(Biomass Integrated Gasification Gas Turbine) technology in Europe, and the organization of the Global Environment Facility (GEF), provided the unique opportunity for the implementation of a commercial demonstration in Brazil.

This paper describes the idea, the scope, the technical challenges, and actual status of development of the WBP, a project which aims to demonstrate the commercial viability of the BIG-GT technology.

It also highlights, the project management structure, the role of the GEF, World Bank and of the United Nations Development Program (UNDP), and the participation of the Brazilian Federal Government, through the Ministry of Science and Technology (MCT).

Finally it describes the Participants (ELETROBRAS, CVRD, CIENTEC, SHELL and CHESF), their role in the project, and how the group was formed and operates.

1 - Introduction

Nowadays Brazil may be regarded as one of the leaders, amongst the countries which rely on renewable as its main primary source of energy. Almost all of its electricity comes from hydro, about 200.000 barrels a day of alcohol (ethanol from sugar cane) is used as a substitute for gasoline, and around 38% of its pig iron and 20% of its steel production is based on charcoal.

Located in the tropics, with a vast area, the country may be regarded as having all the basic conditions to develop a modern Biomass industry.

Those characteristics, and the necessity of developing new energy resources for electricity production, in the Northeastern part of the country, were the motive to make Chesf (Companhia Hidro Eletrica do São Francisco) look for biomass as a new option to supply its future demand.

The results of the studies made by Princeton University, Shell and Chesf, the progress achieved by the BIG-GT(Biomass Integrated Gasification Gas Turbine) in Europe, and the organization of the GEF (Global Environment Facility), provided the unique opportunity for the implementation of a commercial demonstration of this technology in Brazil.

This paper intends to describe the idea, scope, challenges, and actual status of development of the Brazilian Wood Big-Gt Project (WBP), a project which aims to demonstrate the commercial viability of that technology.

It also highlights, its management structure, the role of GEF, World Bank and United Nations Development Program (UNDP),and the participation of the Brazilian Government through the Ministry of Science and Technology (MCT).

Finally a description of the Participants, their role in the project, and how the group was formed and operates, is made.

2 - Key Factors and Basic Ideas

Over the last years a number of factors have converged to create the ideal conditions which are supporting the development of a Big-Gt demonstration project in Brazil. Those conditions and the basic ideas leading to the WBP are summarized in the following topics.

a) In the Northeast region of the country the low cost hydro resources will be fully tapped by the year 2000. This fact has been recognized by Chesf, the regional utility, ten years ago and has opened the discussion about the available alternatives, that would have the potential to make a substantive contribution to meet the company's further demand. In the process biomass has been chosen as one of the best options.

b) The reasons considered to high rank biomass as a primary source for electricity production and its inherent characteristics, constituted a strong argument in favor of pushing Big-Gt into its commercial stage. Those reasons are as follows;

- the technology has been studied by a number of international institutions and all have reached the same conclusions, which indicate that the conversion of biomass into electricity, through the use of gasification and gas turbines, may result in a highly competitive option to produce electric energy;
- biomass, regarded as wood from plantations or bagasse from the sugar industry, represents a large potential to be exploited;
- the same technology can be used for wood and for bagasse;
- the widespread use of biomass power may result in a large number of rural employments;
- it may represent a significant contribution to boost development in the interior of the region;
- it may contribute to organize the infrastructure necessary to bring biomass into new and modern fashion of exploitation;
- the envisaged commercial model for future wood biomass power, utilizing power plants in the order of 60MW, see Fig.01, may bring the opportunity to introduce new private investors into the electrical sector;
- the possibility of worldwide utilization of biomass for electricity production.

c) The creation of the Global Environment Facility (GEF) with its mandate to promote investment ,in the protection of the ozone layer, biodiversity, international waters, and in the depletion of carbon dioxide in the atmosphere,which has been the key factor in providing the funds necessary to transform the existing ideas into a real project.

3 - The WBP Project

3.1) Project Description

The scope of the WBP comprises, the installation of a 30MW demonstration power plant, based in the Big-Gt technology, which may be regarded as the core of the project. Besides that it foresees the incorporation of a commercial enterprise with the aim of implementing the construction, assembly, and operation of the plant. In the future this company also could have the objective of exploring the commercial possibilities of this new concept of electricity production.

The 30MW power plant is being conceived to be used as a module of future commercial units, which is foreseen to have an installed capacity in the range of 60MW or larger, depending on site conditions.

The Big-Gt concept, in conjunction with a combined cycle configuration, is aimed to give the demonstration plant an overall efficiency of about 43% . The plant is being designed to be fuelled by wood chips, as its main fuel, but also will run with bagasse for sometime, during a test period.

The demonstration unit will be compounded by the following systems;

a. fuel storage and handling;
b. fuel drying and feeding;
c. gasification and gas cleaning;
d. gasification air;
e. gas cooling;
f. gas turbine and generator;
g. heat recovery and steam generation;
h. steam turbine and generator;
i. steam condensing;
j. cooling ;
k. water treatment;
l. residues disposal;
m. safety and auxiliary systems;
n. control, monitoring and data acquisition;
o. communication.

3.2) Technical Parameters

3.2.1) Demonstration Plant

Installed capacity	~ 30MW
Efficiency	~ 43%
Conversion cycle	Combined Cycle
Capacity factor	0.80
Energy production	210240 MWh/a
Fuel consumption	205825 m^3_{solid}/a (35% moist.)

3.2.2) Fuel

Primitive Fuel	
Main (Raw)	Eucalyptus Chips w/ 35% moisture
Test	Bagasse
Secondary Fuel	
Gas	Low Heating Value Gas from Wood Chips or Bagasse

Gas Characteristics

	(vol %)	
H_2	11	12
CH_4	5	7
CO	16	19
CO_2	11	14
N_2	43	46
H_2O	2	12
Others	1	2

Low Heating Value : 4.5 to 6.5 MJ/m^3

Specific Consumption: 0.75 t/MWh
(35% moist, eff.43%,
LHV 11.1 GJ/t) 0.98 m^3_{solid}/MWh

Gasification Agent : Air

3.2.3) Fuel Supply

Fuel Source : Eucalyptus Energy Plantations

Average Forestry Cycle: 18 years (cut every 6 years; 3 cuts between replanting)

Average Productivity : 20 to 30 m^3_{solid}/ha.a

Planted Area :

m^3_{solid}/ha.a	ha
20	10290
30	6890

Energy Production :

m^3_{solid}/ha.a	KWh/ha.a
20	20200
30	30570

3.3) Project Costs

Investment

Specific cost:	1st plant	2750 US$	original est.
	1st plant	> 2000 US$	present est.
	commercial	1300-1500 US$	target cost
Total invst:	1st plant	US$ 60-75 million	present est.
	commercial	US$ 39-45 million	present est.
Energy cost:	1st&comm	45-55 US$/MWh(*)	present est.

* Includes GEF grant for the 1st plant.

3.4) Project Phases

3.4.1) Phases

The Project has been conceived to be developed in the 5 (five) phases listed below, Phase-I began in July 1991 and ended in March 1992. Phase-II, which is being carried out at the moment, started in April 1992 and is scheduled to end in the first quarter of 1995.

3.6) Project Major Challenges

The Project major challenges are located in three areas, technical, economic and organizational.

Technically is imperative achieving, high overall efficiency, high reliability, dependable fuel feeding, and the production of a gas with heating value and quality which is acceptable for the gas turbine.

Economically the plant must be able to produce cost competitive energy, which means investment, operation and maintenance costs compatible with acceptable rates of return for the investors, considering the energy tariff, to be negotiated with the regional utility, and the conditions to raise the funds necessary to complement the GEF grant.

In organizational terms will be necessary to structure the entity, which will bind the actual participants and the new investors in the Project, and also will be responsible for the erection and operation of the demonstration plant.

3.7) Project Schedule

To give a better idea of the Project chronogram two different schedules are shown, the first is an overview of all its phases and the second gives a more detailed insight of Phase-II.

3.7.1) Overall Schedule

Phase-I	July	1991	to	March	1992
Phase-II	April	1992	to	March	1995
Phase-III	April	1995	to	Oct.	1997
Phase-IV	Nov.	1997	to	Dec.	1999
Phase-V	Jan.	2000	and on		

3.7.2) Phase - II Schedule

01 - MCT&UNDP Project Formalization	March to June 1992
02 - Contract of Eng. Services	April/92 to July/93
03 - Contract of Equip. Developers	March/92 to Dec./92
04 - Equip. Dev. & Progress Monitor.	Jan./93 to March/95
05 - Provision of Feedstock for Tests	April/93 to June/93
06 - Survey of Local Suppliers	April/94 to Aug./94
07 - Site Selection	March/93 to Aug./93
08 - Grid Connection Studies	Aug./93 to Oct./93

The group of Participants is formed by :

Fundação de Ciência e Tecnologia - CIENTEC
CIENTEC is a major Brazilian research institute, located in the State of Rio Grande do Sul, with large experience in combustion and gasification;

Companhia Vale do Rio Doce - CVRD
CVRD is internationally kownn as one of the largest iron ore exporter. It also has interests in the pulp and paper industry, and in forestry.

Centrais Elétricas Brasileiras - ELETROBRAS
ELETROBRAS is the holding company of the main utilities in Brazil and the parent company of CHESF;

SHELL BRAZIL & SHELL INTERNATIONAL
SHELL is one of the major petroleum companies in the world, has been one of the original proposers of the Project, and has made major contributions for its development;

Companhia Hidro Elétrica do São Francisco - CHESF
CHESF is a regional utility, subsidiary of ELETROBRAS, responsible for the generation and transmission of bulk power for the Northeast region of Brazil. It has been interested in biomass for power production for many years, was one of the original proposers of the idea and has supported the Project from the outset.

4.4) The Equipment Developers

The Equipment Developers (ED's) are the three companies responsible by the development of the main equipment or systems, and the concept of the WBP demonstration plant.

Those companies, as already mentioned, are GE, encharged of the gas turbine modifications, TPS, and Bioflow, the last two have the responsibility, not only for the gasification and gas cleaning systems, but also for the concept of the whole plant. In fact they are considered the main players in Phase-II, as the result of their work will be the key factor to determine the Project chances of succeeding.

4.5) The Technical Observers

In order to divulge the Project and make its progress known to specific entities, which may, in the future, be users of the technology or make significant contributions towards its commercial demonstration, a new class of participant, named Technical Observers (TO), has been created.

The TO's, which are listed below, participate in specific meetings where the progress and activities being developed at the moment, are discussed and evaluated. At those meetings they also have the opportunity to make suggestions and express their opinion about the project development.

Technical Observers;

Wood	Tropical Farming
Bagasse	Distillery Santo Antonio Copersucar State of São Paulo

4.6) Extension towards Cogeneration

Given the large sugar cane industry existing in Brazil, and its enormous potential for cogeneration an extension of the scope of the Project, to cover this area is under consideration.

The idea is to build on the previous work, made by the actual Participants, and using the same framework extend the project scope to get, as an additional output, the Basic Engineering of a cogeneration plant designed to fit the average of the Brazilian distilleries and sugar mills.

Copersucar is leading the cogeneration extension of the WBP.

5 - Organization and Management

The organization and management structure of Phase-II has been defined in a Memorandum of Understanding (MOU) signed by all the Participants and by the MCT.

The MOU defines the project goals, organization and management structure, and the commitments and obligations of each Participant.

MCT, having assumed formal responsibility to UNDP for the Phase-II development, will accomplish its obligations through a Management Committee (MC) chaired by its representative and formed by nominees of each Participant. Figure 03 illustrates the formal management structure of the WBP.

The functional structure, which is used to operate on a daily basis, is shown in Figure 04. It is important to mention that this simplified organization is working very well, and has been one of the key factors to acheive the present Project stage of progress.

6 - Project Background

The results of the studies made by Princeton University, Shell and Chesf, and the knowledge developed in Europe, provided the technical background to support the idea of developing a commercial demonstration of the Big-Gt technology in Brazil.

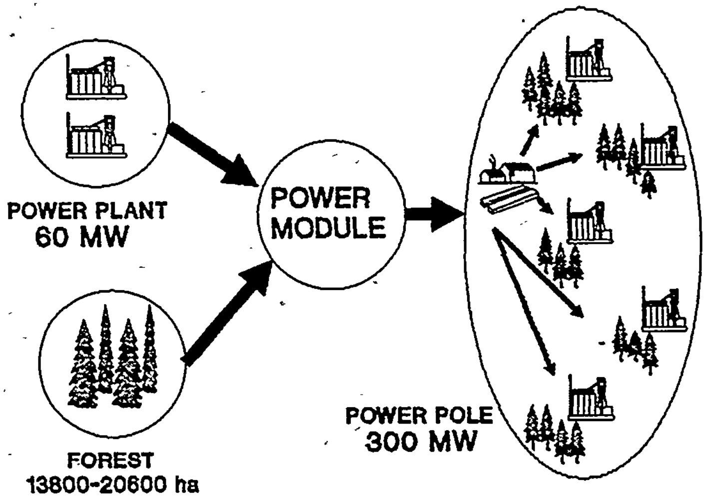
Initially Shell and Chesf, independently and at different time, have tried to start their own demonstration projects. Both, for various reasons, failed.

In June 1991 the Brazilian Federal Government, through, at that time the Secretary of State for Science and Technology, Professor José Goldemberg, expressed its interest in supporting a commercial demonstration of the Big-Gt technology in Brazil. After that, nine organizations have shown interest in joining their efforts to prepare a formal proposal to the GEF, to get the funds necessary to implement the demonstration project. From that group six companies went to the end of Phase-I and five, CIENTEC, CVRD, ELETROBRAS, SHELL and CHESF, have committed themselves to Phase-II.

Finally, it is important to mention that all the progress achieved in the "Brazilian Wood Big-Gt Demonstration Project" up to this moment, has been accomplished as a result of the group's binding philosophy, which relies on complete transparency and trustfulness.

WOOD BIG-GT COMMERCIAL UNITS CONCEPT AND PHILOSOPHY

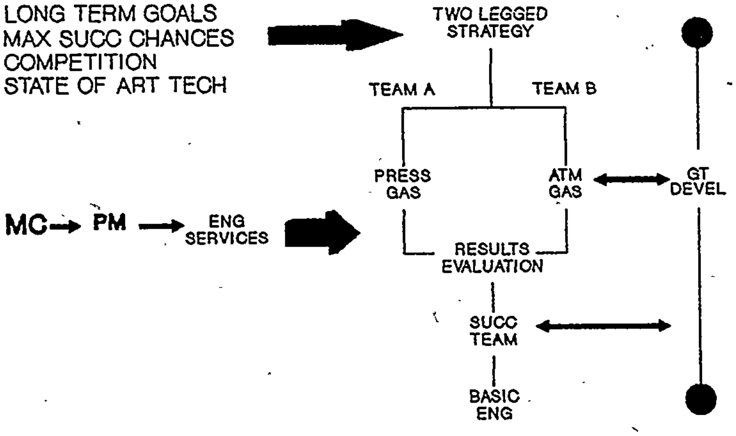
FIG.01



PHASE II MANAGEMENT PHILOSOPHY

FIG.02

BASIC ASPECTS

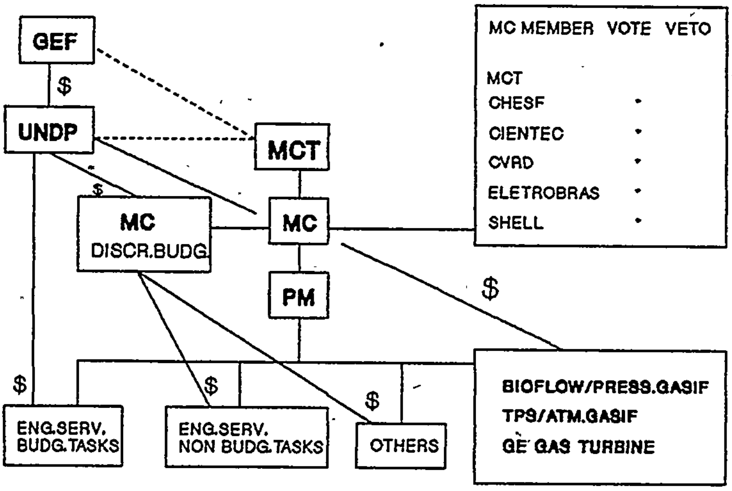


LONG TERM GOALS
MAX SUCC CHANCES
COMPETITION
STATE OF ART TECH

TWO LEGGED STRATEGY
TEAM A
TEAM B
PRESS GAS
ATM GAS
GT DEVEL
MC → PM → ENG SERVICES
RESULTS EVALUATION
SUCC TEAM
BASIC ENG

Brazilian BIG-GT / WBP Project
Phase II Organization and Management

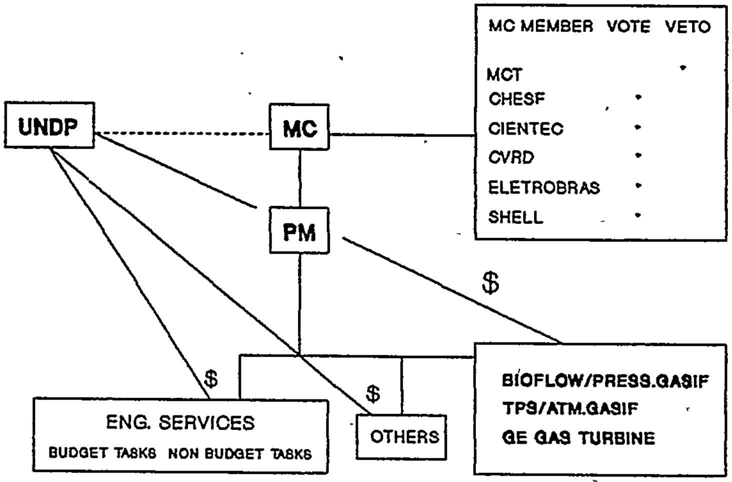
FIG.03



MC MEMBER	VOTE	VETO
MCT		
CHESF	•	
CIENTEC	•	
CVRD	•	
ELETROBRAS	•	
SHELL	•	

Brazilian BIG-GT / WBP Project
PHASE-II FUNCTIONAL ORGANIZATION

FIG.04



MC MEMBER	VOTE	VETO
MCT		•
CHESF	•	
CIENTEC	•	
CVRD	•	
ELETROBRAS	•	
SHELL	•	

ALKALI SLAGGING PROBLEMS WITH BIOMASS FUELS

Thomas R. Miles, Thomas R. Miles, Jr., Larry L. Baxter,
Bryan M. Jenkins, Laurance L. Oden

Abstract

Biomass fueled power boilers are unable to burn more than minor percentages of annually generated agricultural fuels. Determining the mechanisms of deposit formation, and developing means of increasing the proportion of these annual biofuels to be fired are the aims of the ongoing Alkali Deposit Investigation sponsored by DOE/NREL with matching funds from industry sponsors, combining Science, Engineering and Industry.

BIOFUELS RESOURCES

Over recorded time, man's primary biomass resource has been wood, and its availability has dictated the rise and fall of dynasties and civilizations. As early as 4700 BC we know that wars were fought over wood supplies for fuel, shelter and ships - to make more war. The eastern Mediterranean was once heavily wooded, but the advent of the Bronze Age in 2000 BC and its voracious demands for smelting fuel denuded whole countries while erosion of bare slopes silted harbors and isolated cities up to 5 miles inland (Perlin).

In the 1600s England was running out of wood for these same historic reasons and turned to New England to import masts for ships and firewood. At about that time coal came to the energy rescue, allowing England to continue growth - albeit with some unbearable environmental problems in the early going.

The young America was also dependent on wood as a fuel well into our century, since coal and more recently natural gas and oil have combined to dominate as energy resources. Meanwhile the centuries-old habit of "cut out and get out" dominated our forest industries in providing wood, some for fuel but mostly for construction, housing, - and to meet the national burgeoning demand for paper products. Only in the late 1950s did a serious effort to reforest begin to develop into what is now a virtually universal practice in the United States.

So we have eventually learned from the past and are determined to avoid repeating the profligate ways with wood of the last 5000 years, toward a possible fate of "energy extinction".

Obviously we must get cracking on utilizing every potential source of fuel from wastes and from plantations, from increased conversion efficiencies, from conservation measures, and from thoughtful evaluation of applying the "highest and best use" principle to our fuel resources. A current example of this principle is the increasingly widespread use of Urban Wood Waste, UWW, that fairly clean wood now being diverted from landfills to power plants. The CO_2 produced from combustion is approximately one-fifteenth as hard on global warming as the methane produced from landfilling.

Toward these ends of highest and best use, we need to accelerate the utilization of those wastes with proven conversion systems: tires, municipal wastes, industrial wastes, etc. - and we must develop ways to convert annually available biomass crop residues and short rotation tree species into energy.

These agricultural residues, the straws, stalks, stems, pits, shells, weeds, and grasses represent a substantial energy resource that we cannot now realize by combustion in conventional boilers.

THE ALKALI PROBLEM

The high alkali content (up to 35%) in the ash from burning annual crop residues lowers the fusion or "sticky temperature" of these ashes from 2200° F. for wood ash to as low as 1300° F. This results in serious slagging on the boiler grate or in the bed and fouling of convection heat transfer surfaces. Even small percentages (10%) of some of these high alkali residues burned with wood in conventional boilers will cause serious slagging and fouling in a day or two, causing shutdown. Power plants must rely on longer periods of continued flow of energy - 2 to 4 months.

Wood alone is comparatively very low in both ash <1%) and alkali (3-5% in ash) but still requires some deposit management such as soot blowing to sustain operations.

All living fauna and flora are critically dependent on potassium and some sodium ions for their growth processes. The biofuel containing the least alkali is the stemwood or trunk of a tree, and the larger limbs and branches. The sap in the cambium layer is rich in alkali but does not deposit it in the wood itself. The small branches, twigs and foliage consisting of high percentages of annual growth and cambium tissue are quite rich in potassium and with sodium salts and organic complexes. Figure 1 illustrates the differences between pine stemwood, chips and tree trimmings, as well as showing the high alkali content of shells and straws.

ALKALI CONTENT IN BIOFUELS

Fuel	Btu/lb Dry	Ash %	Total Alkali			
			% in Ash	lb/ton	lb/MMBtu	
WOOD						Minimal
Pine Chips	8,550	0.7%	3.0%	0.4	0.07	Slagging
White Oak	8,165	0.4%	31.8%	2.3	0.14	.4 lb/MM Btu
Hybrid Poplar	8,178	1.9%	19.8%	7.5	0.46	
Urban Wood Waste "Clean"	8,174	6.0%	6.2%	7.4	0.46	Probable Slagging
Tree Trimmings	8,144	3.6%	16.5%	11.9	0.73	
						.8 lb/MM Btu
PITS, NUTS, SHELLS						
Almond Shells	7,580	3.5%	21.1%	14.8	0.97	Certain Slagging
Refuse Derived Fuel	5,473	9.5%	9.2%	17.5	1.60	
STRAWS						
Switch Grass	7,741	10.1%	15.1%	30.5	1.97	
Wheat Straw - average	7,978	5.1%	31.5%	32.1	2.00	
Wheat Straw - hi alkali	7,167	11.0%	36.4%	80.0	5.59	
Rice Straw	6,486	18.7%	13.3%	49.7	3.80	
Bagasse - washed	8,229	1.7%	12.3%	4.2	0.25	

Figure 1

Note that the hybrid poplar chips in this case are whole tree chips from 6" diameter trees, plantation grown. The combination of a small stem with its higher cambium-to-bole ratio, plus the branches and twigs, results in higher alkali levels. The clean Urban Wood Waste consists of ground pallets, crating, and construction lumber but does pick up various contaminants along the way. The white oak is an example of an high alkali percentage in the ash, but very little ash, illustrating the point that all the values shown must be considered to properly evaluate a fuel. Similarly, any annual crop will contain substantial percentages of alkali deposited throughout the plant, since the entire plant is annual growth.

In addition to the characteristic alkali and ash content of a specie, growth site, sensitivity to soil content, rainfall, and the crop variety all contribute to this spread. Another unusual item of interest is the fairly low alkali content of bagasse, resulting from the sugar cane having been crushed and the soluble alkali rinsed out with the sugar. Also there is a wide spread in wheat straw that should be noted. Finally, the very high ash content plus moderate alkali in rice straw presents a very serious deposit and agglomeration problem as a fuel.

A FOULING/SLAGGING INDEX

The coal industry has a long history of dealing with and researching this alkali deposit problem. Although there are major differences between coal and biofuels, one method they have developed to roughly classify various coals relative to slagging and deposits involves calculating the weight in pounds of alkali ($K_2O + Na_2O$) per million Btu in the fuel. The calculation is:

$$\frac{1 \times 10^6 \text{ Btu}}{\text{Btu/lb (dry)}} \times \text{Ash \%} \times \text{Alkali \% of the Ash} = \frac{\text{lb Alkali}}{\text{MM Btu}}$$

This method combines all of the pertinent data in one Index Number. A range of 0 to 0.4 lb/MM Btu is considered fairly low slagging risk. 0.4 lb to 0.8 lb/MM Btu will probably slag, with increasing certainty as 0.8 lb/MM Btu is approached. Above 0.8 lb/MM Btu the fuel is virtually certain to slag and foul. We have had occasion recently to field test some of these values and found them to be good indicators of slagging in biofuels.

Applying this calculation to Figure 1 we find that clean wood chips are below 0.4 lb/MM Btu and they produce only the traditional loose deposits, easily removed by soot blowers. Bagasse is also low but does slag to a limited but manageable degree, as evidenced by 200 sugar mills around the world that depend on bagasse for steam. Urban Wood Waste (UWW) at 0.5 lb/MM Btu also slags to an annoying, often -- unmanageable degree, requiring as much as two hours of manual poking per shift to keep the agglomerated clinkers and wall sloughings moving across a traveling grate. Fluid beds are somewhat more tolerant of UWW characteristics and facilitate the use of inhibitors such as dolomite, kaolin, etc. Screening the

UWW fuel, either by trommel or oscillating deck screen, to remove minus 1/8" fines significantly reduces the alkali, and hence the slagging.

ALKALI DEPOSITS FOUND IN BIOMASS PLANTS

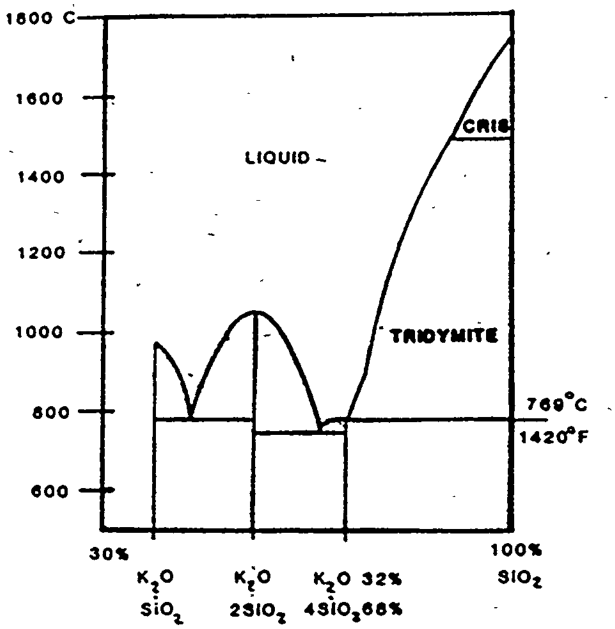
In recognition of the constraining effect of this problem in utilizing the substantial volume of annual agricultural residues in existing conventional power plants - many of which are sited in the midst of those croplands - the U.S. Department of Energy/National Renewable Energy Laboratory (DOE/NREL) has funded a project with the above title. More than equal matching funds and services are provided from eight sponsoring biofueled power plants and four industries associations. Scientific advisors from the University of California at Davis - Dr. Bryan Jenkins; Sandia Laboratories in Livermore, California - Dr. L. L. Baxter; and the US Department of Interior Bureau of Mines Research Center in Albany, Oregon - Dr. L. L. Oden provide science and advanced diagnostic and analytical facilities. Principal Investigator is Thomas R. Miles, Consulting Design Engineer, and Contract Administrator is Thomas R. Miles, Jr. Thus there is an unusual collaboration of Science, Industry, and Engineering investigating the problems.

The goal of the project is to discover the chemistry and kinetics of deposit formation from biofuels and to seek ways to at least increase the percentages that can be safely fired with wood in existing power plants.

Five extended firing tests have been conducted with biofuel blends in sponsors' power plants. Fuels, ash, and deposits have been collected, and analyzed by as many as five different methods. Hundreds of biofuel samples have been collected and analyses conducted in the assembling of an analytical database. Special counseling is being provided by experts who are experienced in similar deposit problems in coal. The project is continuing through January of 1994.

ALKALI/SILICA MIXTURES

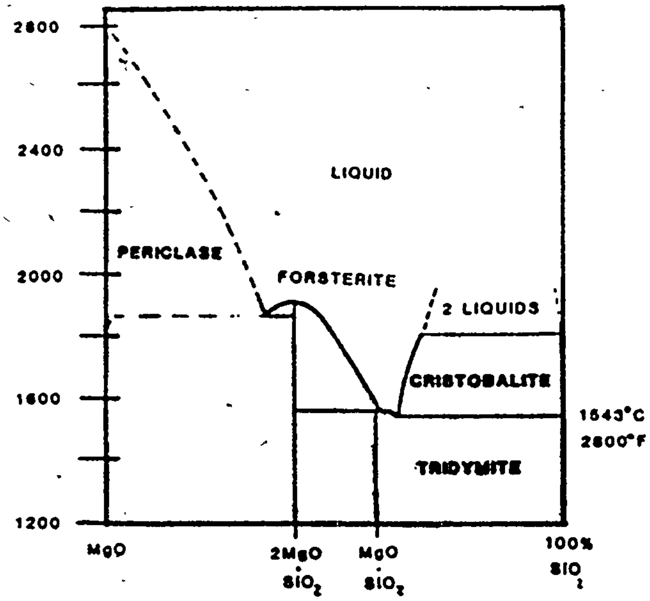
Potassium and sodium, the alkali metals, as oxides, hydroxides, or in metallo-organic compounds have an eutectic effect on the melting point of a mixture with various other minerals such as SiO_2.



PHASE DIAGRAM FOR K2O-SIO2

AM. IRON & STEEL INST

Figure 2



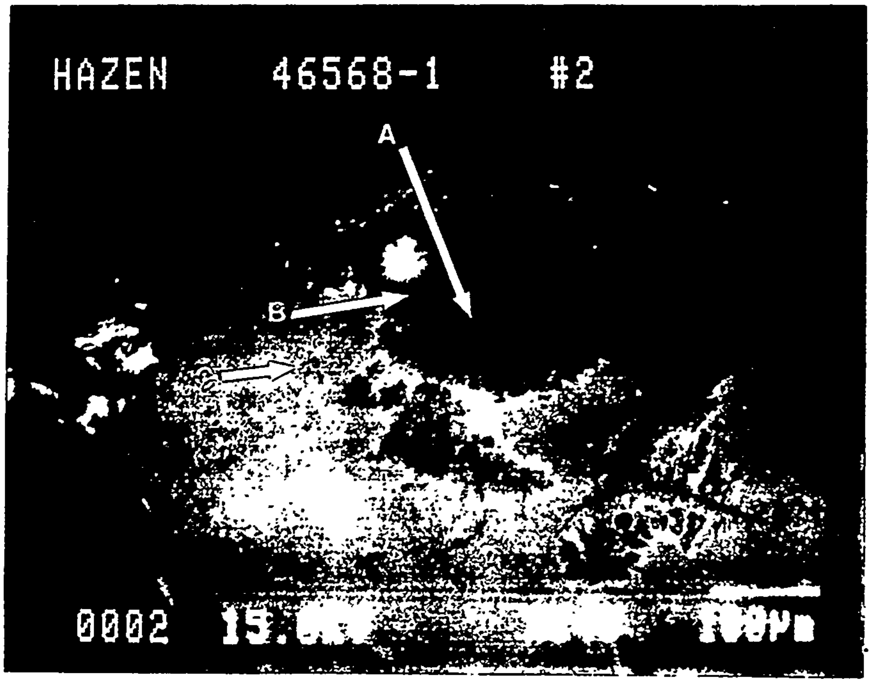
PHASE DIAGRAM FOR MgO-SIO

Figure 3

Figure 2 is a Phase Diagram showing the melting point of various mixtures of potassium oxides (K_2O) with silica (SiO_2), which makes up the bulk of the ash in biofuels. The upper area in Figure 2 is the liquid phase while areas below are solid phase. It is possible to have solid phases of one or more minerals in a liquid phase of another. Cristobalite and Tridymite are both crystalline phases of SiO_2, formed at different temperatures.

Figure 2 also shows that a mixture of 32% K_2O and 68% SiO_2 melts at 769° C, or 1420° F. Note that SiO_2 alone melts at 1700° C or 3100° F. Interestingly enough, this ratio is very close to the 25%-35% alkali (K_2O + Na_2O) found in many biomass ashes. This confirms the values we and others have experienced. We are now using this as a sintering test, or the "sticky temperature", where these compounds begin to stick to eachother and begin to pose slagging problems. For comparison, Figure 3 is a phase diagram for mixtures of magnesia (MgO) and silica (SiO_2). Magnesia produces the reverse effect of alkali by increasing the melting point of the mixtures.

Figure 4 is an SEM sample of grate ash from a 5% straw/95% UWW test firing. An electron microprobe analysis produced the composition chart below. Note the wide variation in composition of the distinct phases in this "mixture", typical of the majority of deposit samples.



Sample ADI-100

Backscatter electron image showing resorbed fragment of siliceous component (Area A) with intermediate phase (Area B) embedded in continuous glass phase (Area C). Note the high K_2O (21.2%) content of the intermediate phase.

	Analysis, Weight Percent						
	SiO_2	Al_2O_3	CaO	MgO	K_2O	TiO_2	Fe_2O_3
A)	64.2	26.2	4.4	0.01	5.1	0.01	0.15
B)	54.6	24.0	0.01	0.01	21.2	0.01	0.14
C)	58.6	12.7	17.1	3.4	5.1	0.01	3.1

Figure 4

SLAGGING AND FOULING

There are actually three types of alkaline deposits:

1) Fouling of convective passes is caused by the very fine, micron-size, molten alkali/silica particles that escape the grate or fluid bed. Some collect on the walls and fall back. Others carry on into the convection passes - first encountering the superheater, which is hotter than the water walls and tends to collect these molten particles, forming weird patterns and eventually blanking off or fouling heat transfer and shutting down the boiler.

2) Larger particles coalesce on the grate or in the bed and form a low-melting glaze-like liquid that settles down and fuses the sand, rock, and dirt particles into an agglomerated clinker, growing to 5"-6" deep on a grate, or agglomerating fluid bed sand particlres into "sand babies" or a solid bed.

3) If subjected to temperatures in the 1600°-1700° F. range, these potassium silicates dissolve the included silica pebbles and sand into an amorphous vesicular slag which resembles lava. A wide variety of slags are formed. Some are almost clear, others many-hued "moon rocks", others almost perfect spheres. Iron is particularly effective in aiding the slagging process.

The usual case is the progression of all three forms of fouling/agglomeration/slagging until the boiler is shut down for 2 to 4 days, to painstakingly jackhammer, chisel, and/or wire brush to clean up the boiler.

One of the goals of the Alkali Deposit Investigation is to provide analytical data, slagging indices, and other recommendations to aid in blending fuels to realize a maximum utilization of the other biofuels without slagging and fouling.

NEW ANALYTICAL METHODS

Two analytical techniques new to biofuels have been used by Dr. Larry Baxter at Sandia Laboratories.

Chemical Fractionation subjects the sample to a series of leachings that measures those percentages of each constituent that are:

1) Soluble in water and atomically dispersed - also readily available to react in the furnace;

2) Soluble in ammonium acetate and ion exchangeable - less readily available;

3) Soluble in acid - not readily available;

4) Residues - minerals.

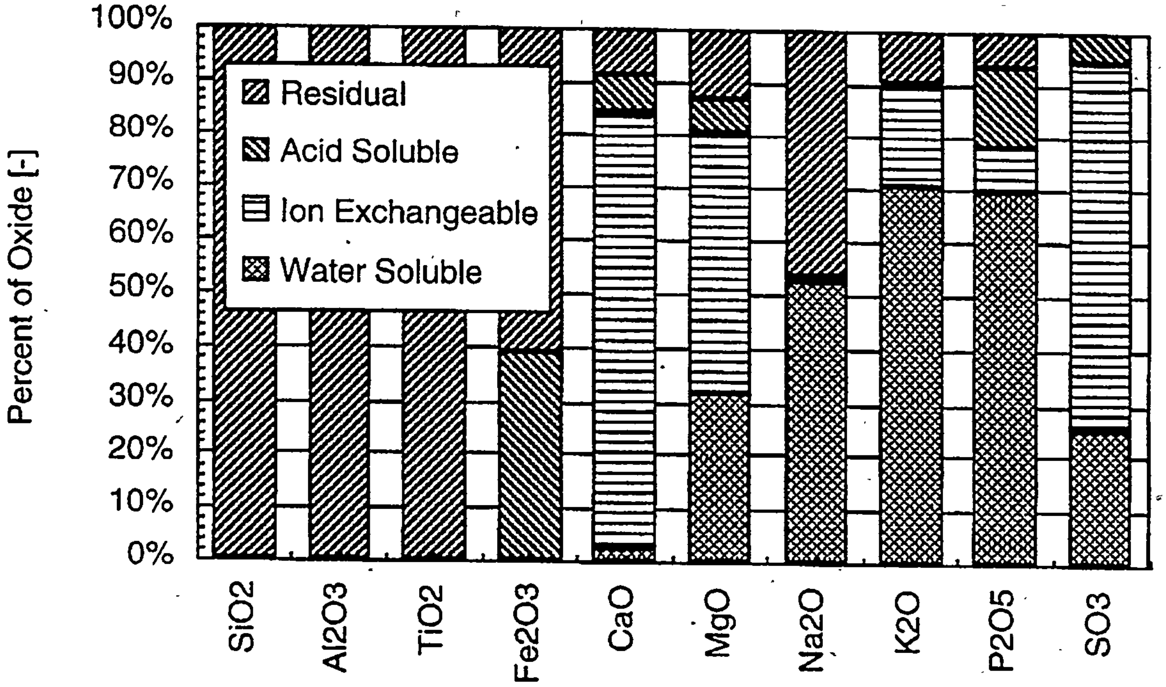


Figure 5

Results of the chemical fractionation procedure for switch grass illustrating the mode of occurrence for each major inorganic constituent. (Baxter).

CHEMICAL CHARACTERIZATION OF MODE OF OCCURRENCE

The mode of occurrence of each element in several raw biomass fuel samples has been quantified through a consecutive series of leaching steps.

A modification of a coal characterization procedure known as chemical fractionation (Baxter and Hardesty, 1992; Benson and Holm, 1985; Miller and Given, 1978) is used to characterize the inorganic constituents of biomass. Results from the switchgass sample, the one that appears to include the greatest amount of soil impurity, are shown in Figure 5. The technique classifies the fraction of each element as water soluble, ion echangeable, acid soluble, or residual. Non-granular and ionically bound material in a plant should be either water soluble or ion exchangeable. This includes most alkali and alkaline earth materials in plants. During combustion, most of this material is readily volatile. Alkali or alkaline earth materials bound in clays contrast with the atomically dispersed material in that they are largely nonsoluble in acid or water and nonexchangeable. The data indicate that 90 percent of the potassium and 85 percent of the calcium is either soluble or exchangeable whereas none of the alumina or silicon is. This is consistent with our experiences based on the physiological forms of the materials in the plant and the idea that most of the aluminum and small amounts of alkali and alkaline earth materials are in the form of clay or other soil impurities.

In summary, the inorganic material inherent in these biomass fuels is dominated by silica that is hydrated and granular with few if any heteroatoms in it. Alkali and alkaline earth elements are atomically dispersed (non-granular). Soil contamination of the sample introduces aluminum, silicon, alkali and alkaline earth elements, and other materials that are predominantly in the form of clays and oxides.

As will be shown, the combustion behavior of these inorganic materials depends strongly on their mode of occurrence. For example, potassium in the form of illite (a clay mineral common to many soils) is reasonably benign during combustion. Atomically dispersed potassium (the principal form of potassium in the biomass fuels) vaporizes and subsequently recondenses. This latter form of potassium plays a central role in much of the bed agglomeration, slagging, and fouling in commercial biomass-fired boilers.

PHYSIOLOGICAL OCCURRENCE OF INORGANIC MATERIAL IN PLANTS

The most prevalent inorganic component of each of the fuels tested (other than oxygen) is silicon. Silicon is incorporated in plants by absorption of silicic acid from the soil solution. There is controversy as to whether silicon is an essential element for plant growth. Silicon is present in most plants at macronutrient levels (0.1-10% dry basis). Rice straw is noted by some investigators for its ability to concentrate silicon, primarily in apoplastic forms, as a structural component of the plant (Marschner, 1986). Silicon is deposited as a hydrated oxide ($SiO_2.nH_2O$) usually in amorphous, but occasionally in crystalline forms. The ratio of silicon found in rice straw to the amount that would be deposited based on the rate of transpiration varies from 54:1 to 3:1, with a typical value being about 10:1. Wheat straw also concentrates silicon, but to a lesser extent, with silicon ratios varying from 5:1 to 1:1. The behavior of switchgrass is not well established. The literature does illustrate that other plants preferentially exclude silicon. For example, soybean silicon ratios vary from 1:1 to 0.1:1. In all cases, the highest ratios are observed when the silicon concentration in the nutrient solution is low.

Potassium is the second most prevalent component of the straws and a significant component of switchgrass. Potassium in plants occurs in a distinctly different form from silicon. Potassium occurs as a univalent ion (K^+) that is highly mobile with little structural function. Potassium uptake is highly selective and correlates with plant metabolic activity. Osmotic potentials across membranes and ionic potentials in the cytoplasm are regulated to a large degree by potassium. Potassium also plays important roles in enzyme activation, membrane transport, and stomatal regulation. Because of these metabolic and transport roles, potassium is often found in regions where plant growth is most vigorous (Marschner, 1986).

MULTIFUEL COMBUSTION FURNACE (MFC)

The second method being used at Sandia is the Multi-Fuel Combustion furnace (MFC) which simulates various combustion conditions in a furnace collecting the resultant deposits for analysis.

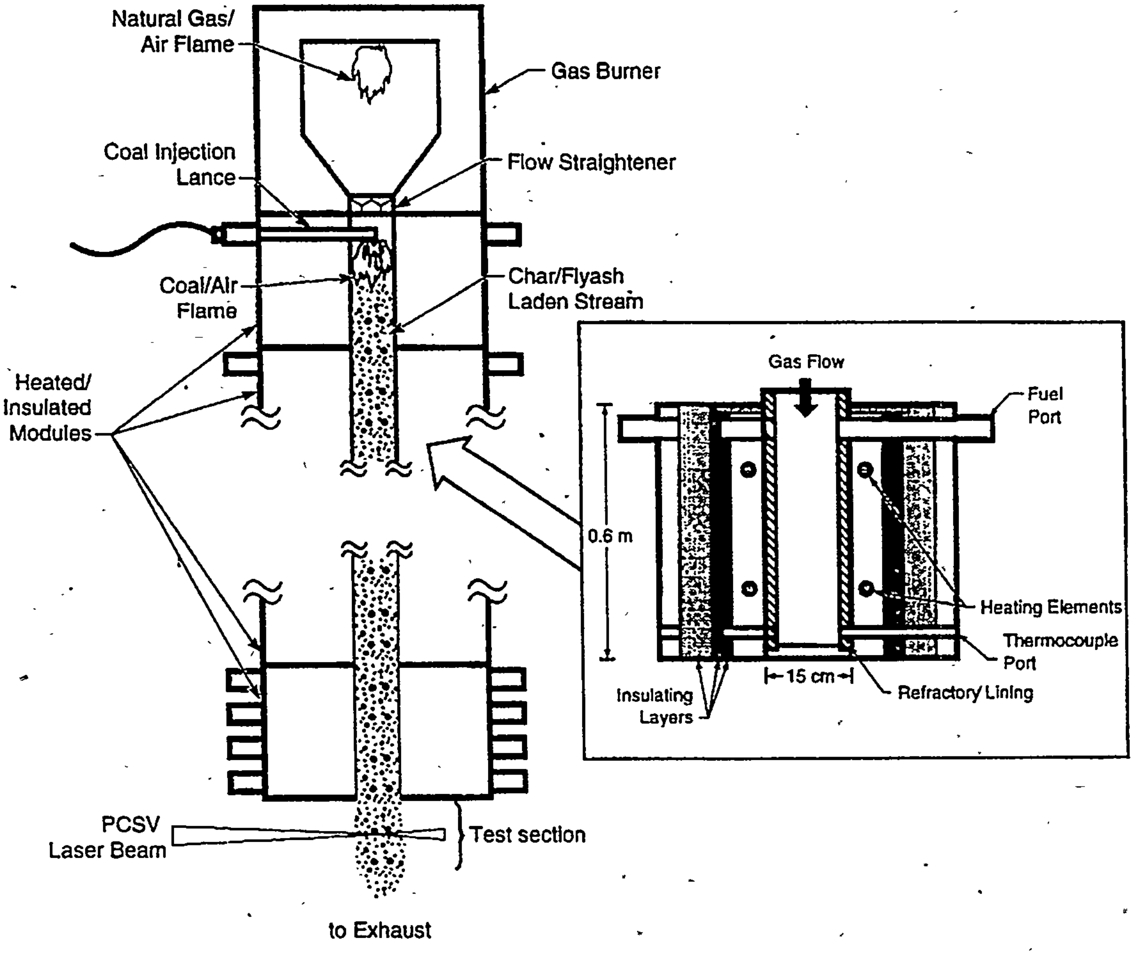


Figure 6
Schematic diagram of the Sandia Multifuel Combustor
with modular guard heater (inset).

The MFC was designed to simulate conditions in a coal combustor and has nominal fuel residence times of up to about four seconds. Typical fuel residence times in pulverized coal combustors is about two seconds. In the biomass tests, fuels were comminuted, typically to sizes less than 1 mm. This provided for nearly complete carbon conversion of the straws within the maximum residence time available in the combustor.

In all straw combustion tests, fuel was inserted into the MFC at a height of approximately 4.3 m (14 ft) above the beginning of the test section. Ash deposits were collected from a simulated water wall and convection pass tube as well as from the internal ceramic liner of the MFC.

The deposits on the probe or simulated water wall targets of the MFC are not only analyzed for composition but indicate the depositing mechanism for that material. It is possible to characterize the deposit and to determine whether it deposited by Condensation from a vapor, or Impact as a particle, or whether it was Thermophoretically deposited all around the tube as very fine particles.

Also subsequent chemical reactions between layers can be studied, yielding a new dimension to analyzing both the chemistry and kinetics of deposition in boilers.

Nine fuels have been combusted in the MFC and the results are being interpreted in the light of results of full scale boiler tests of the same fuels. This work is being done under the direction of Dr. Larry Baxter at the Sandia Laboratories in Livermore, California.

Dr. Bryan Jenkins at the University of California in Davis is concentrating in the field examination of boilers conducting firing tests, before and after, and in correlating the fuel analyses, deposits analyses, and observed field conditions as well as working with Dr. Baxter in running the MFC tests at Sandia. Dr. Laurence Oden at the Bureau of Mines Albany Research Laboratory is literally "probing" the mineralogical compositions, phases and probable deposition mechanismms of deposits from the various field test firings.

SOME INTERIM CONCLUSIONS

1) Analyzing biofuels for only Proximate and Ultimate analyses is not enough. Elemental Ash Analysis must be included to be able to assess slagging and other combustion characteristics.

2) Ash Fusion analysis (ASTM 1857) of high alkali biofuel is completely misleading, a portion of the volatile alkali compounds having been vaporized during the standard ashing and calcining processes. It is necessary to use a low temperature technique such as ASTM 1102 for wood, which ashes at 600° C. It was found that inspecting the ashing at 600° C, 700° C, 800° C and 900° C for sintering or fusion is a fairly reliable indication of the "sticky temperature" which we have found to be as low as 650° C or 1200° F. with some straws.

3) Total Alkali Content as analyzed from an ashed sample (ASTM 2795) is also misleading. Water soluble alkali analysis indicates that as much as 23% of the total alkali is lost with ashed samples. This method may turn out to be useful as a quick method to gage the slagging potential of an annual crop fuel.

4) Preliminary study suggests that a percentage of the alkali in wood is bound with silica and is therefore not as available as the atomically dispersed alkali ions in straws.

5) Test results have confirmed that firing even small percentages <10% of high alkali annual crop fuels can produce unmanageable slagging and fouling on traveling grates. Fluid bed tests are ongoing and they appear to be somewhat more tolerant of these fuels. The addition of lime increases the tolerance level and is an example of the possibilities a fluid bed (FB) offers in providing intimate mixing and contact opportunities for slagging inhibitors to be effective.

6) From analysis and pilot tests to date it appears that a lot of work remains to find ways to utilize the herbaceous and short rotation tree crops that are being so enthusiastically promoted as the energy sources of the future. As of now, the only hope appears to be low temperature gasification <1400° F., and using all the aids at hand. High alumina FB media, kaolin type additives, are all worth trying. It is mandatory to be able to achieve uninterrupted operation of at least a month at a time to make these fuels attractive to the power industry.

Extensive large scale extended period pilot tests are a necessary first step in this direction. Laboratory or Process Demonstration Unit (PDU) scale units will not suffice. Such a test should be conducted at a 5 to 6 ton per hour rate with a minimum of 50% high alkali fuels blended with wood and be sustained for at least a week.

ACKNOWLEDGMENTS

We wish to recognize and thank the Alkali Projects industry sponsors and individuals for providing support data, experiences, and conducting field tests; the expert advisors Richard Bryers, Al Duzy, Jerry Radway, and George Wiltsee for their interest and counseling; Sandia Laboratory, UC/Davis and the US Bureau of Mines for their active participation; and numerous colleagues around the country - and abroad - who have shared their knowledge with us. And of course DOE/NREL, the National Renewable Energy Laboratory in Golden, Colorado for funding and data support.

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ON-SITE POWER GENERATION FOR THE FUTURE

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Abstract

Power Generating, Inc. is developing a direct-fired gas turbine power system designed to operate on solid fuel. This presentation will summarize the results of the development work performed to date and will outline the program currently underway to demonstrate the technical and economic viability of a gas turbine fired on white wood and subsequently on coal. The presentation will describe testing already completed on a pressurized cyclonic burner which forms the external combustion stage for the solid fuel fired gas turbine and the testing that has been done on various fuels categorized as acceptable "fuels of choice" for the demonstration project. Also to be covered will be a discussion of the equipment to be used in the demonstration project, the reasons why specific pieces of equipment have been selected, and how they might be modified for the gas turbine application.

Introduction

Power Generating Incorporated ("PGI" or the "Company") has developed and patented a direct-fired gas turbine power system (the "PGI Power System") which is designed to operate on solid fuels. The Company plans to offer the PGI System in different models which will generate from 500 kilowatts to 3.5 megawatts of electrical power for a variety of industrial and utility applications. The exhaust from the PGI Power System is also anticipated to be useable directly as a source of thermal energy or fed into a heat recovery steam generator to produce process steam. Full utilization of both its electrical and thermal energy allows the PGI Power System to operate at system efficiencies in excess of 70%. A partial prototype of the PGI Power System has been tested with good results, and the Company is currently conducting a commercial-scale demonstration project to confirm the technical and economic feasibility of the PGI Power System.

The PGI Power System has several significant advantages over other power systems currently available on the commercial market. Its general design is relatively simple and it is considerably smaller than other power generating systems on the commercial market which are able to operate on solid fuel. It also has the inherent advantages of gas turbine based power systems, including good operating and system efficiency, low cost per installed kilowatt of capacity, easy installation, and long life. The PGI Power System is available in a range of sizes that can be matched to both the thermal and electrical energy requirements of a given host facility, and, in many instances, use waste material generated by the host facility as fuel. As such, the PGI Power System is able to function as a true cogeneration power system. The PGI Power System also has the important advantage of causing minimal adverse impact on its surrounding environment and, in some situations, a net positive environmental effect. Another important advantage of the PGI Power System is its ability to operate without water or associated piping and waste water treatment systems. Preassembled modular construction and skid mounting capability also facilitate the application of the PGI Power System in temporary and remote locations.

The Company believes that there is a large potential market for the PGI Power System both in the U.S. and abroad. From both an economic and environmental perspective, there are compelling arguments for increased application of small-scale, privately-owned power and cogeneration systems where the majority of the electrical and thermal energy generated is used by a host facility. The PGI Power System fits this description, plus it has the added advantage of being able to operate on relatively inexpensive and readily available solid fuels. It is designed to allow a host facility to reduce its current and long-term energy costs significantly. In many instances, these economic benefits can be accomplished while utilizing a waste material, which is otherwise costly to dispose of, as fuel for the PGI Power System. Initially, the primary market for PGI Power Systems is expected to be in wood products and associated industries in the U.S. As the PGI Power System gains market acceptance and as additional types of solid fuel are demonstrated to be useable in the system, the potential domestic and foreign markets for the PGI Power System are expected to expand significantly. Ultimately, the Company believes that the PGI Power System will be feasible for virtually any host facility which produces a relatively clean, combustible by-product for use as fuel and requires an adequate source of thermal and electrical energy in its production processes.

The primary focus and objective of PGI since its formation in 1982, has been the commercial development of the PGI Power System. During the 1980s, the basic design was developed and major equipment components were selected for the PGI System. The Company also conducted a series of tests on a partial prototype system during this period which partially confirmed the technical feasibility of the system. For the past two years, PGI has been working to organize a commercial-scale demonstration project at the Western Research Institute ("WRI") in Laramie, Wyoming, to confirm fully the technical and economic feasibility of the PGI Power System. PGI is currently working on detailed engineering for the project and making final arrangements to build and operate a prototype system. The demonstration project is expected to cost approximately $5.1 million and to require approximately three years to complete testing on both wood and coal fuels. The U.S. Department of Energy has committed $3.4 million of funding for the project. PGI is also working with several industry contacts, state agencies, foreign governments, and other sources to provide additional funding for the project. The Company believes that successful completion of the demonstration project on either fuel will clear the way for rapid commercial development of the PGI Power System.

Description of the PGI System

The PGI Power System is a direct-fired, gas turbine power system which has been designed to operate on solid fuels. The basic operating principle behind the PGI Power System is relatively simple. The compressor section of the gas turbine pressurizes the combustion air to burn solid fuel in a specially designed pressurized combustor. The hot gases are ducted through a cyclonic separator and then directly into a gas turbine hot section to drive an electrical generator. The exhaust gases can be used directly for thermal energy. Variations of the PGI Power System have been designed to generate from 500 kilowatts to 3.5 megawatts of electricity which can be used either on site to serve the specific electrical needs of a host facility or sold to a local utility. Up to 30 million Btu's per hour of approximately 900°F gas are also exhausted from the turbine and can be used either directly as a source of thermal energy or fed into a heat recovery steam generator to produce process steam. Full utilization of both types of energy is expected to allow the PGI Power System to operate at system efficiency rates in excess of 70%. In other words, the PGI Power System is a true cogeneration power system.

Gas turbine technology has been in continuous development since the turn of the century and is now well established as a stable drive mechanism in the generation of electrical and thermal power. The advantages of gas turbine generator sets are (a) quick start-up; (b) low cost per installed kilowatt of capacity; (c) ease of installation and operation; (d) high efficiency; (e) long life; and (f) mobility. A major drawback of traditional gas turbine generator sets is their requirement for a low level of particulate matter and minimal corrosive contaminates in the airstream to the power turbine. As a result, conventional wisdom has held the belief that these systems require higher quality hydrocarbon fuels such as natural gas or kerosene in order to operate effectively. The Company believes that the PGI Power System's design and method of operation solves the traditional problems which have prevented the use of solid fuels in direct-fired gas turbine power systems in the past. This enables the PGI Power System to benefit from the inherent advantages of gas turbines while minimizing their primary disadvantage, i.e., the requirement for an adequate and continuous supply of clean hydrocarbon fuel which is generally more expensive than various types of solid fuel on a cost per Btu basis and in many instances is not readily available.

In order to be able to use solid fuels in a gas turbine, PGI has designed, developed, and tested a pressurized, "off base" (not directly incorporated in the gas turbine) combustor capable of operating at the pressure levels required by gas turbines (approximately 90-150 psig). PGI has also integrated this combustor with a special valve system used to feed solid fuels from atmospheric pressure into a pressurized system. The PGI Power System will incorporate a cyclonic separation system which is capable of reducing particulate matter entrained in the combustion gas stream to a level acceptable for extended gas turbine operation. A microcomputer based system will provide the PGI Power System with real time operating control, continuous instrumentation monitoring, data logging, and instantaneous shut-down capability.

The initial fuel of choice which the Company has selected for the PGI Power System is "white wood". More specifically, this is defined as debarked wood at less than 1/8" major dimension and containing less than 15% moisture. The Company believes that it is particularly important during initial testing and operating phases to use a closely controlled fuel which will minimize operating variability and risk for the gas turbine. White wood is expected to have a low ash content (.5% to 1.0%), virtually no sulfur, and very low levels of trace metals and silica. Based on the experience gained through operation on white wood, PGI hopes to be able to qualify other solid fuels (e.g., whole tree chips, herbaceous grasses, sugarcane bagasse, peanut shells, citrus rinds, etc.) and certain types of coal and peat for operation in the PGI Power System. As additional fuels are qualified for use in the PGI Power System, its potential is expected to expand significantly.

The basic design philosophy of the PGI Power System throughout its development has been to use state-of-the-art equipment and controls. The intent has been to utilize as much standard equipment as possible that could be modified as needed to suit the specific requirements for the PGI gas turbine power system. The four major subsystems in the PGI Power System include:

1. Fuel receiving and preparation
2. Pressurized combustor
3. Hot gas clean-up
4. Gas turbine

A simplified flow diagram of how the equipment in the PGI Power System will be arranged is included as Figure 1. As you can see in this figure, the four subsystems noted above are easily adapted into the total system configuration.

History of Development and Testing

Testing at McConnell Industries in Trussville, Alabama

The basic design for the PGI Power System was developed and major equipment components were selected based on research and development work conducted from 1978 through 1982. PGI then conducted a series of successful operating tests on a partial prototype system at McConnell Industries in Trussville, Alabama, from 1983 through early 1985. The partial prototype system included a wood feed system, a pressurized combustor at about two-thirds scale, and a cyclone separator. Unfortunately, the prototype system did not include a gas turbine, and was only able to operate at pressures up to 52 psig due to limited air compressor capacity. The primary purpose of this initial testing was to determine the proper configuration for the length to diameter ratio for the cyclonic burner when operated at elevated pressure. This testing also determined the suitability of the cyclonic burner for use as an "off-unit" combustor for a gas turbine.

Data collection included determining the maximum attainable volumetric energy release rate for the pressurized combustor configuration tested, maximum pressure of operation within the limitations of the air compressor capabilities, time responses due to complete fuel interruptions, iso-kinetic sampling of raw combustion gas and cleaned combustion gas streams and mechanical scale-up data for subsequent pressurized combustor designs. These tests confirmed the ability of the PGI combustor to operate at sustained pressure levels consistent with gas turbine requirements and with volumetric heat release rates in excess of 1.8 million Btu's per cubic foot of chamber volume. The testing also helped to establish the initial performance parameters for gas clean-up equipment operating on various types of fuel. This included testing on hogged fuel with approximately twenty to thirty times more ash than expected with white wood, experimentation with larger fuel particle sizes and data collection on the pulverization of hogged fuel.

Testing at a Louisiana Pacific Sawmill in Cleveland, Texas

Of primary concern whenever considering solid fuel for a gas turbine is the constituents of the fuel. As previously indicated in this report, the fuel of choice for the initial PGI Power Systems will be white wood. One of the primary reasons for this initial choice is to minimize the possible variables in the fuel source as much as possible. This will make it easier to concentrate on the operational characteristics of the system without having to continually relate back to how fuel variations might have affected operational results. Consistent with this objective, PGI and WRI took flue gas measurements in January, 1992, at an operating sawmill in Cleveland, Texas, burning debarked southern yellow pine to determine the combustion gas characteristics and the particle size distribution of ash exiting an atmospheric cyclonic burner. This particular sawmill is currently burning planer shavings in an atmospheric McConnell combustor and using the quenched flue gas in lumber kilns to dry lumber. The planer shavings are identical to the fuel that would be used in the pressurized cyclonic burner incorporated in the PGI Power System demonstration project.

The flue gas samples were taken at the location in the McConnell combustor indicated in Figure 2. This location was selected because it would approximate the temperatures that would be seen at the inlet to the turbine in the demonstration project. An air cooled probe containing several thermocouples was installed in the combustor at the location indicated. The probe was constructed of 6-inch long type 304 ss tubular elements of 1-inch diameter schedule 80 tube stock. Each element carried a thermocouple at the mid wall. The air cooling simulated the range of temperatures, 900-1700° F, that would be experienced in the demonstration project gas stream through the gas turbine.

Typical temperature profiles during high-fire and low-fire conditions along the length of the probe are shown in Figure 3. Ash deposits were analyzed from the probe after exposures ranging from a few minutes to a few hours. The ash analyses are shown in Table 1.

Table 1. **Chemical Analysis of Deposits From Air Cooled Probe**

Chemical Analysis of Deposits from Air-Cooled Probe

Temperature Element	>1400°F wt %	700 - 900°F wt %	<700°F wt %
Mg	5.47	22.16	20.12
Al	0.72		0.35
Si	0.95	4.28	2.52
P	1.89	22.16	11.62
S	6.30	10.75	9.58
Cl	0.18		
K	49.41	16.93	14.52
Ca	30.73	22.16	39.11
Mn	3.77	1.58	2.18

During the course of these tests several on-line gas analyses were performed. Results are summarized in Table 2. The water content of the gases was calculated from the amount of gas sampled and the amount of condensed water. Other gases were monitored directly using the gas analyzer. Data indicate that CO, NO_x, and SO_2 concentrations in the combustion gases were higher during the high-fire condition than during the low-fire. The behavior is expected to be a direct consequence of the excess air condition, and flame temperature during the two firing conditions.

Table 2. **Gas Analyses**

Gas Analyses				
Gas	Concentration			
	Low	Fire	High	Fire
O_2	17.3	% v	12.5	% v
CO_2	6.4	% v	6.4	% v
CO	275	ppmv	380	ppmv
SO_2	4	ppmv	46	ppmv
NO_x	24	ppmv	48	ppmv
H_2O	11.6	% v	12.9	% v
N_2	Bal.		Bal.	

Particle size distribution of the ashes collected by a Mark III Impactor are shown in Figure 4. Two different firing conditions were sampled, labeled as high- and low-fire indicating the amount of fuel being fired. Mean particle size during the high-fire condition was deduced to be approximately 1.0 micron whereas during the low-fire condition the mean particle size was about 4.0 micron. Total dust loading during the low-fire condition was about 200 parts per million by weight (ppmw) while during the high-fire condition the loading was about 300 ppmw.

It is speculated that larger residence time afforded by the low-fire condition may have caused some ash sintering and hence larger particulates. It is also possible that products of incomplete combustion during the high-fire condition are responsible for skewing the particle size distribution toward smaller sizes. The later is consistent with the increased overall particulate loading observed during the high-fire condition.

Particles were also collected on a positive filter during a high-fire run. These were then analyzed using a Coulter counter. Particle size distribution determined by this method is displayed in Figure 5. The total dust loading determined from this test was again about 300 ppmw. The mean particle size however is about 6.0 micron. This apparent anomaly in the mean particle size as determined by the two techniques results from the limits of the analysis techniques. The smallest particles counted by the Coulter counter were 2.2 micron in diameter whereas the impactor had a cutoff at 0.54 micron. Since a large fraction of the particles are in the less than 2.2 micron range, the apparent mean diameter deduced from the Coulter counter data is larger.

Particulates collected at various plates of the Mark III Impactor were also analyzed using a scanning electron microscope coupled with an energy dispersive X-ray analyzer. The results are displayed in Table 3. The data indicate a great deal of variability in the particulate composition as a function of the size.

Table 3. **Chemical Analysis of Particulates Collected on Mark II Impactor**

Chemical Analysis of Particulates Collected on Mark II Impactor				
	Low Fire			High Fire
Plate Number-〉	1	4	8	4
Particle Size (μm)-〉	〉13.7	4.0 - 5.8	〈0.52	
Element	wt %	wt %	wt %	wt %
Mg	7.26	6.07	0.89	9.22
Al	3.23			
Si	11.18	0.69	0.46	0.75
P	2.65	1.71	0.38	2.47
S	23.65	6.04	16.03	2.84
Cl	0.94	1.64	3.67	1.20
K	16.88	29.24	67.35	15.56
Ca	30.02	50.82	5.51	63.29
Mn	4.20	3.79	1.95	4.66

Prediction of gas cleanup efficiencies was also done as part of this testing. From the data obtained, it appears that erosion of the turbine components is not a major concern in a wood-fired system provided the fuel has little or no bark. Overall uncontrolled dust loading in the system is expected to be 200-300 ppmv range. The particle size distribution of the entrained material is such that conventional or high efficiency cyclones can reduce the dust loading in the turbine gas path by a factor of approximately two. Predicted gas cleanup efficiencies are illustrated in Figures 6 and 7.

Based on the results of this series of tests and prior testing, foreseeable problems related to erosion, corrosion or deposition on the gas turbine hot section are expected to be manageable within the economics and technical constraints of the demonstration project. Because the ash softening point for white wood is so much higher than the inlet temperature into the turbine, any deposits are expected to be loose and easily removed by mechanical means. Because the particle sizes are so small, any erosion problems are also considered minimal. Because there are no salts in the fuel, alkalies are also considered to be minimal and corrosion is also thought to be a minimal problem. All of these technical assessments will be confirmed by the demonstration project described in a following section of this paper.

Testing at the VTT Combustion and Thermal Energy Laboratory in Jyväskylä, Finland

A series of tests on white wood samples has been conducted by VTT at its laboratory facilities in Jyväskylä, Finland, during the winter of 1992/1993. These combustion tests have been conducted in both atmospheric and pressurized conditions to develop data pertinent to the PGI Power System demonstration project. The preliminary results of that testing program indicate that any potential problems with erosion, corrosion, and deposition will be manageable through available control techniques.

Discussions of the PGI Power System Demonstration Project

PGI Power System Demonstration Project

PGI plans to build, operate, and test a prototype system at the Western Research Institute in Laramie, Wyoming. WRI is a nonprofit organization which is affiliated with the University of Wyoming and has extensive experience in research and development relating to energy and environmental technologies. The demonstration project is expected to cost approximately $5.1 million and to require approximately three years of work. Final engineering and construction of the prototype system is expected to take approximately one year. During the second year of the project, the prototype system will be operated on white wood. The prototype system will then be modified as needed and operated for approximately six months on selected coal fuels. Depending on the results of the initial test program, the prototype system could then continue to be used to test additional fuels and to evaluate potential refinements in the technology.

Funding for the demonstration project is expected to be provided one third each by two separate branches of the U.S. Department of Energy ("DOE") and by PGI. The Office of Fossil Energy of the DOE has committed to provide one third of the funding for the demonstration project or approximately $1.7 million through its established Joint Sponsorship Research Program at WRI. The Office of Conservation and Renewable Energy of the DOE has also contracted to provide $1.7 million of funding for the demonstration project. PGI will be required to provide the balance of the necessary funds for the demonstration project. The Company intends to provide a portion of the funding itself and to raise the balance from various foreign governments, research foundations, and industry participants.

As with any new technology, there is risk associated with demonstrating the technical and commercial viability of the PGI System. There have been a number of attempts in the past to demonstrate the feasibility of solid fuel firing a gas turbine with both coal and wood. PGI believes that its approach is unique from the previous attempts due to the design of its system and the exclusive use of white wood as fuel during the initial testing phase of the project, which should minimize the problems previously associated with solid fuel firing of gas turbines. By using a fuel with less harmful constituents, it should be possible to concentrate on defining the operational parameters of the equipment incorporated in the system. Once the operational latitudes of the system are confirmed, it will be easier to determine the effects of using dirtier fuels such as low sulfur coal.

PGI has been working with WRI since early 1990 to plan and organize all aspects of the demonstration project. During this period, considerable design and engineering work has been done on the prototype system to be used in the project. Various aspects of system start-up and operation, data acquisition and testing, and project organization have also been determined by PGI in conjunction with WRI. Design work on the prototype system is underway and equipment is expected to begin to be ordered this fall. PGI is committed to the demonstration project as the next critical and necessary step in successfully completing the commercial development of the PGI System.

The Prototype PGI Power System

The prototype system for the demonstration project will generally be the same as the basic system described previously in this report. However, the prototype system will be somewhat smaller than most commercial systems are expected to be and include some differences in equipment. A flow sheet for the actual prototype system has been included as Figure 8.

PGI plans to use a Garrett Model IE831-800 gas turbine in the prototype system. At ISO conditions, the output of the Garrett turbine is rated at 550 kilowatts. The Garrett turbine output is expected to decline to approximately 391 kilowatts in the demonstration project due to the decreased atmospheric pressure caused by the relatively high elevation of the WRI site. The Garrett turbine is also expected to operate at a pressure of approximately 110 psig with a nominal turbine inlet temperature of 1716°F. The prototype system incorporating the Garrett turbine is expected to burn approximately 800 to 900 pounds of dry wood fuel per hour.

From a mechanical standpoint, the external combustor can on the Garrett turbine lends itself well to modification to an external pressurized combustor such as that proposed by PGI. In the prototype system, the conventional combustion can will be removed. A new can will be constructed that will allow the compressor air to be directed to the PGI combustor. These gases will be heated by the combustion of wood fuel, passed through a gas clean-up system and finally back into the gas turbine. No internal modifications will be required to the gas flow path in the turbine.

Availability of hardware and a ready source of spare parts and service expertise were also major factors in selecting the Garrett turbine for the demonstration project. This engine has been in commercial production for many years and there is an excellent experience base on units used on offshore oil rigs, as standby power supply units, and for other industrial uses. A good supply of spare parts is available at reasonable prices. Most importantly, there is a large operational and maintenance base line of experience to call upon during the design of this demonstration project.

Prior to bringing the Garret 831 to Laramie, a detailed baseline analysis will be performed on the engine. The purpose of the analysis will be to provide baseline data to evaluate performance deterioration during operation on solid fuel. A complete vibration spectrum analysis will be performed under standard operating conditions. As an example, the engine will be instrumented with accelerometers at the machine inlet bearing case, at the discharge bearing case and at the machine axial bearing case. Pressure sensors, temperature sensors, accelerometers and Eddy current vibration probes are some of the instruments that will be installed. All of this will be combined with a high speed data acquisition system to monitor all operational parameters critical to the safe operation of the turbine. This monitoring will allow operational latitudes to be set so that the machine will be automatically shut down if any operational constraint is exceeded. It will also be used to determine trending in the operation of the system to detect any deterioration in the performance of critical turbine parameter. As a last resort, the system will make it possible to do a more thorough failure analysis through the use of the high speed data acquisition capability.

As indicated in the prototype system flow sheet, PGI plans to use an auxiliary compressor to provide fuel transport air from the wood fuel valves to the pressurized combustor. This was done to provide additional operating control for the demonstration project. In standard commercial systems, this transport air will be provided by a portion of the output of the gas turbine compressor.

In view of the cost of interconnection and minimal purchase price for electricity in the Laramie area, the Company has elected not to pursue selling power from the demonstration project. This will require the installation of a bank of resistance heaters to dissipate the electrical output of the prototype system. This approach has the added advantage of freeing the project from having to synchronize its operations and output with a commercial utility system. This should minimize potential problems related to start-up, variations in operating parameters, and testing.

PGI plans to incorporate considerable additional instrumentation and testing equipment in the prototype system. This equipment will be used to monitor and accumulate data on the operation of the prototype system. Among other things, the equipment will evaluate environmental impact, turbine inlet air quality, air flow pressure, fuel flow, operating temperature etc., on a continuous basis.

Critical Technical Issues

In order to successfully complete the development of the PGI Power System, several technical issues will need to be addressed. In the Company's opinion, all of these areas of technical concern are manageable, but they must be given proper consideration in final design of equipment and operating procedures in order to assure successful operation of the PGI Power System. The issues which are considered to be particularly important and a brief description of how PGI intends to deal with each of them are as follows:

a) Fuel Feed Valves. The function of the fuel feed valves is to systematically introduce solid fuel into the pressurized PGI Power System. In other words, the valves must introduce solid fuel from the fuel bin at atmospheric pressure into the pressured fuel feed line of the PGI Power System. During the course of the demonstration project, PGI must confirm the long-term operability of its fuel feed system and confirm that leakage across the feed valves is within an acceptable level for commercial operation. In order to reduce risk in this area, PGI has located two companies offering commercial valves which meet the specification of the PGI Power System. Sprout-Bauer, a subsidiary of Combustion Engineering, Inc., manufactures a valve which meets the requirements of 3.0 megawatt and larger PGI Power Systems. The Beaumont Birch Company, located in Pennsauken, New Jersey, offers a line of smaller valves which are expected to work well in 500 kilowatt to 2.0 megawatt systems.

b) Erosion, Corrosion, and Deposition. The major technical hindrance to long-term operation of a gas turbine power system on solid fuel has been degradation of the hot section in the gas turbine. This degradation typically occurs as a result of erosion, corrosion, and/or deposition of or on turbine blades and interstices caused by impurities in the inlet gas stream to the gas turbine. In many instances, this degradation has a substantial deleterious effect on the long-term operating efficiency of the gas turbine in this type of power system. The Company believes that this problem can be overcome in the PGI Power System as a result of its design, closely controlled fuel specification, and planned operating procedures.

c) Hot Gas Ducting. The hot gases used in the PGI Power System must be transferred between the major pieces of process equipment, i.e., combustor to gas cleaning, gas cleaning to the turbine. The hot gas ducting used to accomplish this function will be an important technical consideration in the final design of the PGI Power System. The primary objective will be to keep the hot gas ducts as short as possible to reduce the effects of thermal expansion during operation, as a result of the difference between ambient conditions and actual operating conditions. This temperature range could vary from minus 20°F to 1800°F. Proper ducting design will also reduce the possibility of pressure leakage. The ducting proposed for the PGI Power System is conventional refractory lined ducting from the combustor to the gas cleaning equipment. The ducting from the gas cleaning equipment to the gas turbine will be high temperature alloy lined refractory ducting. This lining will consist of a thin sleeve covering the refractory which provides the maximum protection to the turbine from any extraneous particulate matter coming from the refractory. The carbon steel outer shell will provide structural integrity at the intended operating temperatures and pressures.

d) Gas Turbine Manifolding. In order to incorporate a standard commercial gas turbine in the PGI Power System, it must be adapted to accommodate an external combustor. This generally involves designing special manifolding to introduce hot gas from the combustor into the gas turbine. One of the primary criteria PGI has used in selecting gas turbines for use in its PGI Power System has been the adaptability of their design to an off-base combustor. That was one of the main factors leading to selection of a Garrett Model IE831-800 for the demonstration project.

e) System Control. Instruments and controls are an essential part of any combustion system and serve to assure that the system operates safely, economically, and reliably. Start-up and operation of the PGI Power System will make maximum use of state-of-the-art control strategies. The PGI Power System will be monitored and controlled through a sophisticated digital control and data acquisition system for detailed performance evaluations. Since the demonstration project will be the first on-line operation of a complete PGI Power System, additional instrumentation is planned in order to closely monitor system performance.

Facility and Personnel

The demonstration project will be constructed and operated at a 22-acre pilot plant facility which is owned by WRI. The pilot plant facility is located about one mile north of Laramie, Wyoming, on U.S. Highway 30. WRI currently operates several pilot plants at this site including fine coal drying, mild coal gasification, oil shale retorting, tar sands pyrolysis, and organic waste incineration. In addition to the pilot plant operations, WRI also performs a variety of small-scale testing functions in laboratory facilities at the site.

A driving distance of about 2.5 miles separates the pilot plant facility from the main WRI laboratory complex on the campus of the University of Wyoming. The main laboratory complex includes a complete analytical testing service that specializes in detailed analyses of organic solids and liquids.

WRI employs about 120 people including approximately 70 scientists and engineers. About 20 of these employees are assigned full-time to the pilot plant facility. The pilot plant staff includes a highly skilled group of technicians. The engineering staff and technicians are experienced in the start-up and operation of pilot-scale equipment. Individual technicians have specialized craft skills such as welding, instrumentation, and electrical wiring; and the pilot plant facility includes shops for these craft services.

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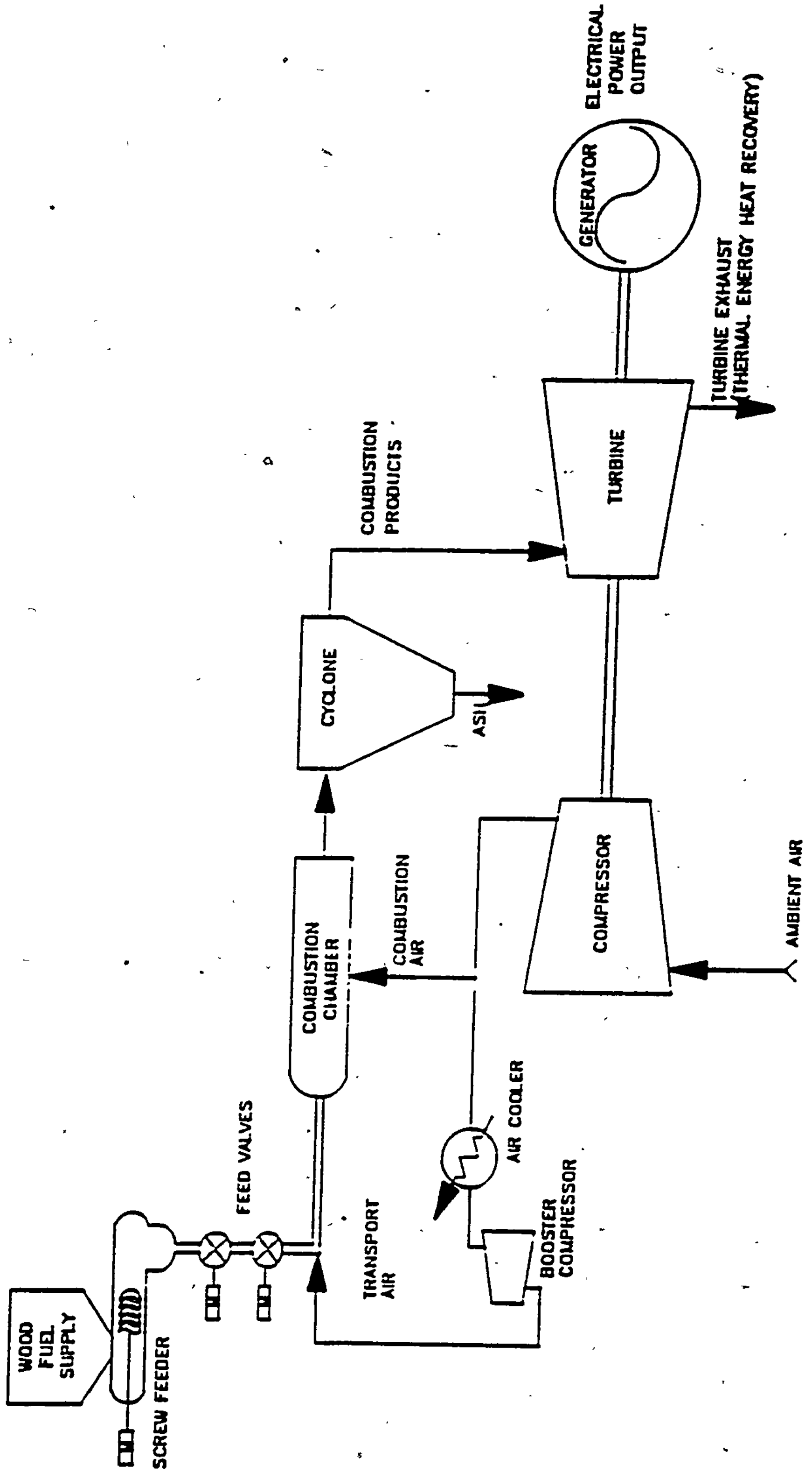

Figure 1. PGI System Description

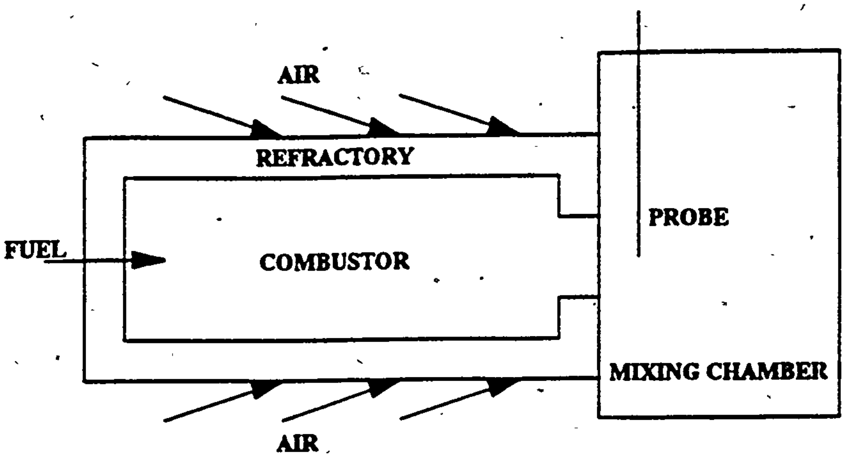

Figure 2. A Schematic of an Atmospheric Pressure McConnell Combustor Showing Sampling Location

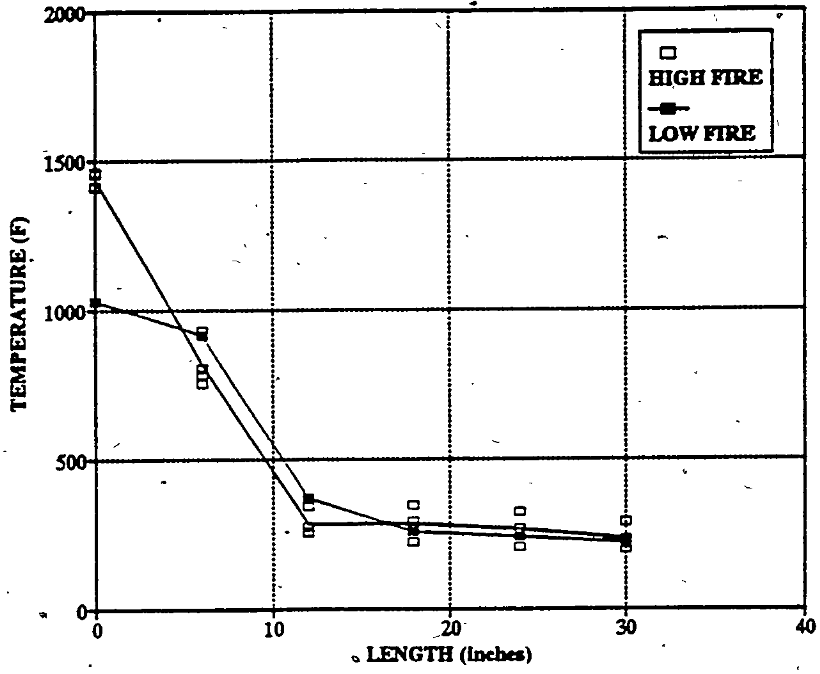

Figure 3. Longitudinal Temperature Profile of Internally Air-Cooled Probe

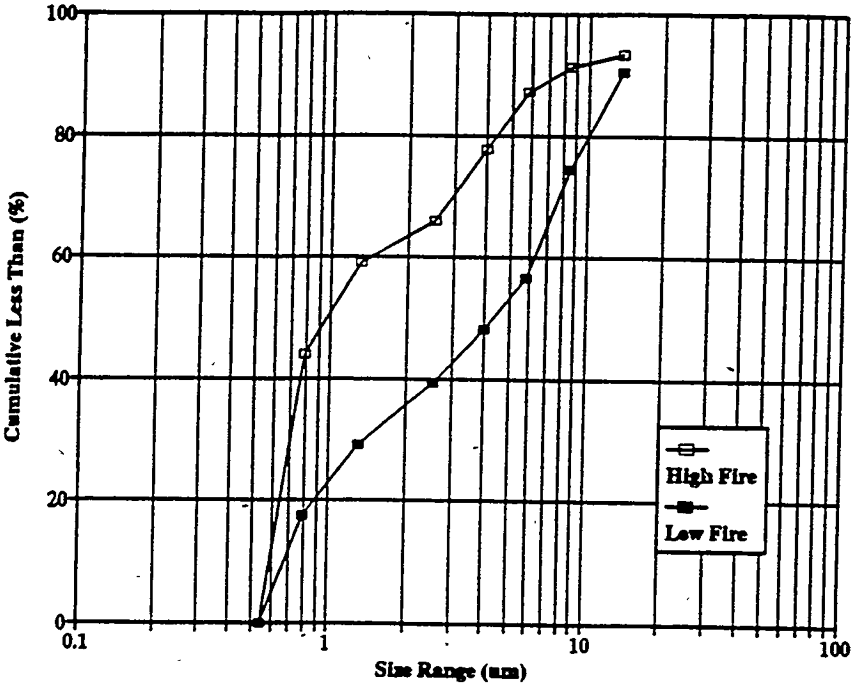

Figure 4. Particle Size Distribution of Ash Collected by Mark III Impactor

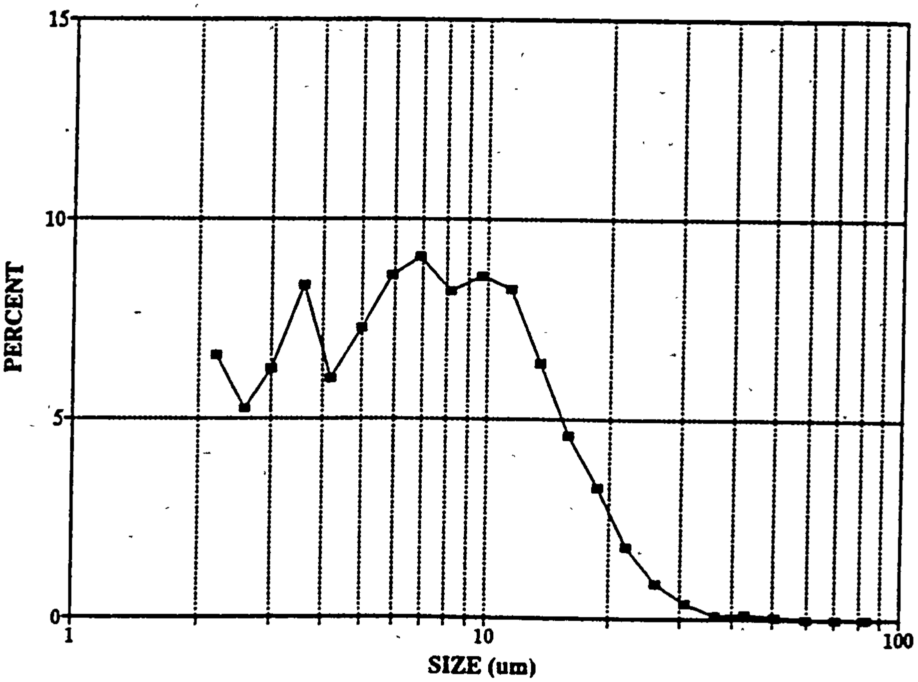

Figure 5. Particle Size Distribution of Ash as Determined by Coulter Counter

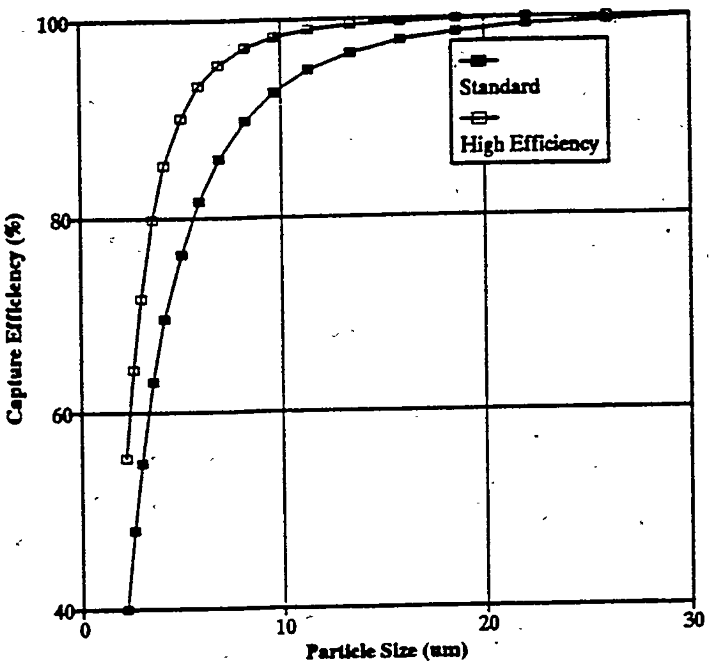

Figure 6. Particulate Collection Efficiencies of a Conventional Cyclone and a High Efficiency Cyclone

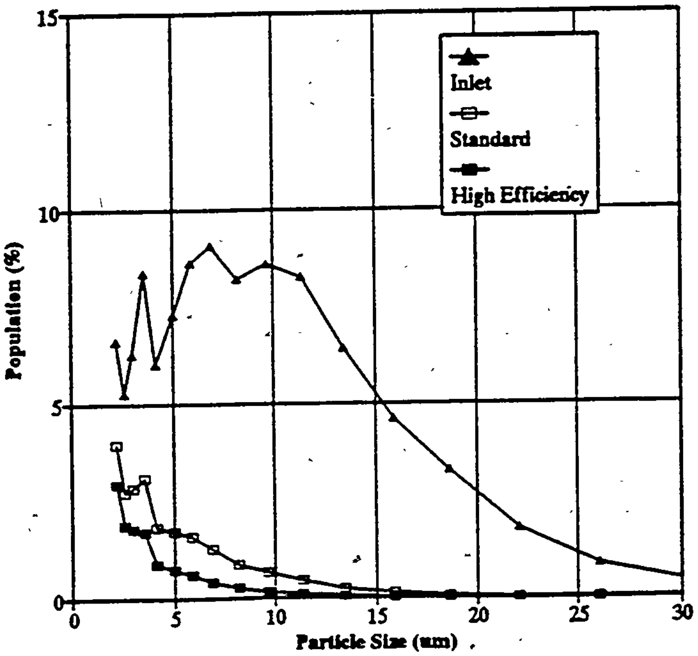

Figure 7. Calculated Particle Size Distribution at the Outlet of a Conventional and of a High Efficiency Cyclone

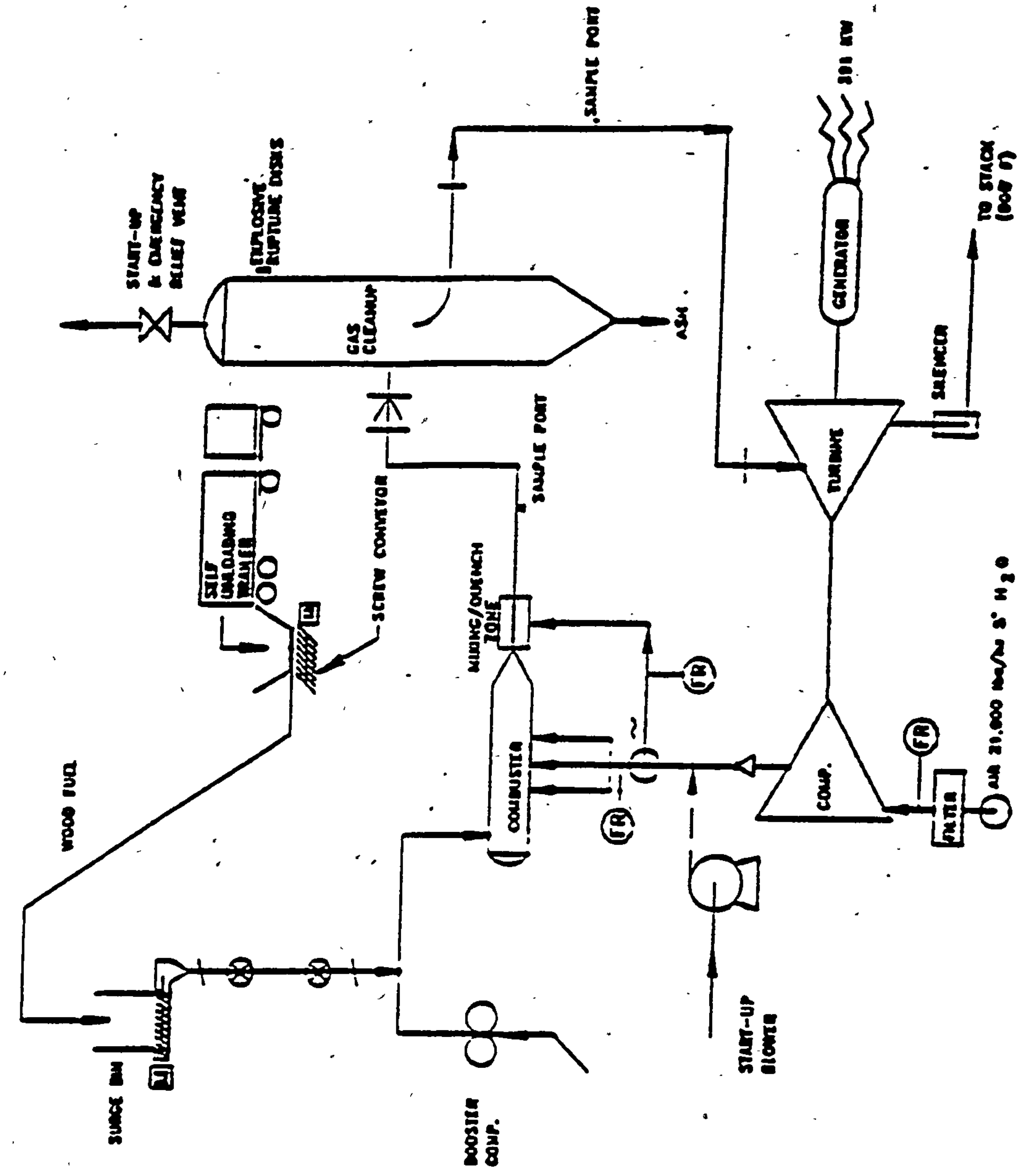

Figure 8. Prototype PGI Power System Preliminary Flow Diagram

WOOD POWER IN NORTH CAROLINA

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Abstract

North Carolina (NC) is one of the most forested states, and supports a major wood products industry. The NC Department of Natural Resources sponsored a study by Research Triangle Institute to examine new, productive uses of the State's wood resources, especially electric power generation by co-firing with coal. This paper summarizes our research of the main factors influencing wood power generation opportunities, i.e., 1) electricity demand, 2) initiative and experience of developers, 3) available fuel resources, 4) incentives for alternate fuels, and 5) power plant technology and economics. The results cover NC forests, short rotation woody crops, existing wood energy facilities, electrical power requirements, and environmental regulations/incentives. Quantitative assessments are based on the interests of government agencies, utilities, electrical cooperatives, developers and independent power producers, forest products industries, and the general public. Several specific, new opportunities for wood-to-electricity in the State are identified and described. Comparisons are made with nationwide resources and wood energy operations. Preferred approaches in NC are co-generation in existing or modified boilers and in dedicated wood power plants in forest industry regions. Co-firing is mainly an option for supplementing unreliable primary fuel supplies to existing boilers.

Introduction

This paper summarizes a study titled "Wood Energy Guide for North Carolina," (Cleland 1993) completed by Research Triangle Institute (RTI) for the North Carolina (NC) Division of Forestry, Department of Natural Resources. The study objective was to examine new opportunities for 1) wood-fueled electrical power in the State, and 2) wood co-firing with coal, emphasizing pollution abatement. North Carolina offers relatively promising opportunities for new wood energy since

- NC is 60% forested, ranking 4th in timberland area among all the 50 states
- NC annual removals of forest growing stock represent 5% of all US removals.
- NC contains a major, thriving forest industry and the largest short rotation woody crop plantation in the US. (22,000 acres of sweetgum; 3 dry tons per acre-year maximum; Union Corp. of NC).
- Electric cooperatives and independent power producers (IPPs) are active in NC.
- There are over 300 wood fuel boilers operating in NC.

Information was accumulated from the entire spectrum of forestry and energy agencies, wood products industries, and electric power producers. The study documents and compares the NC, Southeast and US wood resource, major wood industry groups, technical and economic issues for wood-fired power plants, environmental issues, and opportunities for new wood-fired power plants in NC. The study has sought the best opportunities for wood energy, while keeping a perspective on the real demands of utilizing renewable energy, as seen in Figure 1.

Conclusions

Wood conversion to electric power is a niche industry. Optimistically, new wood power plants could add 1% to 3% to the 15,000 MW power grid in NC in the next 10 to 20 years. Table 1 shows that wood fuel use is completely dominated by the wood products and residential firewood industries. Less than 1% of US electric power is generated using wood, and complete use of existing surplus wood resources could provide about 3.4% of US electric demand, although only 10% to 20% of this surplus is econmically available.

Wood energy production is mainly limited by existing levels of annual excess growth of growing stock and of logging residues (see Table 2). RTI calculated available Annual Growth Surplus as [(Annual Growth)/Annual Removal)-1] x 100%. NC has a 23% growth surplus, but this is decreasing slightly and is negative in some regions of the State. For example, hardwoods are often emphasized as wood fuel, but excess growing stock for hardwoods decreased 55% in NC from 1984 to 1991. Also, non-merchantable surplus in NC is less than 4% of the total wood surplus resource.

Significant increase in wood energy for new power plants would depend on the success of short rotation woody crops (SRWC), which are still in the experimental stages. Typical land investment for SRWC supplying wood-fired power plants in NC would be about $1200 per kW, which would encompass the stumpage cost.

Wood firing offers considerable reduction in air pollution compared to coal firing -- i.e., negligible SO_2, lower NO_x and significantly reduced net CO_2 based on the photosynthesis carbon cycle for the renewable resource. In terms of the environment, however, about 500 acres of clearcut trees, or 10,000 acres of managed forest with 5% annual removal, are required to supplant the energy represented by one (1) acre of strip mining of a 4 foot deep coal seam.

Figure 2 illustrates that the new Clean Air Act requirements for coal-fired units cannot be satisfied by any practical co-firing of wood with coal. Other disadvantages of co-firing are handling and preparation of two different fuels, burning non-homogenous fuel, capturing fly ash with varying composition, and boiler derating. Co-firing succeeds where fuel supplies are limited and one fuel can be used to supplement the other.

The study confirms that wood energy power plant construction and operation can compete technically and economically with conventional units that burn coal or oil. Wood fuel drying is an essential factor for efficient operation. Engineering analysis by RTI shows that wood fuel size is also a factor in the final levelized busbar electricity cost (LBBEC) for wood energy operations. Very large fuels (e.g., logs) present problems with handling, storage and rate of combustion. On the other hand, pulverizing wood to very small size is expensive, both in energy and equipment costs. Figure 3 shows that typical wood chips, hogged fuel, and fist-sized chunks are preferred fuel sizes.

It has been recommended that NC place emphasis on the following 4 areas of wood energy:

1) More efficient recovery of wood waste and more efficient wood energy conversion by the wood products industry, and by IPPs, for selling power to the major electric utilities (NC-based utilities have studied wood energy but have no plans to adopt it). Wood-fired units operated by the pulp and paper industry and IPPs using wood waste are producing up to 150 MW of electrical power in NC. Improved wood energy conversion efficiency by the wood industry could result in an additional 50 MW capacity in NC. 400 MW could be co-generated if 25% of the non-electrical, wood-fuel energy consumed by industries in NC were switched to produce electricity.

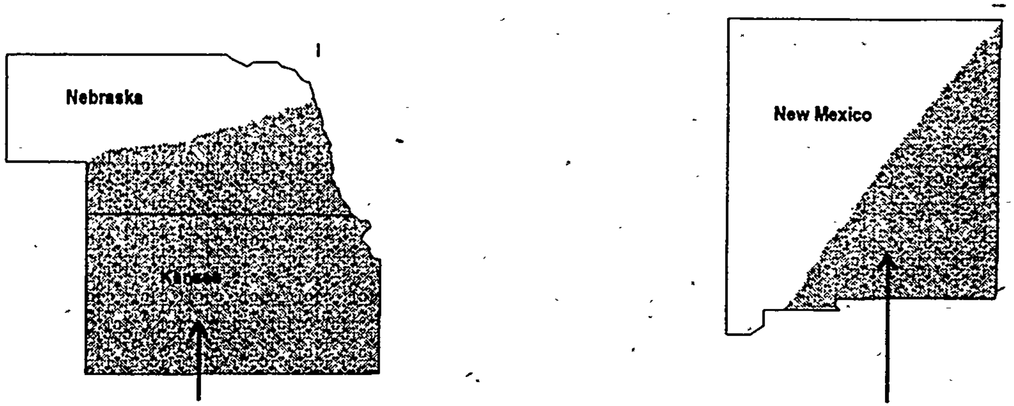
2) More efficient, convenient, and pollution-free residential wood stoves.

3) Consideration of from one to three new wood fuel power plants. The latter plants should be not larger than 25 MW to 50 MW and involve multi-county cooperatives. Figure 4 shows groups of counties (boundaries outlined in bold) where new wood power plants of at least 25 MW might be located. Selection is based on 10% to 20% wood fuel resource recoverability, and on the local existing electrical grid, local wood industry, and boilers already operating in each region which could be retrofitted for wood fuel.

4) Local initiatives. State (and National) programs should be limited to externalities (e.g., credits for renewable fuel proposals to utility commissions), tax credits, and research funding for SRWC, wood sizing, wood drying, and wood combustion efficiency.

Reference

(1) Cleland, J.G. and L. Guessous. 1993. "Wood Energy Guide for North Carolina." Research Triangle Park, NC: Research Triangle Institute. [This reference cites 67 other related references.]



60 Million Acres (Shaded Area) of High-Yield SRWC (New Trees) = 5% of U.S. Electrical Consumption

30 Million Acres (Shaded Area) of 3% Efficient Solar Panels = 100% of U.S. Electrical Consumption

Figure 1. One Perspective of Renewable Energy

Table 1: Wood derived energy consumption in US in 1987

WOOD ENERGY CONSUMER	QUADS / YEAR
Lumber & Wood Products Industry	0.460
Pulp & Paper Industry	
• as hog fuel	0.258
• as bark	0.135
• as black liquor	0.950
Other Industry	0.049
Residential	0.840
Commercial	0.022
Utilities	0.009
Total	2.720

Table 2: Estimate of Annual Wood Availability in US, South, and NC

(Million cuft/yr)	US (1986)	South (1986)	NC (1990)
Growing Stock (GS) Inventory	754,913	238,033	32,742
Growth of Growing Stock	22,387	10,429	1,160
Removal of Growing Stock	17,040	8,698	940
Excess GS Growth	5,347	1,731	220
Non-merchantable Surplus[A]	535	173	13
Logging Residues[B]	1,582	764	160
Total Available[C]	7,464	2,668	393
Max Quads Available /yr[D]	1.48	0.53	0.08
Power Potential (MW)[E]	**18,990**	**6,825**	**1,017**

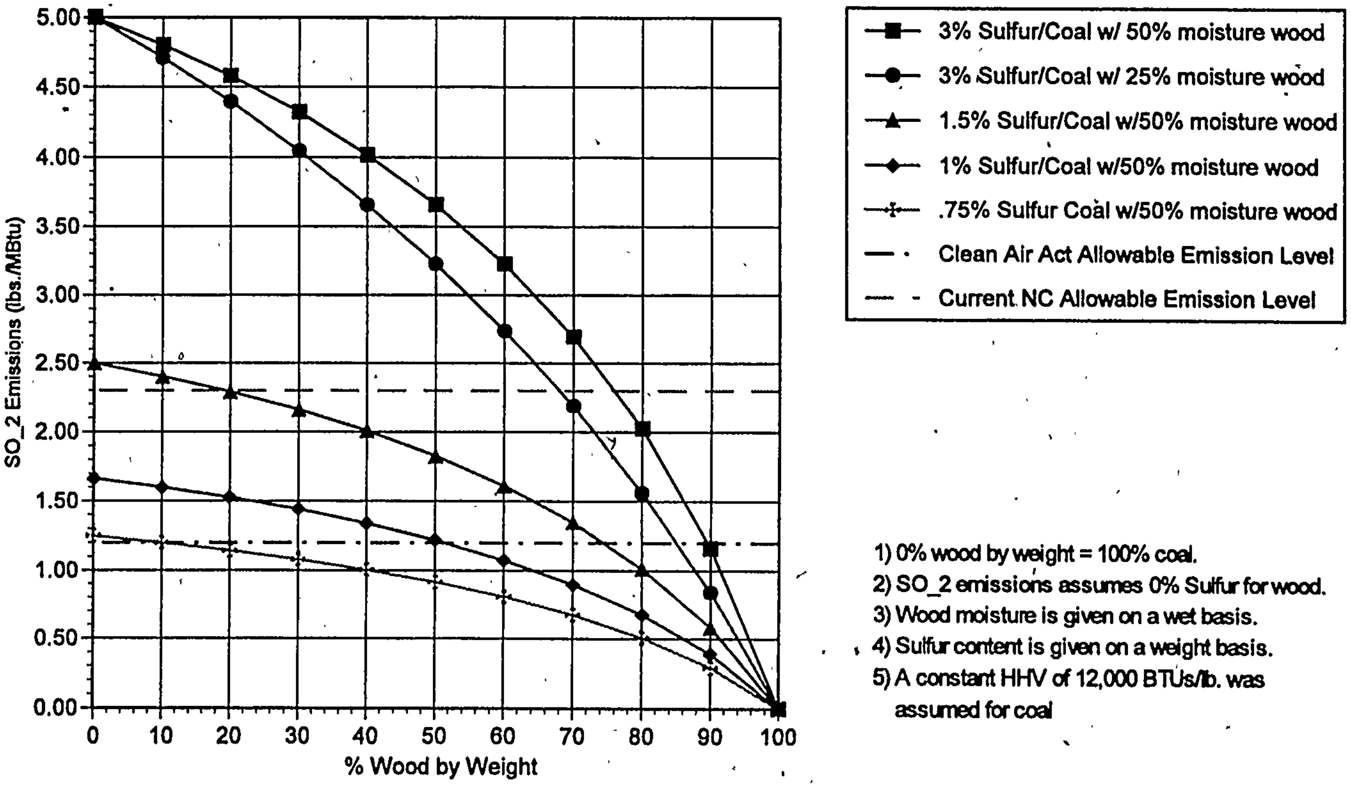
A. Based on 1986 Forest Service statistics, the amount of non-merchantable wood available annually was approximated by 10% of annual excess growing stock growth, for the US and the South. From 1990 NC forest statistics, that percentage was 6% for NC.

B. The volume of logging residues in the US and the South was taken from 1986 Forest Service statistics. In North Carolina, logging residues were approximately 17% of all removals.

C. The maximum amount of wood potential for energy production was calculated based on annual excess growing stock growth, annual excess growth of non-merchantable wood, and annual logging residues.

D. The maximum number of quads potentially available for energy production were estimated using a wood density of 45 lb/cuft and a heating value, at 50% moisture content, of 4,400 Btu/lb.

E. The electrical power potential was calculated assuming a 25% plant efficiency and a 65% capacity factor.



1) 0% wood by weight = 100% coal.
2) SO_2 emissions assumes 0% Sulfur for wood.
3) Wood moisture is given on a wet basis.
4) Sulfur content is given on a weight basis.
5) A constant HHV of 12,000 BTUs/lb. was assumed for coal

Figure 2. SO_2 Uncontrolled Emissions Reduction by Co-Firing Wood with Coal

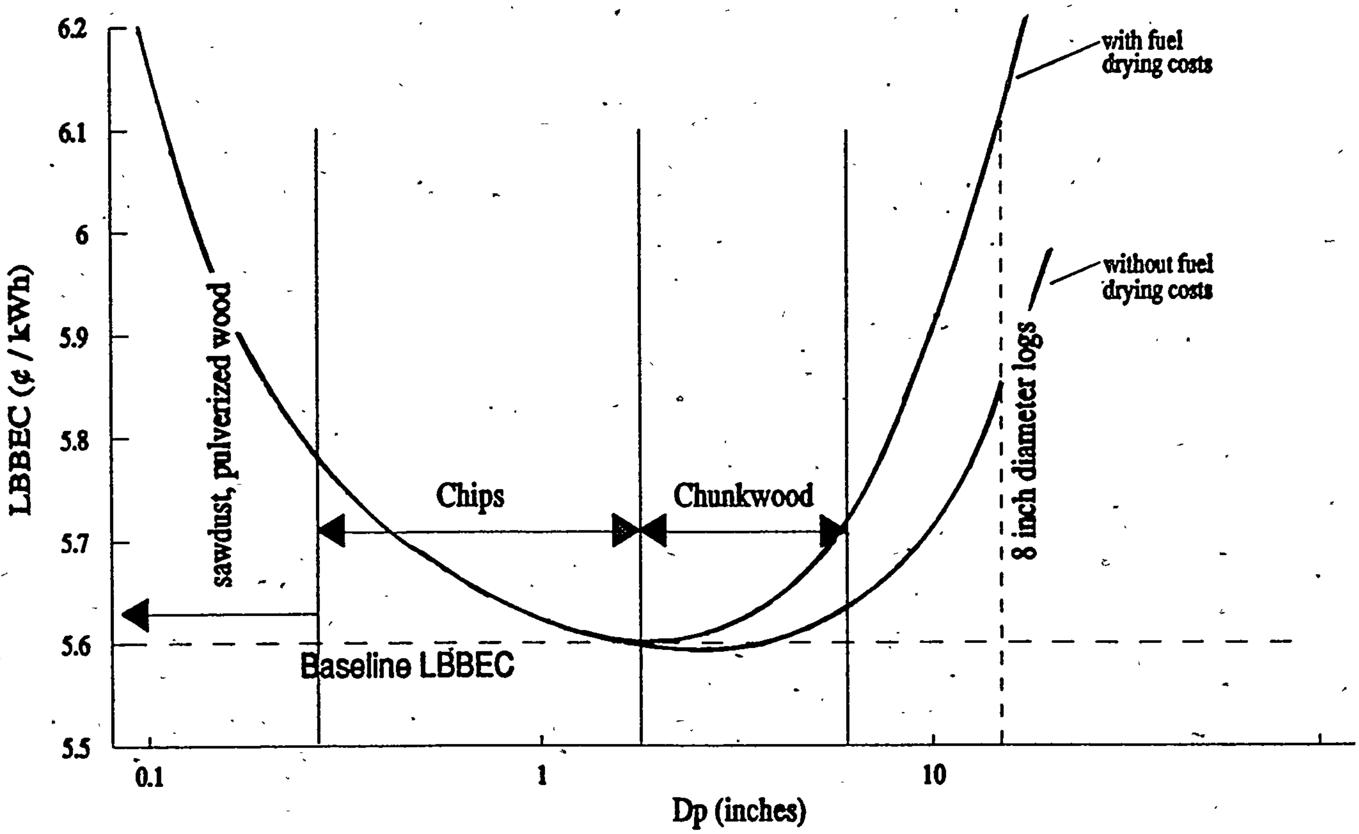
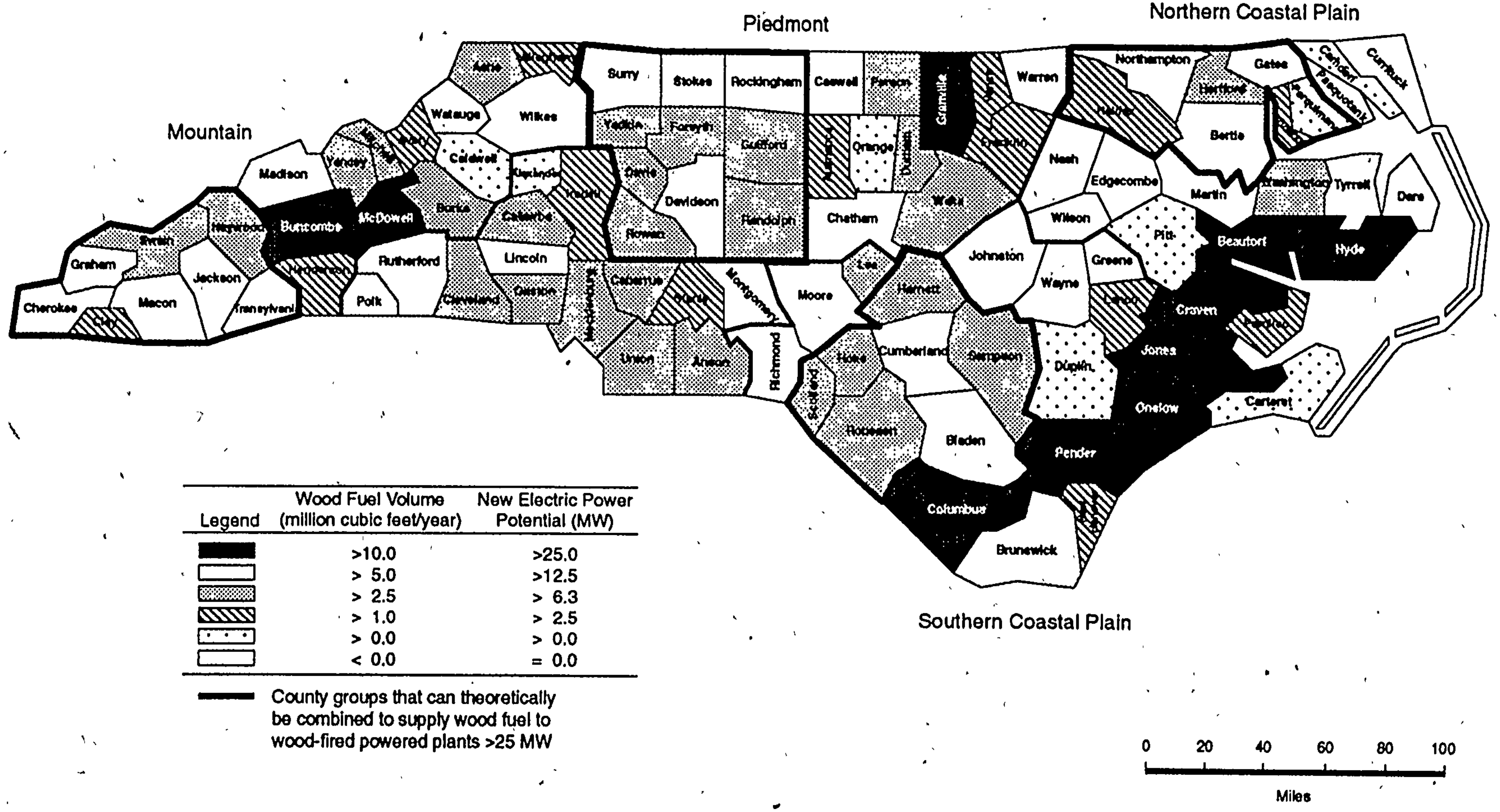


Figure 3. Levelized Busbar Cost for a 100 MW Wood-fueled Utility Plant as a Function of Wood Fuel Size

Figure 4. County Total Wood Fuel Resources

Annual Excess Growth of Growing Stock and
Non-merchantable Wood and Logging Residues



Legend	Wood Fuel Volume (million cubic feet/year)	New Electric Power Potential (MW)
■	>10.0	>25.0
□	> 5.0	>12.5
▒	> 2.5	> 6.3
▨	> 1.0	> 2.5
⁙	> 0.0	> 0.0
□	< 0.0	= 0.0

▬ County groups that can theoretically be combined to supply wood fuel to wood-fired powered plants >25 MW

Assessment of Ethanol-Fueled IMHEX® Fuel Cell Power Plants in Distributed Generation

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Abstract

Ethanol-fueled fuel cell power plants presents several significant opportunities for the power generation industry. The potential exists to reduce pollution, help the nation shift from its dependence on imported fuels, reduce global warming, and strengthen the economy. Two important developments can be merged to create a clean, high-technology, bio-based energy system: the production of ethanol fuels and the application of fuel cell power plants. Utilization of ethanol will be in dual-fueled applications initially, and evolve toward the primary fuel as the need for renewable energy sources increase and the economic competitiveness improves.

This assessment addresses the major issues of this proposed concept and outlines the benefits anticipated to the environment, U.S. agriculture, energy supplies, and electric power customers. Economic and technical aspects of the concept are also reviewed. One of PSI Energy's primary interests is the utilization of renewable fuels supplied by their customer base. The IMHEX® fuel cell is an advanced electric power generation technology currently under development by M-C Power. Commercial applications within the power generation industry are scheduled to begin during the late 1990s.

Introduction

With the turn of the decade, the power generation industry in the United States is continuing the evolutionary process that began in the 1980s. Increased competition and stronger environmental restrictions are at the center of these changes. The typical electric utility may appear quite different after the turn of the century although this evolution may continue for another twenty years. Competitive bidding is responding to the need for new capacity, and it appears, transmission system access is on the horizon. Natural gas is becoming the fuel of choice in the near term for most new capacity or repowering projects.

The electric utilities are beginning to examine the concepts of "energy service" to improve their economic competitiveness. This concept dates back to Edison's vision for the electric utility industry. Not only would utilities provide central station generation (the production of kWh), but also, electric power conversion into useful products (lumen-hours of light). Today, these products potentially can include demand side management and on-site services which improve application-specific electric quality or reliability in addition to conventional services such as lighting, cooling, information processing, etc.

The environmental issues are becoming the single most uncertain aspect of the power business. These may be manifested in air emissions permits or allowances for NO_x or SO_2, energy taxes, CO_2 limits, "carbon taxes", etc. The issue also appears as siting permits for generation, transmission, or distribution facilities. These issues and increased focus on cost-effective supply are leading utilities to examine the benefits of distributed generation. Siting small capacity generation near the customer loads or at distribution substations can improve system efficiency and reduce distribution system costs.

Renewable energy sources also represent opportunities to improve the environment and increase the nations energy self-sufficiency. By utilizing energy sources derived from domestic agricultural sources, the nations dependence on imported energy can be decreased. In addition, renewable fuels, such as ethanol and digester-gas, can improve local farming economies by increasing markets for agricultural products and animal wastes. These fuels also reduce environmental impacts of greenhouse gases by closing the carbon dioxide cycle and preventing the release of methane gas.

The Distributed Generation Concept

The overall concept is to utilize renewable energy supplies in distributed electric generation facilities. With the increased competition and environmental restrictions around the corner, electric utilities are beginning to assess the advantages of smaller scale generation facilities located at utility substations or customer sites. Distributed generation can improve the energy efficiency by eliminating the transmission losses and utilizing by-product heat in commercial or industrial applications or for residential district heating systems.

Distributed generation is any type of small generating capacity that is sited at or near the distribution substation or customer load. Some utilities are beginning to consider and evaluate distributed generation when planning future production or transmission additions in order to meet power requirements as well as customizing electric supply to individual customer needs. Progress in the commercial development of fuel cells and photovoltaic continue to enhance the applications of distributed generation.

When considering the total cost of distributed generation the capital cost of the installation must be offset by the savings in avoided transmission and distribution investments, potential for improved power quality (eg: voltage support), reduced energy losses and cogeneration applications. The ability to add smaller increments of capacity increases the flexibility of system planning by addressing the needs of a specific area. With reduced issues in siting and improved economics, distributed generation will play a larger role in meeting many utilities' future capacity expansion plans.

Renewable Energy Sources

These distributed generation sites may initially rely on the natural-gas pipeline network for their primary fuel source, but other sources of energy may increase the overall benefits, both economically and environmentally. Renewable energy sources, such as ethanol, can easily be transported and stored on-site. Other biofuels, such as woody energy crops and animal wastes, can be gasified into useful energy sources. This alternate fuel option provides secondary benefits to the economy and the environment.

One primary consideration of biofuels is that they are believed to close the carbon dioxide (CO_2) cycle. Since CO_2 is consumed during the photosynthetic process which is central to the plants growth, any CO_2 emitted from the power generation cycle must have originated in the atmosphere. In effect, biofuels are considered to be at least CO_2 neutral. These biofuels also contain negligible sulfur and fuel-bound nitrogen in comparison to fossil fuel sources. Estimates have been made that indicate 50 GW of dedicated-biofueled electric capacity could be realized by 2010.

Ethanol, as a biofuel option, provides advantages in transportation and on-site storage. It allows for a centralized ethanol production facility which should improve the overall economics of the biofuel option. With the fuel cell power plant option, ethanol also appears to be directly interchangeable with natural gas. This allows distributed generation facilities to use natural gas as a primary fuel source initially and transition into increased ethanol use as economic-drivers change.

The IMHEX® Fuel Cell Concept

The development of advanced power generation technologies, such as the fuel cell, introduces equipment options which have not been available in the past. Modular fuel cells in capacities of one to several MW can produce electric energy more efficiently than today's best, large capacity, central station technologies. Fuel cells are devises that directly convert the chemical energy of fuel to electrical power. Based on concepts that are over 100 years old, fuel cells were first used to provide the primary electric power in manned-space mission such as the Appollo and Space Shuttle flights. Beginning in the early 1970s researchers began developing fuel cell types that could have cost-effective applications in the power generation industry.

The IMHEX® fuel cell being developed by M-C Power Corporation is based on molten carbonate fuel cell technology. Borrowing concepts from advanced plate and frame heat exchanger designs, a fuel cell design concepts known as the internally manifolded heat exchangers (IMHEX®) was invented by the researchers at the Institute of Gas Technology in the mid-1980s. M-C Power was formed in 1987 with the sole mission of bring molten carbonate fuel cells based on the IMHEX® approach to commercial readiness.

An IMHEX® fuel cell is a skid mounted power plants which generates electricity and useful thermal energy. The primary benefits are their high electric generation efficiency, their fuel flexibility and minimal environmental impacts. The electrochemical process used to generate electricity results in power plants that can achieve electric generation efficiencies of 50% or greater based on the higher heating value of the input fuel. This process also does not require the combustion of the fuel prior to electric generation, and therefore, the emissions, such as NO_x, are extremely low, below 1ppm in comparison to conventional technologies which range from 10 to 100ppm. Fuel sources, such as pipeline natural gas, ethanol, methanol, propane, land-fill and biomass gases, coal derived gases, etc., are all feasible for utilization in a fuel cell power plant.

A power plant consists of three major sections, fuel processing section, fuel cell assembly, and power conditioning section. The fuel required by a molten carbonate fuel cell is hydrogen or carbon monoxide, which is typically produced by the steam reforming of available hydrocarbon fuels. The fuel processing section which has been designed to process natural gas can also process evaporated ethanol. The steam or water source required for the reforming process can be supplied independent of the ethanol or premixed and stored on-site. This has the potential to reduce the processing costs of the ethanol and therefore, improve the overall economics of the biofuel to electricity cycle.

In the fuel cell assembly, hydrogen is electrochemically combined with oxygen from the air to form water, direct current electricity and heat. At the cathode electrode of a molten carbonate fuel cell oxygen and carbon dioxide are combined with two electrons to form a carbonate ion. This ion moves through fuel cells electrolyte and transfers the current to the anode electrode. Hydrogen reacts with the carbonate ion releasing the electrons to form water and carbon dioxide. The carbon dioxide is returned to the cathode to continue the process. Fuel cells will continue to generate power as long as hydrogen and oxygen are supplied to their electrodes. By-product thermal energy is recovered from the fuel cell assembly as high pressure steam used by the fuel processing section and exported for cogeneration applications.

The direct current electricity is converted to alternating current electricity in the power conditioning section. Voltage and frequency characteristics of the output power is determined by the power conditioning equipment which is designed to produce electrical energy that can be directly interfaced with an electric utilities distribution system.

Benefits and Issues

The concept of ethanol-fueled, distributed fuel cell power plants has benefits to the environment, U.S. agriculture, energy supplies and electric power customers. Before implementation of this concept can be realized several issues must be addressed and the potential benefits quantified.

Power generation is a major contributor to the greenhouse gases produced in the U.S. An ethanol-fueled fuel cell power plant produces approximately one third the CO_2 in comparison to conventional coal-fired power plants. The use of biofuels will also reduce this pollution by closing the CO_2 cycle and making the fuel to electricity cycle CO_2 neutral. The fuel cell also does not rely on the combustion of the primary fuel, and therefore, emissions of other pollutants, such as NO_x and SO_2, are a small fraction of conventional technologies. In addition, the distributed generation concept allows the direct utilization of by-product heat through cogeneration which further increases the energy efficiency of the process (as high as 80%) and minimizes the emissions per useful energy produced.

The benefits to U.S. agriculture and energy supplies are potentially the most important aspect of this overall concept. Implementation of dedicated agricultural resources to the production of biofuels could provide the nation with an environmentally superior energy resource that would reduce our dependence on imported fossil fuels. This could also reduce the need for agricultural subsidies and eliminate present constraints on the use of more than 100 to 200 Gm^2 (25 to 50 million acres) of agricultural reserve program lands. Biofuels could also create additional jobs in farming communities and in the ethanol and transportation industries. About 3.8 Mm^3 (billion gallons) of ethanol is produced with corn crops in the U.S. today. This represents less than 1% of our transportation fuel requirements, but indicates that the ethanol production industry is well established and is a good basis for larger energy-crop to alcohol-fuel industry.

The concept of distributed generation also provides benefits to the electric power industry and customers. The use of small capacity generation, sited near the load centers, can reduce the need to construct new central power stations and transmission lines. This can also improve power quality and reliability by adding voltage support for outlying distribution sites. By freeing-up existing transmission systems and deferring distribution system upgrades, customer savings can be generated by reducing the utility's capital investments which are needed to serve their customers.

Economic Issues

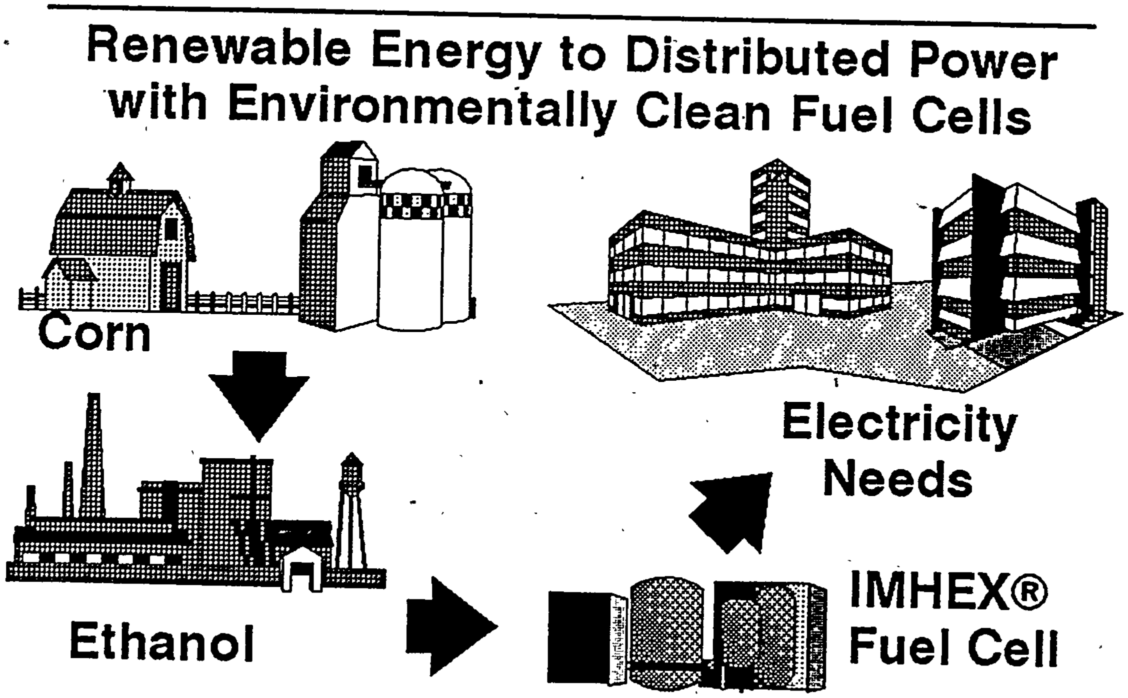
Economics is the primary factor which inhibits the use of ethanol as a biofuel for power generation today. Using corn as the feed stock at $57/$m^3$ ($2 per bushel), the cost of ethanol on a $/unit energy basis is a factor of 3 or 4 greater than natural gas. Today's cost of corn is about $180 to $240/$m^3$ of ethanol ($0.70 to $0.90 per gallon), while the processing cost adds another $130/$m^3$ ($0.50 per gallon) for a total ethanol price of $320 to $370/$m^3$ ($1.20 to $1.40 per gallon). Proposed subsidies for ethanol for vehicle fuels reduce this price by approximately $130/$m^3$ ($0.50 per gallon). The net result is a biofuel price that is approximately $3.3/GJ ($3.5/MMBtu) greater than the projected price of $5.7/GJ ($6/MMBtu) for natural gas in the 2000 to 2010 time frame.

Even at today's prices, ethanol can have one economic advantage in distributed generation. Ethanol provides a dual-fuel option. The use of ethanol as a back-up fuel allows the use of interruptable natural gas rates. This provides a $0.28 to $0.66/GJ ($0.30 to

$0.70/MMBtu) natural gas price saving to the utility or customer. This savings will allow the cost-effective operation of the power plant on ethanol for periods of 5-10% of the year. Although this is a minimal biofuel use, it does provide an initial starting point from which dedicated ethanol-fueled distributed generation facilities can evolve.

Summary

Ethanol-fueled fuel cells presents several significant opportunities for the power generation industry. The potential exists to reduce pollution, help the nation shift from its dependence on imported fuels, reduce global warming, and strengthen the economy. Two important developments can be merged to create a clean, high-technology, bio-based energy system: the production of ethanol fuels and the application of fuel cell power plants. Utilization of ethanol will be in dual-fueled applications initially, and evolve toward the primary fuel as the need for renewable energy sources increase and the economic competitiveness improves.



COMPUTATIONAL MODEL OF A WHOLE TREE COMBUSTOR

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ABSTRACT

A preliminary computational model has been developed for the whole tree combustor and compared to test results. In the simulation model presented hardwood logs, 15 cm in diameter are burned in a 4 m deep fuel bed. Solid and gas temperature, solid and gas velocity, CO, CO_2, H_2O, HC and O_2 profiles are calculated. This deep, fixed bed combustor obtains high energy release rates per unit area due to the high inlet air velocity and extended reaction zone. The lowest portion of the overall bed is an oxidizing region and the remainder of the bed acts as a gasification and drying region. The overfire air region completes the combustion. Approximately 40% of the energy is released in the lower oxidizing region. The wood consumption rate obtained from the computational model is 4110 kg/m^2-hr which matches well the consumption rate of 3770 kg/m^2-hr observed during the peak test period of the Aurora, MN test. The predicted heat release rate is 16 MW/m^2 (5.0*10^6 Btu/hr-ft^2).

INTRODUCTION

A steam powerplant utilizing whole trees as the renewable fuel (Whole Tree Energy™) is being developed by Energy Performance Systems, Inc. of Minneapolis, MN. Hardwood trees are grown and harvested on energy plantations, or harvested from inferior, over-aged standing trees, transported in trucks as whole trees, and stored in a large covered stack at the powerplant site where the stack is dried with waste heat from the powerplant. The whole trees are burned in a fixed bed boiler. This innovative system completed stacking, drying and combustion tests at a site near Aurora, MN in August, 1992 [1].

The advantages of the Whole Tree Energy system are 1) time, energy and processing costs are saved by not chipping the wood, 2) a 30 day supply of wood may be stored on site without degradation of the fuel, and 3) the combustion heat release per unit boiler area is greater than with woodchips. The concept is envisioned for 25 MW to 400 MW Rankine cycle powerplants.

In the whole tree combustor a ram feeder located 6 m above a fixed grate injects batches of trees trimmed to 8 m in length (for a 100 MW plant) with trunks up to 20 cm in diameter. The fuel feed rate is set to maintain a fuel bed on the grate of 3 to 5 m deep. Preheated air is blown up through the fuel bed such that the lower section of the bed has an oxidizing environment and the upper part of the fuel bed has a reducing environment. Combustion is completed by means of overbed air jets.

The purpose of this paper is to present the preliminary findings of a computational model of the performance of the whole tree combustor. The results are compared to the Aurora, MN tests. The model is useful for analyzing relationships between fuel burning rate, bed depth, inlet air flow, inlet air preheat, and fuel moisture, for example. The computational work is continuing, and single log combustion tests in a specially designed furnace are being conducted in order to improve the accuracy of the model.

DESCRIPTION OF THE MODEL

The model is a one-dimensional, steady-state model for a top feed, updraft, packed bed combustor (Fig. 1). There is no heat loss to the walls within the bed. The char reaction is assumed to be the rate limiting step because it has been observed that for large pieces of wood such as logs, the wood behind the char layer remains undisturbed [2] (see Fig. 2). An initial log diameter, a constant surface to volume ratio, and a constant void fraction is used to characterize the pile, and the logs are assumed to be oriented across the gas flow As the log shrinks due to reaction with oxygen, carbon dioxide and water vapor, moisture and wood volatiles are released from the wood. The proportion of wood to wood plus char, which is initially 100% at the top of the pile, decreases as the diameter shrinks, and when 4 cm diameter is reached, it is assumed to be all char. The chemical reaction rates between char and oxygen; char and carbon dioxide; char and water vapor; hydrogen and oxygen; hydrocarbons and oxygen; and carbon monoxide and oxygen are calculated. The model solves the equations of conservation of mass for the solid and gas, conservation of species CO, CO_2, H_2O, HC and O_2, and conservation of energy for the gas.

The gaseous species conservation equations in differential form are,

$$d(G_{CO})/dz = r_{CO} \quad (1)$$

$$d(G_{CO2})/dz = r_{CO2} \quad (2)$$

$$d(G_{H2O})/dz = r_{H2O} \quad (3)$$

$$d(G_{O2})/dz = r_{O2} \quad (4)$$

$$d(G_{HC})/dz = r_{HC} \quad (5)$$

$$d(G_{H2})/dz = r_{H2} \quad (6)$$

where G is the mass flow rate of per unit area, z the the height of the combustor, and r is the chemical reaction rate. The chemical reaction rate for each species is formed from the reactions shown in Table 1 in the following way:

$r_{CO} = 2*r_1*28/32 - r_2 + 2*r_3*28/44 + y_{CO}*r_w$
$r_{CO2} = r_2*44/28 - r_3 + y_{CO2}*r_w$
$r_{H2O} = h_{H2O}*r_w + 0.167*r_5*18/12.4 + y_{H2}*r_w*18/2$
$r_{O2} = -r_1 - 0.5*r_2*32/28 - 0.5*y_{H2}*r_w*32/2 + 0.5815*r_w*32/12.4 + 0.5*r_4*32/18$
$r_{HC} = y_{HC}*r_w - r_5$
$r_{H2} = y_{H2}*r_w + r_4*2/18$
$r_w = [2*r_1*2/32 + r_3*12/44 + r_4*12/18]*K_{wood}/y_c$

where the r_i's include both chemical kinetics and diffusion, and each term is multiplied by the surface to volume ratio of the log, A_v. The kinetic rate constants are given in Table 2. The diffusion terms are formed using the Rantz-Marshall correlation.

Upon integration of Equations 1-6 the mass flow rate of gas is,

$$G_g = G_{CO} + G_{CO2} + G_{H2O} + G_{O2} + G_{HC} + G_{H2} + G_{N2} \tag{7}$$

Conservation of mass for the solid is,

$$(1-\varepsilon)\rho_s dV_s/dz = -r_w \tag{8}$$

where ε is the void fraction of the wood in the pile, ρ_s is the density of the solid, r_w is the net reaction rate per unit volume of the wood, and V_s is the velocity at which the wood moves down the combustor.

Conservation of energy for the gas is,

$$d(G_g h_g)/dz = H_1 r_1 + H_2 r_2 + H_3 r_3 + H_4 r_4 + H_5 r_5 + H_5 r_6 \tag{9}$$

where c_p is the specific heat of the mixture, T_g is the gas temperature, and H_i is heat of reaction for reaction i. Conservation of energy for the solid is based on a surface energy balance,

$$h_{conv}(T_s - T_g) = E_{comb.} + m_r h_r - m_p h_p \tag{10}$$

where r is reactants and p is products.

Table 1. Chemical Reactions Used in the Model.

Reaction #	Chemical Reaction	Heat of reaction (kJ/kg)
1	$C + 1/2\ O_2 = CO$	2,210
2	$CO + 1/2\ O_2 = CO_2$	10,100
3	$C + CO_2 = 2\ CO$	-14,300
4	$C + H_2O = H_2 + CO$	-10,900
5	$CH_{0.334}O_{0.00461} + 0.581\ O_2 = 0.167\ H_2O + CO$	19,700
6	$H_2 + 1/2\ O_2 = H_2O$	141,800

Table 2. Kinetic Reaction Rates.

Reaction #	Reaction Rate
1	$145*\exp[-20000/(1.987*T_s)]$
2	$10^{14.7}*\exp[-4.0E4/(1.987*T_g)]*[CO]*[O_2]^{1/4}*[H_2O]^{0.5} + 500*\exp[-4.0E4/(1.987*T_g)]*[CO_2]$
3	$2.0E5*\exp[-50000/(1.987*T_s)]$
4	$4.0E5*\exp[-50000/(1.987*T_s)]$
5	$1.0E5*[HC]^{0.5}*[O_2]*\exp[-1.917E7/(1.987*T_g)]$
6	infinitely fast

The boundary conditions at the grate (z=0) are that the air flow rate per unit area, the inlet air temperature are specified, the solid velocity is zero and the CO, CO_2 and H_2O fluxes are zero. The initial values for various parameters are given in Table 3. The equations are integrated using a Gear-B type ordinary differential equation solver. The gas temperature profile, velocity profile, concentration profiles, and heat release rate are obtained. Then the particle size and surface temperature are found by iterative solution.

Table 3. Model Input Values

FUEL	initial diameter	15 cm
	initial dry density	0.41 g/cm^3
	moisture (as-received)	29%
	composition (dry, ash-free)	
	char	24.5%
	hydrocarbons	30.2%
	hydrogen	0.6%
	carbon monoxide	14.1%
	carbon dioxide	30.6%
	fuel bed height	4 m
	fuel bed void fraction	0.4
AIR	underfire air temperature	550 K
	underfire air velocity	3.4 m/s
	overfire air temperature	300 K

RESULTS AND DISCUSSION

The model was run for the conditions used during the peak test period of the Aurora, MN tests, as indicated in Table 3. Note that the under-grate air is preheated to 550 K and has a velocity of 3.4 m/s. The predicted solid surface temperature and gas temperature profiles are shown in Fig. 3. The lower portion of the bed consists of a thin region of small diameter char where the oxygen is rapidly consumed. Above this region is a long reducing region where the diameter of the logs slowly decreases as the char layer is formed and the logs are dried and pyrolized. The oxidizing region is very thin and accompanied by high surface temperatures and rapidly rising gas temperatures. In the reducing region the gas and surface temperatures slowly drop as energy is drawn from the gas to dry the logs and support the pyrolization and reduction reactions. Following this in the overfire air region the gas temperature rises rapidly at first as the CO is consumed and then more slowly as the hydrocarbons are consumed. The CO_2 rapidly rises in the oxidizing region (Fig. 4) and then slowly drops in the reducing region. The pyrolysis products and CO rise slowly through through the reducing region and are then consumed in the overfire air region. The model predicts that approximately 40% of the energy is released in the lower oxidizing region. The wood consumption rate obtained from the computational model is 4110 kg/m^2-hr which matches well the consumption rate of 3770 kg/m^2-hr observed during the peak test period of the Aurora, MN test. The predicted heat release rate is 16 MW/m^2 ($5.0*10^6$ Btu/hr-ft^2).

Various assumptions made in the computational model may impact the temperature distribution and consequently the heat release rate and will be the subject of further study. These include 1) the impact axial heat conduction and radiation on the axial temperature distribution and wood combustion, 2) the effect of feeding varied sized material into the deep bed material, 3) the growth of the char layer, and pyrolysis and drying rates of the wood under various conditions, 4) the final breakdown and consumption of the char, and 5) the volatile reaction rates. It is anticipated that inclusion of the axial heat conduction and radiation will reduce and spread the peak surface temperatures. A better understanding of how the final particle size occurs may increase the predicted length of the oxidizing zone, however it is anticipated that the lower oxidizing region will still be a small portion of the total bed height and that gasification will remain an important consideration in the overall combustor design.

CONCLUSIONS

A preliminary computational model has been developed for the whole tree combustor and compared to test results. This deep, fixed bed combustor obtains high energy release rates per unit area due to the high inlet air velocity and extended reaction zone. The lowest portion of the overall bed is an oxidizing region and the remainder of the bed acts as a gasification and drying region. The overfire air region completes the combustion. Approximately 40% of the energy is released in the lower oxidizing region. The wood consumption rate obtained from the computational model is 4110 kg/m^2-hr which matches well the consumption rate of 3770 kg/m^2-hr observed during the peak test period of the Aurora, MN test. The predicted heat release rate is 16 MW/m^2 ($5.0*10^6$ Btu/hr-ft^2).

ACKNOWLEDGEMENTS

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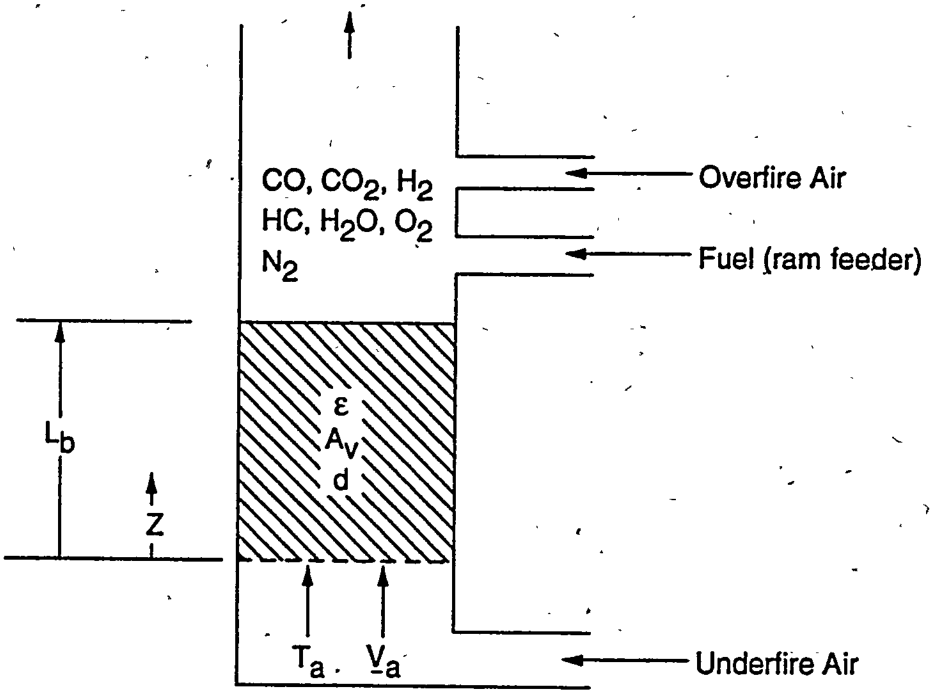

Figure 1. Schematic of combustor

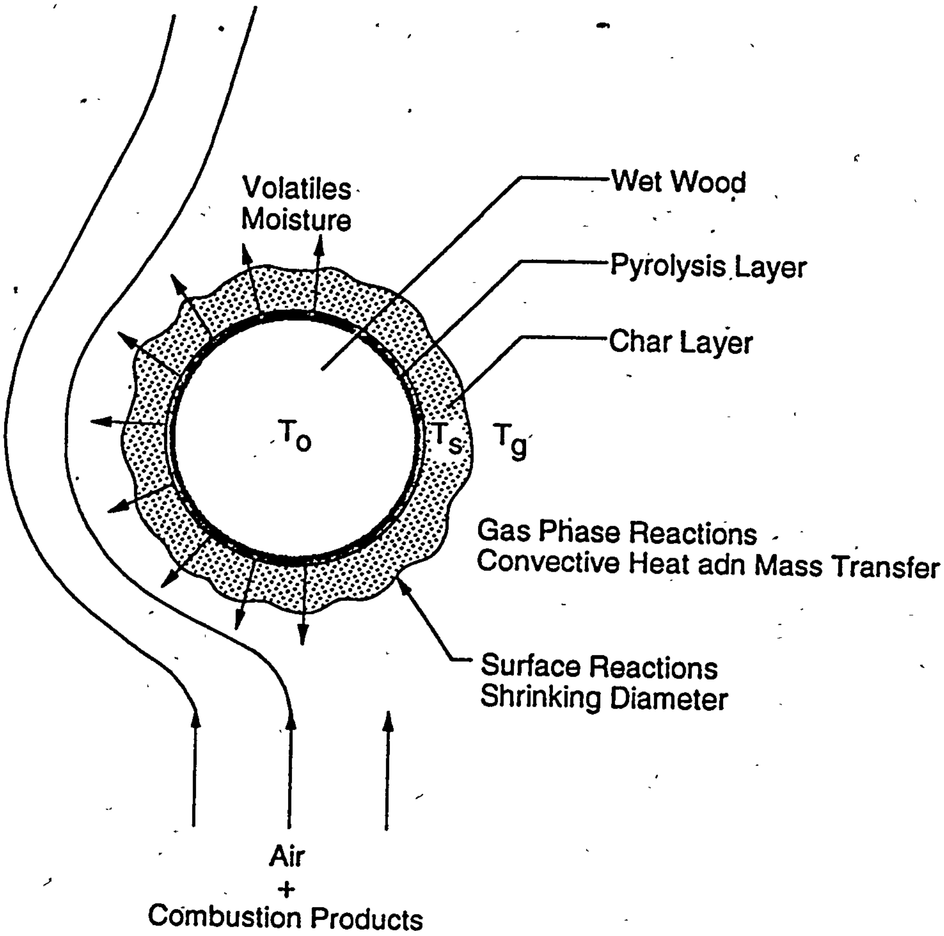

Figure 2. Single reacting log

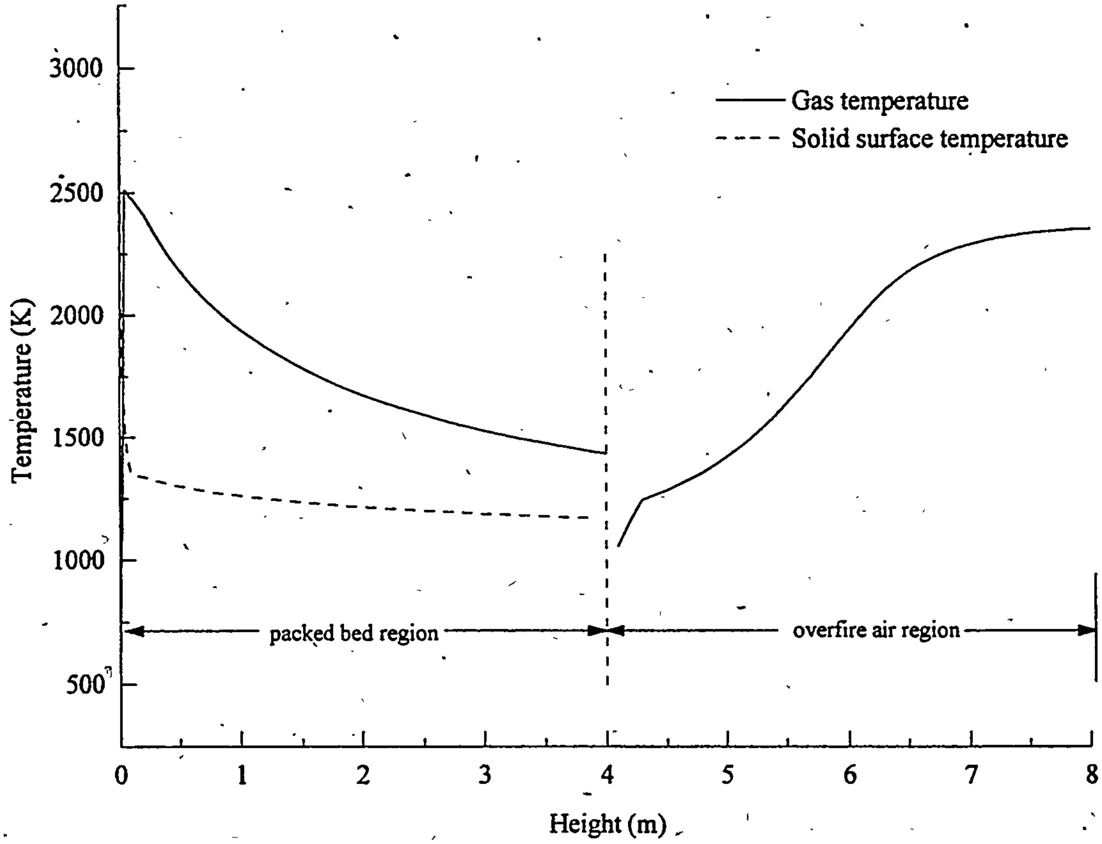

Figure 3. Temperature profiles

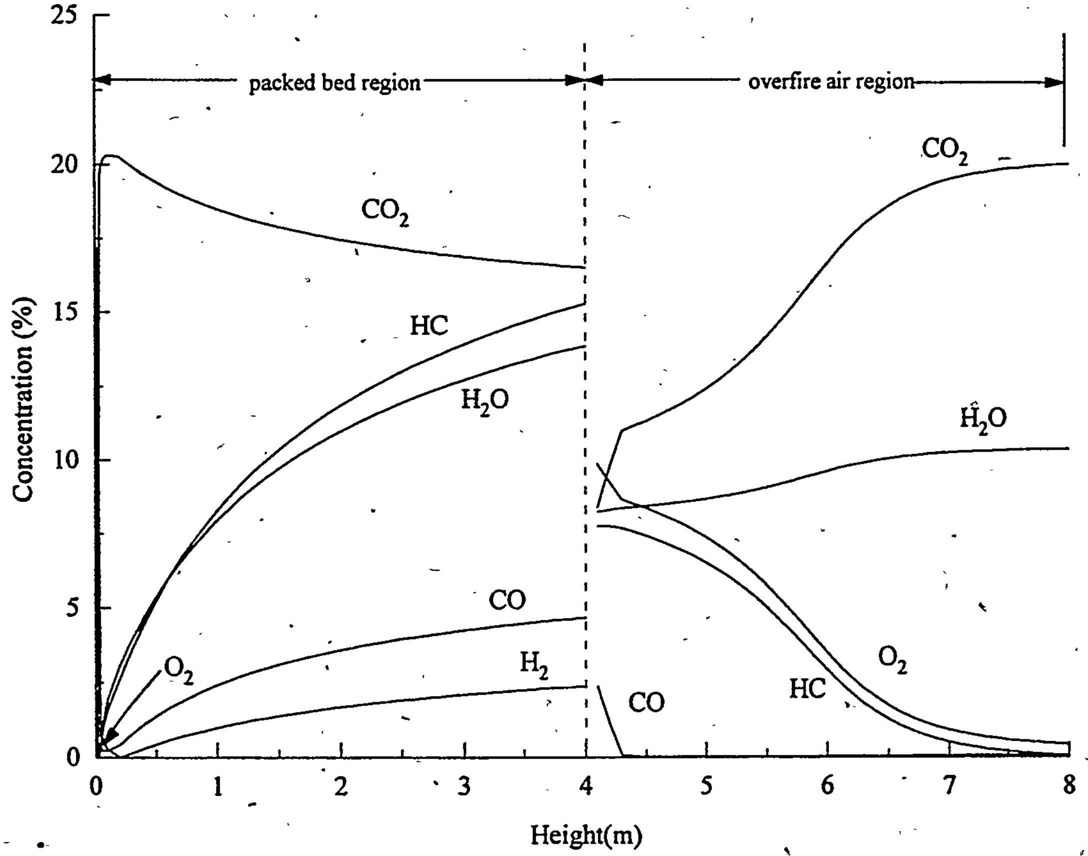

Figure 4. Gaseous species profiles

ECONOMICAL IMPACT OF THE BIG/CC TECHNOLOGY USE ON THE SUGAR CANE INDUSTRY

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ABSTRACT

The use of biomass as primary fuel for power and steam production using modern conversion technology such as the Biomass Integrated Gas Turbine/Combined Cycle (BIG/CC) has both technical and commercial potential. Brazil is implementing a BIG/CC Demonstration Plant to burn wood from eucaliptus short rotation forest and to test sugar cane bagasse as feedstock. The purpose of this project is to demonstrate the commercial viability of using biomass as a feedstock for power generation, its suitability for applications in developing countries, and the possibilities it offers for commercial activities in regions which currently have a low level of economic activities.

The purpose of this paper is to show the potential applicability of this technology in the sugar cane Industries of Developing Countries such as Brazil. The same quantity of sugar cane already processed in each sugar mill can produce sizable quantities of electric power at competitive costs, in addition to the traditional products - sugar and/or ethanol, which will cause an economical impact, duplicating the revenue of these industries. The application of the BIG/CC technology in the Sugar Cane Industry may lead to the following scenario in developing countries:

- power shall be produced at very competitive prices by specialized private firms associated with sugar mills;
- plant sizes will be smaller - 15 to 100 MW - when based on biomass, as compared to large fossil fuel plants now prevailing;
- ethanol and sugar production costs will be reduced due to more efficient and economical processes and due to the additional revenue from power production;
- becoming more competitive with gasoline, ethanol production tends to increase, which will influence the automobile industry and improve the quality of life in big cities.

1. THERMOELECTRIC CYCLES

1.1 RANKINE Cycle

Most conventional thermal electric power plants are based on the RANKINE cycle, in which steam raised in boilers propels condensing turbines driving alternators which generate electricity. The complexity of these plants is related to the degree of optimization of the process to increase efficiency and reduce pollutant emissions. Measures include reheaters, superheaters and economizers as well as precipitators and FGD for environmental control.

Although the efficiency of this type of plant has increased over the last thirty years, there are practical and theoretical limits constraining future improvement. The best efficiency attainable today in a plant of 500 MW is only 43%. Coming to Plant sizes of 15-50 MW, which are the plants normally using biomass as prime fuel the efficiency would be around 30%, which is substantially below what is expected with new developments in other cycles reviewed here.

1.2 BIG/GT Cycle

Recent evaluations of emerging technology suggest that thermal plants of 15-50 MW using biomass can reach efficiencies higher than 40%, with potential to eventually pass 50%. The associated costs would be sufficiently low to make them commercially viable in a broad range of situations.

The most promising technology, derived from the IGCC system, involves the combination of a pressurized gasifier (or, alternatively, an atmospheric gasifier) and a gas turbine. The generic name for this family of cycle is "Biomass Integrated Gaseification/Gas Turbine" - BIG/GT which includes the following alternative cycles:

- *available technologies*
. open cycle - BIG/OC
. steam injection - BIG/STIG
. combined cycle - BIG/CC
- *future technologies*
. steam injection with intercooler - BIG/ISTIG
. cycle with intercooler and regeneration - BIG/ICR

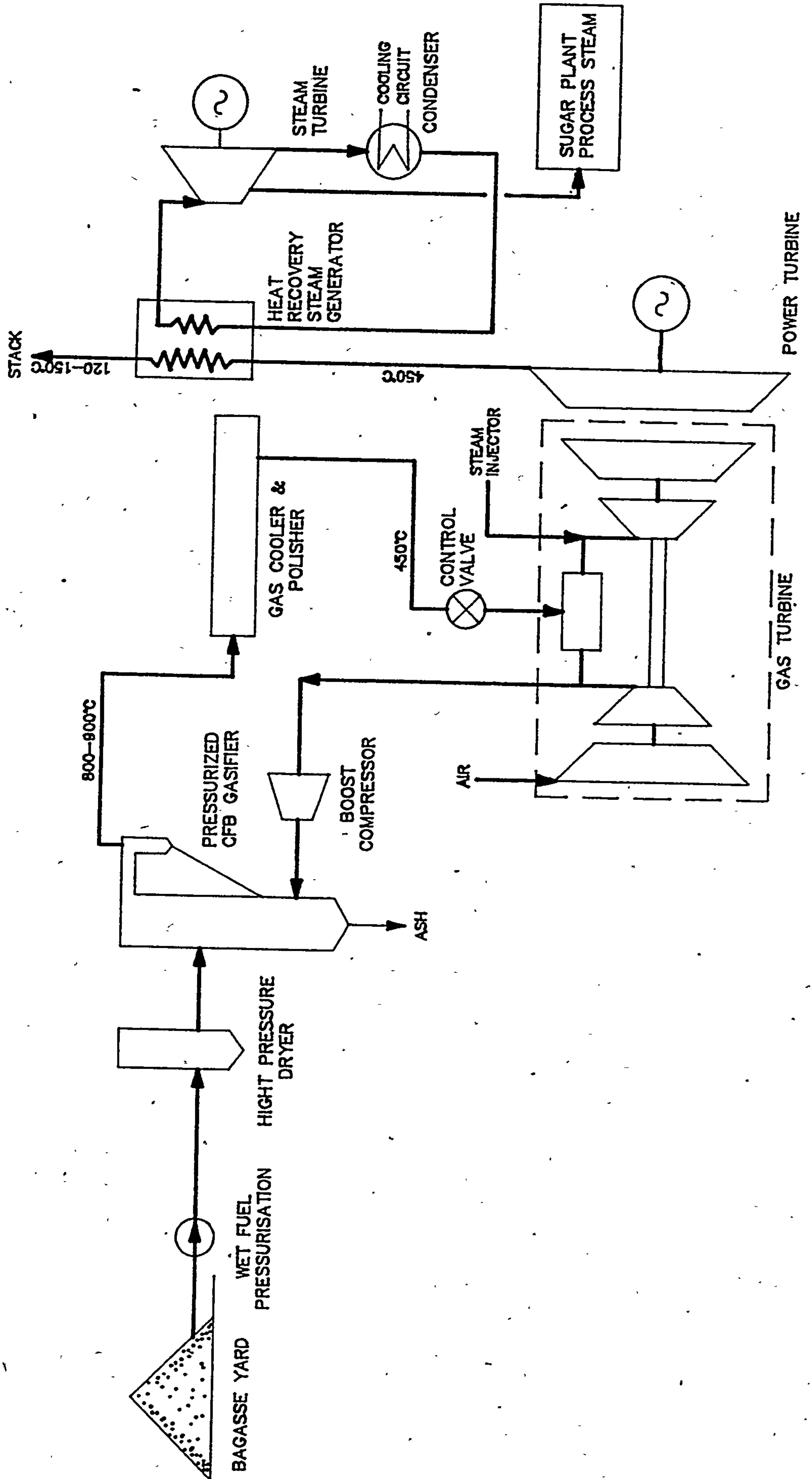
Among the cycles using available technology, BIG/STIG and BIG/CC are of most interest. The BIG/OC suffers from low efficiency and from not producing process steam.
This article will concentrate more on BIG/CC, since this is currently the most interesting option for the sugar cane industry.

1.3 Combined Cycle - BIG/CC

The combined cycle is constituted of a gas turbogenerator whose exhaust gases raise steam in a waste heat boiler, which supply steam to a bottom cycle steam turbine and alternator. The combined cycle has an efficiency 50% higher than the open cycle with a modest increase in investment, which significantly increases its performance in economic terms.

Figure 1 presents a summary flow chart for a typical BIG/CC configuration using pressurized gasifiers. The key elements are:
- Fuel Preparation and Handling
. Fuel Pressurization
. Biomass Drier
- Gasifier and Gas Polisher System
. Boost air compressor for gasifier
. Gasifier
. Gas Cooler and Polisher
- Gas Turbine
- Bottoming Cycle
. Waste heat boiler
. Condensing turbine and alternator
. Condenser

FIGURE 1 — BIG / CC — FLOW DIAGRAM



The effective implementation of a BIG/GT system requires the following technological developments from the current state-of-the-art:

- Gas Turbines

Adaptations to use the low BTU gas (LHV = 5850 kJ/Nm^3) from the gasifier, including modifications on the combustion chamber.

- Gasification Systems

Improvements in biomass drying, fuel feeding and on the gas polisher and cooler systems.

2. APPLICATIONS TO THE SUGAR CANE INDUSTRY

2.1 Medium Scale BIG/CC

Using the milled residue of sugar cane - bagasse - as fuel, it is calculated that a combined cycle plant based on the GE-LM-2500 gas turbine would have the following specifications:

Output	
. gas turbine	21 MW
. steam turbine	9 MW
. total	30 MW
Efficiency	43%
Heat rate	2 Gcal/MWh
Specific fuel consumption	1.021 kg bg (50% W)/kWh

Since in Brazil the milling season extends for about six months, two operational strategies are possible.

- Hipothesis A: Mill's bagasse is entirely consumed during the milling (crop) season

Assuming a sugarmill/alcohol distillery with a milling capacity of 340 metric tons of cane per hour (tc/h), process steam requirements of 350 kg/tc and 80% operational efficiency one arrives at the following parameters:

. production of bagasse	345 494 t/crop
. energy equivalent	338 388 MWh/crop
. equivalent power output	90 MW (load factor = 85%)

The calculated equivalent power output was based on a 6 months/year operation (crop season), and does not allow for the 350 kg/tc steam extraction (1,5 bar) for process steam. Allowing for this, reduces net power by about 10 MW to 80 MW total. An extra 10 MW would be consumed by the industry, assuming that the cane crushing mills are electrified. That leaves about 70 MW to sell to the grid. Outside the milling season, 90 MW could be sold to the grid using as fuel natural gas or bagasse purchased from other mills.

- Hipothesis B: Mill's bagasse is stored during the milling season, and consumed throughout the year.

The bagasse produced will be partially stored during the milling season in order to permit a 12 month power generation at the Plant, without requiring any fuel purchase. The Plant will be sized to permit constant sales to the grid.

		Milling Season	Outside Milling Season
Net power generation	- MW	45	35
Mill consumption	- MW	10	0
Sales to grid	- MW	35	35

2.2 Energy Potential of the Brazilian Sugar cane Industry Considering the Previous Table

Assuming continuous generation throughout the year with the mills own bagasse (Hypothesis B), the potential total net power output and sale to the grid in Brazil is:

Cane Production - tc/yr	218 338 000
Bagasse Production - tb/yr	63 300 000
Net Power Output - MW	
- milling season	8 300
- outside milling season	6.400
Sales to Grid - MW	
- milling season	6 400
- outside milling season	6 400

3. ECONOMIC EVALUATION

3.1 Costs of Electricity to the Grid

The two above hypothesis (A and B) are analyzed for a sugar mill/destillery with a milling capacity of 340 tc/h and other parameters as follows:

Hypothesis A: Mill's bagasse entirely consumed in milling season
- purchase of bagasse from third parties to operate outside milling season at $10/t.

- sale of electricity to the grid	
. milling season	70 MW @ 85% load factor
. outside milling season	90 MW @ 85% load factor
- installed capacity	90 MW

Hypothesis B: Mill's bagasse consumed throught the year:
- no purchase of bagasse

- sale of electricity to the grid	
. milling season	35MW @ 85% load factor
. outside milling season	35MW @ 85% load factor
- installed capacity	45 MW

Assuming a discount rate of 10%/year and amortization over twenty years (capital recovery factor = 0,11746), the two hypothesys present the following costs:

	Hypothesis A	Hypothesis B
CAPITAL COST		
Specific investment -US$/kW	1500	1 500
Total investment - USx10^3$	135 000	67 500
Annual capital cost - USx10^3$	15 857	7 929
Energy sold - MWh/yr	595 680	260 610
Specific capital cost - US$/MWh	26.6	30.4

OPERATIONAL COST		
- Purchase Fuel		
- milling season-US\$x10^3	--	--
- outside milling season-US\$x10^3	3 421	--
Specific fuel cost-US\$/MWh	5.7	--
Operation and maintenance-US\$/MWh	4.0	4.0
Specific Operational Cost	9.7	4.0
TOTAL COST - US\$/MWh	36.3	34.4

The calculation refer to the cost of electricity sold to the grid. It absorbs the costs of process steam and the mill's electricity consumption, whose transfer price is considered to be zero (as is the mill's bagasse).

It is important to recognize that the difference in cost between these hypothesis is quite small.

3.2 Economic Evaluation

Assuming that the electricity can be sold at a price of US\$50/MWh, annual income from sales to the grid by a 340 tc/h mill should be US\$29.8 million in Hypothesis A and US\$13.0 million in Hypothesis B. By way of comparison, annual income from sugar is roughly US\$25 million.

4. CONCLUSIONS

BIG/GT systems are the future for the use of biomass in electricity generation. It will be possible to generate electricity in many small blocks with relatively low investmente and high efficiency. BIG/CC (combined cycle) is currently the promising of these systems.

THeir adaptability to the sugar cane industry is obvious. Bagasse is an available subproduct of the milling process. BIG/GT system can maximize generation for sale to the grid while satisfying internal mill needs (electricity and process steam). The seasonality of supply can be compensated by purchasing bagasse from other mills, though this is not a universal solution once the technology is widely adopted in the industry. Another approach is to store the mill's own bagasse for use outside the milling season. Finally, other biomass (e. g. field residues - currently burned in the open) or natural gas may be used at this time.

The commercialization of BIG/GT technology in the sugar cane industry may bring the following consequences in developing countries.

- power produced at very competitive prices by private firms associated with sugar mills;

- smaller plant sizes - in the range of 15-100 MW;

- sugar and ethanol production costs reduced due to more efficient and economic processes and increased revenue from power production;

- ethanol will become more competitive with gasoline, allowing greater penetration of this market with impacts on the automotive industry and urban air pollution.

Unfortunately, BIG/GT cannot be immediately adopted by the sugar cane industry, because the technology is still in a final phase of development. It is our expectation that, by the end of the decade, a BIG/GT demonstration plant to be buiolt in the state of Bahia, Brazil will have proven commercial operation. With the results of this demonstration and necessary adaptations in its design, a fully developed technology should be ready for use in the sugar cane industry for the first years of the next decade.

Steam Generation by Combustion of Processed Waste Fats

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Abstract

The use of specially processed waste fats as a fuel oil substitute offers, at attractive costs, an environmentally friendly alternative to convential disposal like refuse incineration or deposition. For that purpose the processed fat is mixed with EL fuel oil and burned in a standard steam generation plant equipped with special accessories. The measured emission values of the combustion process are very low.

Introduction

It is known that vegetable oils and fats which have a high energetical potential are suitable for use as a fuel oil substitute which can be burned in conventional steam generation plants. From ecology's point of view the combustion process is advantageous because no additional CO_2 and not much SO_2 are produced. However the production costs of vegetable oils and fats are very high so that their energetical use at present is uneconomic.

In contrast to this various qualities of waste fats are available which are either cheaper like fats which were used for deep-frying or difficault to dispose like used technical oils and fats of biological orign. This waste fats can be used as a fuel oil substitute if they are to a great extend free of impurities. This is to realize by previous processing.

Objective

The made investigations aimed to demonstrate the combustion of a processed waste fat in a standard steam generation plant and to prove lower emission values in comparison with the combustion of pure fuel oil. For that purpose a fat which was use for deep-frying was processed and burned.

Processing of Waste Fats

Before it can be burned the fat which was used for deep-frying is to processed. Especially several impurities like solids of different size, water and chlorides are to remove. Because of the dangers of

- mechanical blockage by solids
- disturbance of the combustion process by a free water-phase
- formation of chlorinated hydrocarbons by chlorides

it is necessary to save the following quality parameters

- solids: size <20 µm, content <0,05%
- water content <0,2%
- chloride content <0,0015%.

For that purpose a special method of processing was developed.

Choice of the Burner

Several combustion systems were analysed and the selected burner was tested. This special two phase burner is suitable to burn a mixture of previous processed fat which was used for deep-frying and EL fuel oil in a maximum ratio of 60 to 40.

Pilot Plant

To carry out detailed investigantions a pilot plant was designed and realised. This steam generation plant with a nominal heating power of 330 kW was installed in the OEHMI-Building to heat it and to produce warm water and steam.

The pilot plant is a standard steam generation plant which was completed with the chosen burner and equipments to preheat the processed waste-fat and to store it.
The pilot plant is operated since December of 1992. It works stable and undisturbed. Depositions or pollutions inspecially in the head of the burner didn't appear.

Emission Values

Over a period of more than 4 months the emission values were measured. The table shows that all emission values in the case of the combustion of a mixture of waste fats and fuel oil are lower than the admissible values.
In comparison with the combustion of pure fuel oil little higher values of NO_X-emissions and clear lower values of SO_2-emissions can be noticed.

pollutant	measure	emission values pure fuel oil	emission values mixture of processed waste fat and fuel oil	admissible emission values
O_2	Vol.-%	6,9	4,4	
CO_2	Vol.-%	10,3	12,1	
CO 1)	mg/m^3	-5	-5	<170
NO 1)	mg/m^3	130	147	
NO_2 1)	mg/m^3	8	6	
NO_X 1)	mg/m^3	212	226	<250
SO_2 1)	mg/m^3	232	96	<330
dust 1)	mg/m^3			<80
soot number		0,5	0,5	<1

1) related to 3 Vol.-% O_2

View

To continue this works the following investigations are planned.

- Optimisation of the operation of the steam generation plant and proof of stable long-term operation.
- Proof of low emissions of nonlimited pollutions.
- Combustion of several other waste fats.
- Official recognition of processed waste fats as a "non standard fuel" under 4. BImSchV.

Summary

It is reported on experiences of operating a steam generation plant which is equipped with a special burner to the combustion of a mixture of processed waste fat which was used for deep-frying and EL oil fuel.
The investigations were supported by the federal ministry of food, agriculture and forest.

THERMAL AND BIOLOGICAL GASIFICATION

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Abstract

Gasification is being developed to enable a diverse range of biomass resources to meet modern secondary energy uses, especially in the electrical utility sector. Biological or anaerobic gasification in U.S. landfills has resulted in the installation of almost 500 MW_e of capacity and represents the largest scale application of gasification technology today. The development of integrated gasification combined cycle generation for coal technologies is being paralleled by bagasse and wood thermal gasification systems in Hawaii and Scandinavia, and will lead to significant deployment in the next decade as the current scale-up activities are commercialized. The advantages of highly reactive biomass over coal in the design of process units are being realized as new thermal gasifiers are being scaled up to produce medium-energy-content gas for conversion to synthetic natural gas and transportation fuels and to hydrogen for use in fuel cells. The advent of high solids anaerobic digestion reactors is leading to commercialization of controlled municipal solid waste biological gasification rather than landfill application. In both thermal and biological gasification, high rate process reactors are a necessary development for economic applications that address waste and residue management and the production and use of new crops for energy. The environmental contribution of biomass in reducing greenhouse gas emissions will also be improved.

Introduction

Through the gasification of biomass, a very heterogeneous material can be converted into a consistent intermediate that can be used reliably for heating, industrial process applications, electricity generation, and liquid fuels production. As received, biomass can range from very clean wood chips at 50% moisture, to urban wood residues that are dry but contaminated with ferrous and other materials, to animal residues, sludges, and the organic component of municipal solid waste (MSW). The process of gasification can convert these materials into carbon- and hydrogen-rich fuel gases that can be more easily utilized, often with a gain in efficiency and environmental performance compared to direct combustion of the biomass. If the biomass resource has less than 50% moisture content, it is usually gasified by thermal processes.

Biological gasification is generally applied to moist feedstocks for which the drying energy requirement would be too large to justify thermal gasification. By reforming and purifying the gases produced from biomass, synthesis gases can be manufactured and used to produce liquid fuels such as methanol, gasoline, and diesel, or can be used to manufacture synthetic natural gas, ammonia, or hydrogen. Figure 1 summarizes the pathways that can be followed from a range of biomass resources including MSW streams that have been processed in an MRF (materials recovery facility) to remove the non-organic fractions. There is an inherent flexibility in the use of medium-energy-content (15-25 MJ/Nm^3) gases because they can be used for power generation in relatively unmodified engines and in gas turbines, as well as for chemical applications that include upgrading to synthetic natural gas (SNG) and liquid fuels such as methanol.

Thermal gasification is based on the use of a gasifying agent and heat generated either in situ in the gasifier (the autothermal case) or externally (the allothermal case) to convert the biomass into a mixture of fuel gases. Depending on the gasification agents, and whether or not the process is auto- or allothermal, the product gas can be either a low-energy-content gas with about one-eighth of the volumetric heat content of natural gas (37 MJ/Nm^3) or a medium-energy-content gas with about 50 ± 10% of the natural gas equivalent heating value.

Biological gasification takes place through the action of microorganisms and enzymes in a process known as anaerobic digestion, which primarily produces a mixture of methane and carbon dioxide, again with a medium heating value. In both biological and thermal gas production, the gas contains some contaminants that may have to be removed before use, either to protect the environment or to protect the downstream processing step.

Gasification processes form the core of the discussion in this paper with only limited attention given to applications. This focus is appropriate because one of the objectives of modern gasification research is to demonstrate that gasification is the key transformer between the primary biomass resource and the major secondary energy forms for which universal tertiary end uses are already in place. This is in contrast to past work, which pursued the production of "producer gas." One of the most important recent strides made in the thermal gasification field is the current level of development in combined Rankine and Brayton cycles for power generation, known as IGCC (Integrated Gasification Combined Cycle, see Figure 2). IGCC technology offers potential biomass-to-electricity conversion efficiencies of greater than 40%. The potential for the production of SNG from medium-energy-content gas has been demonstrated at a commercial scale for coal (Delaney and Mako 1988). Mills (1993) has recently reviewed the potential for producing liquid fuels from syngas produced from medium-energy-content gases.

The major fuel gases produced in thermal gasification are methane, hydrogen, and carbon monoxide; the biological route produces primarily methane. The heating values of these gases as pure compounds are shown in Table 1.

Table 1. Heating Values of Fuel Gases

	HHV[a]	LHV[b]	HHV[a]	LHV[b]
Gas	Btu/ft^3 [c]		MJ/Nm^3 [d]	
Hydrogen	325	275	12.10	10.20
Carbon Monoxide	322	322	11.99	11.99
Methane	1013	913	37.82	33.93
Ethane	1792	1641	66.76	61.00
Propane	2590	2385	96.52	88.70
Butane	3370	3113	127.04	117.12

[a] Higher heating value

[b] Lower heating value

[c] Standard Temperatures and Pressure of dry gas are 60°F and 30 in. Hg. (*Chemical Engineer's Handbook*, 1973)

[d] Converted at 4.1868 kJ/m^3 = 1 kcal/m^3 to the conditions of 288.15 K and 101.325 kPa (ASTM D - 1071-78).

Note: Conversion factors 1 mJ/m^3 at 288.15 K and 101.325 kPa. $\rightarrow$26.8962 Btu/ft^3 at 60°F and 30 in. Hg. Inverse 1 Btu/ft^3 at 60°F 30 in. Hg $\rightarrow$ 0.0372 MJ/m^3.

Gasification applications split very easily into applications for industrialized countries and those for rural and developing country use. For industrialized countries, applications tend toward converting the biomass into a secondary energy form, such as electricity or a liquid fuel (or natural gas for pipelines), which is distributed to the end user along with the same energy carrier generated from petroleum or coal resources. The scale of the process then tends to be large with, for example, proposed electricity generation from IGCC processes accepting biomass inputs of 1000 t d^{-1} or approximately 250 MW$_{th}$. Similarly, anaerobic digestion is tending toward units with fermentation volumes exceeding 500 m^3. In rural and developing countries, the scales discussed or in use are closer to 1-20 MW$_{th}$ of thermal gasification input and fermentation digester volumes of 1-10 m^3. Although the scientific basis of the technology is unchanged, it is clear that the engineering challenges and the economic frameworks are vastly different.

The Science and Technology of Gasification

Thermal Gasification

Biomass gasification is normally a combination of two thermochemical processes: partial oxidation and pyrolysis, as shown in Equations 1 and 2.

$$\text{Biomass} + O_2 \Rightarrow CO + H_2 + CO_2 + H_2O + \text{heat (partial oxidation)} \quad (1)$$

$$\text{Biomass} + \text{heat} + \text{steam} \Rightarrow CO + H_2 + CH_4 + \text{(tars and char) (pyrolysis)} \quad (2)$$

The partial oxidation step generates heat that is used to drive the pyrolysis reaction. Authothermal reactors are described as being either air blown or oxygen blown. In the allothermal case, an external heat source is used to drive the pyrolysis reaction, although this may be derived from either the char or the fuel gas generated in the gasifier.

At small scales, moving bed authothermal gasifiers are often used, and are described as updraft or downdraft in the literature (Overend 1982). At larger scales, the predominant technology is based on fluidized bed reactors. In the last 20 years, it has gradually been recognized that biomass is not coal! In fact, the key difference can be seen in the proximate analyses of biomass and coal in Table 2, where the volatile matter is defined as that amount of weight loss under prescribed conditions such as those described in ASTM D 3175-77.

Table 2. Proximate Fuel Analyses

Fuel Type	Ash Content (%)	Moisture (%)	Volatiles (%)	Heating Value[a] (MJ/Nm^3)
Anthracite	7.83	2.8	1.3	30.93
Bituminous high grade	2.72	2.18	33.4	34.46
Bituminous low grade	26.88	10.88	32.6	18.0
Sub-bituminous	3.71	18.41	44.3	21.24
"Wood"	1.0	20.0	84.9	18.6
Paper	1.01	5.8	83.9	16.9

[a] High heating value on a moisture- and ash-free basis.
Source: Domalski et al. 1978.

The rapid pyrolysis of biomass materials and the very high reactivity of biomass-derived chars result in a very significant reduction in the typical temperatures needed for biomass gasification compared with those needed for coal. For example, the typical temperatures of coal fluidized bed gasifiers are in the neighborhood of 1000°C, and the residence time of the coal in the gasifier varies with the coal from 0.5-3.0 h. Temperatures needed for wood gasification are 850°C and residence times range from 30 s to 5 min. The raw gas produced is usually "dusty" and "tar-laden" and, if the gas is not to be used in a direct coupled manner to a burner, these contaminants have to be removed by filtration, scrubbing, or catalytic destruction.

The efficiency of gasification is quite high, with cold gas efficiency values of 75% to 85% (energy in cold gas/energy in biomass feed) being easily obtained both at small and large scales.

Thermal Gasification Technology

Small Scales: < 1 MW_{th}

Air gasification to provide fuel for engines has a long history, starting with the so-called suction gas engine and gasifier sets in the early part of the twentieth century. The gas was generated by the engine drawing air through a fuel bed in either the up- or downdraft mode to produce a low-energy-content gas (4-5 MJ/Nm^3) known as producer gas. Using either wood or charcoal as the fuel, this concept was widely used in mobile applications during the World War II fuel shortages in many countries. The energy crises of the 1970s rekindled interest in the technology as a means of aiding developing and rural areas (National Academy of Sciences [NAS] 1983). In this period, many gasifiers were put in the field and large-scale manufacturing took place in Brazil (Furtado and Zeferino 1989) and India (Jain 1989; Dayal et al. 1989). However, many of the units rapidly fell into disuse as fuel prices returned to normal and the deficiencies of the technologies became apparent. The World Bank performed field monitoring to identify the problems that were causing the failures (Mendis et al. 1989a,b). Recent experience in India shows that the ASTRA technology, which uses diesel engine generator sets of about 20 kW_e, is indeed viable as demonstrated over four years at Hosahalli, a non-electrified village in South India (Ravindranath 1993).

Small-scale thermal applications of gasification can be found in the direct firing of small boilers. Another interesting application in use in China's rural areas is a crop-residue gasifier cooking stove with an input fuel rate of 20 kW_{th}, which effects fuel savings of more than 50% over traditional stoves (Biomass Users Network 1992).

Large-Scale Gasification Technology

At last count, there were more than 30 different gasifier types being manufactured at different times by commercial companies. Figure 3 shows the pressure versus scale of operation scoreboard for 16 different gasifiers; some were experimental units that are no longer running and some are under construction or are projected. Interestingly, all the units shown are variations on fluidized bed gasifiers, with the exception of the Bioneer unit. The Bioneer is a very successful air-blown fixed-bed updraft unit commercialized in Finland during the 1980s. Eight units are in use in Sweden and Finland, mostly serving small district heating plants that produce about 5 MW_{th} output. The gasifiers are directly coupled to boilers and are very automated (Kurkela et al. 1989).

However, the two most important goals of large-scale gasification are the production of electricity and the production of liquid fuels. The electricity production route under development is the IGCC, in which biomass is gasified and the gas combusted in a gas turbine. The exhaust from this process is transferred to a heat recovery steam generator (HRSG) to generate electricity through the combination of the Brayton gas turbine cycle and the Rankine steam cycle (see Figure 2).

The efficiency of electricity generation with such systems is projected to be as high as 45%. Efficiencies of first generation plants, however, are more likely to range from 33% to 38% in the near future because industrial turbines with both lower turbine inlet temperature capabilities and lower pressure operation will be utilized. Paisley et al. (1992) analyzed the use of the Battelle Columbus Laboratory (BCL) indirect gasifier in an IGCC cycle in both low- and high-pressure variants. They found that the low-pressure unit would produce 56 MW_e power output and achieve an overall efficiency of 32.4%, and the high-pressure unit would produce 62.5 MW_e power output and achieve an efficiency of 36.2% with a daily input of 818 $t\ d^{-1}$. The low-pressure case was based on readily available quench gas cleaning technology; the high-pressure cycle utilized a high-temperature gas filtration unit to ensure a clean gas flow to the turbine. The latter is still under development. The goal, however, is to use highly efficient aeroderivative turbines with high-pressure gasifiers (Williams and Larson 1992), both in IGCC and steam-injected gas turbine (STIG) modes of operation. The BCL study found that the use of an aeroderivative turbine (a GL 6001) would increase the efficiencies to 38% (Paisley et al. 1992). Williams and Larson (1992) have noted the potential for a very large-scale increase in electrical power production if IGCC and gasifier STIG combinations used sugar cane bagasse in combined heat and power applications in the world's sugar industries. The application of black liquor gasification in the pulp and paper industry would increase the electrical power output of that industry by a factor of two over the current recovery boiler systems.

Commercialization of Thermal Gasification

Currently, there are several commercialization activities under way in North America, Brazil, and Scandinavia. Three prominent developments are described in the following sections to give some idea of the current scale of the technology and of how close it is to being ready for commercial implementation.

The World Bank Global Environment Facility Gasifier Project in Brazil

This major project is funded by the World Bank's Global Environment Facility (GEF). The funding is in two increments: the first phase, $7 million, will cover the selection of a gasifier and turbine system and will lead to the second phase, which is the construction of the gasifier turbine in Northeast Brazil. Funding for the second phase is $23 million or 50% of the capital cost, whichever is less. The purpose of the funding is to compensate the developers for a first-of-its-kind 20- to 30-MW installation so that the effective cost of the installed kW to the developers is in the range of the 1500 $/kW anticipated for the N'th plant. The actual cost is, of course, closer to double that.

Shell International (London) is providing the leadership for the first phase. After a preliminary study, the project team has elected to create a competition between two Swedish designs: a low-pressure option with TPS and a high-pressure option with Bioflo. After design studies by both companies, project representatives will select one to go forward as the GEF scaleup.

The designs of both systems are based on a circulating fluidized bed (CFB). The low-pressure system will have a fluidized-bed, dolomite-filled, tar-cracking reactor, followed by some heat recovery, so that particulates will first be trapped in a fabric baghouse filter arrangement operating at 180°C. The gases then will be passed to an aqueous scrubber and compressed and fired in the LM 2500 GE aeroderivative turbine.

The high-pressure system has a pressurized CFB by Ahlstrom (Finland) and will have an unspecified hot gas cleanup system that leads to an LM 2500 GE aeroderivative turbine. Sydkraft and Ahlstrom have formed a joint venture, Bioflo, to develop such systems.

The second phase of the GEF-Brazil activity will take place in Brazil with a consortium composed of two utility companies (Brasep and CHESF, the consortium leader); Electrobras; CIENTEC (a government research and development council); CVRD (an iron and steel company); and Shell (Brazil).

The Värnarmo Bioflo Project

In Sweden, the Bioflo company is undertaking the first example of the application of IGCC concepts to biomass. The small IGCC station will have an overall efficiency of 83% because it is a combined heat and power installation. It will generate 6 MW_e from the combined cycle and supply 9 MW_{th} to the town's district heating system (Anon 1993a,b).

The Pacific International Center for High Technology Research (PICHTR) Project

The U.S. Department of Energy (DOE) and the State of Hawaii have joined with PICHTR in a cooperative project. The objective is to scale up the pilot development unit (PDU) Institute of Gas Technology (IGT) Renugas™ pressurized air/oxygen gasifier to a 45-90 tonnes/day engineering development unit (EDU) operating at 1-2 MPa using bagasse and wood as feed. Other participants in the project are IGT, the Hawaii Natural Energy Institute (HNEI), the Hawaii Commercial and Sugar Company (HC&S), and the Ralph M. Parsons Company, the architectural and engineering firm for the project. The site is the HC&S sugar mill at Paia, Maui, Hawaii. The National Renewable Energy Laboratory (NREL) is providing project oversight in addition to systems analysis.

The scaleup will be completed in several stages. The first phase, which is now under way, consists of the design, construction, and preliminary operation of the gasifier to generate hot, unprocessed gas. The gasifier is being designed to operate with either air or oxygen at pressures up to 2.2 MPa, at typical operating temperatures of 850°-900°C. In Phase 1, the gasifier will be operated for about four months at a feed rate of 45 tonnes/day at a maximum pressure of 1 MPa. Following the end of Phase 1 in mid 1994, a hot gas cleanup unit and gas turbine will be added to the system to generate 3–5 MW of electricity. In this phase, the gasifier feed rate will be

90 tonnes/day, and the system will operate at pressures up to 2.2 MPa. In Phase 3, the system will be operated in an oxygen-blown mode to produce a clean syngas for methanol synthesis in addition to producing electricity. The project is in the final stages of environmental permitting and detailed design for Phase 1.

Anaerobic Digestion

Anaerobic digestion has been used for many years in the treatment of sewage and animal manures to mineralize as much of the carbon content as possible in order to reduce the volume of waste sludge for disposal (McCarty 1982). Because the gases evolved are usually a mixture of methane and carbon dioxide in a ratio of approximately 60:40, they can be used as fuel. The anaerobically treated residues are sometime used as a soil amendment, provided that the process did not receive any waste streams contaminated with heavy metals. The anaerobic process utilizes methanogenic bacteria that are some of the oldest known natural bacteria, and, accordingly, are described as belonging to the class Archeabacteria (Daniels et al. 1984). Their ubiquity is such that in any circumstances where oxygen is absent (anoxia) and an organic substrate is available, they will thrive and produce methane. In nature, this can include sediments at the bottom of lakes and estuaries; in swamps, fens, and peat bogs; and in landfills where MSW is buried. The bacteria also exist in the stomachs of ruminant animals, generating estimates that cattle and other herbivores cause 10%–20% of global methane emissions (a greenhouse gas) to the atmosphere (Cicerone and Oremland 1988; Anon. 1989; Moss 1992). They are also the source of "gas" in the human digestive tract (van den Berg 1980) and, not surprisingly, reside in the colon of most mammals.

The Process of Anaerobic Digestion

The anaerobic digestion process takes place through the synergistic action of a consortium composed of four different types of microorganisms: hydrolytic, fermentative, acetogenic, and methanogenic bacteria, shown in Figure 4. Numerous published reviews cover the level of understanding of the anaerobic digestion process and the terminal steps of methane production (Wolfe 1971; Mah et al. 1977; Zeikus 1977; Balch et al. 1979; Bryant 1979; Boone 1982).

The hydrolytic bacteria in these consortia use cellulase and other hydrolytic enzymes to depolymerize cellulose to simple sugars. Proteins, pectins, hemicellulose, and starches (if present in the feedstock) are also degraded enzymatically to produce soluble sugars, amino acids, and long-chain fatty acids. The fermentative bacteria in the acidogenesis stage convert these monomers mainly to organic acids, coproducing hydrogen and short-chain alcohols. The acids produced are often called volatile fatty acids or VFA, and consist primarily of propionic and acetic acid. The acetogenic bacteria convert alcohols and VFAs to hydrogen, carbon dioxide, and acetate, which the methanogens utilize to produce methane and carbon dioxide by two major pathways.

Anaerobic Digestion Applications

The biological process of anaerobic digestion has been used for centuries in the disposal of municipal sewage wastes (Metcalfe & Eddy, Inc. 1979; Environmental Protection Agency [EPA]

1979). The primary purpose of anaerobic digestion in treating sewage wastes is to reduce the organic content, volume, and odor potential of the sludge, and to reduce the concentration of pathogenic microorganisms. This organic waste stream is relatively dilute, and the overall effect of sewage treatment is to convert a water pollution problem into a solid waste disposal problem. However, because of the high level of water present, the anaerobic digestion process is typically carried out in conventional low-solids, stirred-tank reactor systems, with hydraulic retention times of several days to two weeks. These systems are large and require substantial energy inputs for heating and mixing. However, in the treatment of municipal sewage, system reliability and utility often outweigh process economics.

During the last two decades, a number of high-rate anaerobic treatment technologies have been developed that outperform the traditional stirred tank sewage treatment systems. These new technologies also extend the application of anaerobic treatments to high-strength food processing wastes and farm animal wastes. The key to these systems is that there is a very high concentration of anaerobic bacteria (either as sludge or in the form of fixed films), which is in intimate contact with the incoming feedstock. The incoming feedstock has a rather low hydraulic retention time of less than one day (Lettinga and van Handel 1992).

Adapting the principles of controlled anaerobic digestion to the treatment of the organic fraction of MSW is a promising solution to a long-term problem currently handled by landfill disposal. Several promising systems are being developed in Europe that separate the organic fraction of MSW and treat it in high solids reactors. These systems are competitive with traditional landfill methods in Europe (Fouhy 1993).

However, existing MSW landfills are among the largest anaerobic digestion systems and are increasingly being viewed as a source of energy. As concern about methane emissions increases, collecting methane from landfills is becoming an important greenhouse gas mitigation strategy; Bingemer and Crutzen (1987) have estimated that landfills probably account for 5%–18% of the methane released into the atmosphere.

Landfill Gas

Landfills are large, poorly mixed, and uncontrolled anaerobic digesters in which the organic wastes may take up to 50 years to "stabilize" (Rivard 1989). "Stabilizing" the wastes implies that they will no longer be biologically degradable. Unfortunately, during the period in which the wastes are degradable, they produce flammable gases. If not managed, these gases will migrate to the landfill's periphery and may cause fire and explosion hazards. In addition, they generate a leachate, if the cover is porous to rainfall, which contains many malodorous and possibly toxic intermediates. As a result, landfills are now being managed to recover the gas for either passive venting, flaring, or use in engines. In addition, new landfills are permitted only if they manage the leachate and gas problems. In May 1991, draft EPA regulations were published that require all landfills, both extant or proposed, to have gas collection equipment if their capacity is greater than 100 kt of waste and if they emit 150 tonnes of non-methane organic compounds.

The use of landfills for energy is quite extensive. Some projects collect gas and fire it along with a primary fuel in process heat applications such as brick firing and steam production. Others clean up the gas so that it is of pipeline natural gas quality and put it into the distribution network to generate electricity (Luning 1992). In 1991 there was an installed capacity from landfills of 438.1 MW_e, which generated 2.2 TWh (Edison Electric Institute 1992). Much of the capacity was initially installed using various tax incentives, but most of these incentives are no longer available. Capacity continues to be installed for both consumption on site and sale of electricity to the local utility or an industrial/institutional consumer.

Fuelco (Fuel Resources Development Co.), now Synhytech, has developed a novel application for landfill gas. The technology first converts the gas to a synthesis gas containing carbon monoxide and hydrogen, then passes this over an iron-based catalyst in a slurry reactor to produce a diesel fuel for transportation (Rowley 1990).

Despite the waste reduction resulting from recycling and other uses, some landfill component will always be included in the management of MSW. It is likely that the use of landfill gas will continue for many years at existing sites.

Slurry Digestion Systems

The requirements for controlled anaerobic digestion are relatively easy to meet. It is carried out at temperatures of 25° to 35°C using mesophilic bacterial consortia, or at a higher rate using thermophilic bacteria at 60°C, at pH values of 7–8 in the methanogenic phase, and at preferred feedstock carbon:nitrogen ratios of 16–20. In the classical application to animal manures, these criteria are easily met and have formed the basis for much of the technology development for other wastes and for energy systems for rural India and China. The technology of slurry digestion and the system design choices are well described in Pauss et al. (1987). Two of the same authors, Pauss and Nyns (1993), have recently surveyed the status of anaerobic digestion for the Commission of the European Community (CEC). They found significant growth in the use of slurry digesters in industrial applications and identified the technology as maturing, with experienced industrial suppliers active in both the CEC and elsewhere. The predominant agricultural slurry digester is the continuous stirred tank reactor (CSTR), but the Upflow Anaerobic Sludge Blanket (UASB) is much more important in industrial wastewater applications. In the rural and economic development context, such as in India and China, almost all of the digesters are CSTRs. The industrial waste applications are important and, while not economic in terms of energy; they are economic in terms of environmental control technologies. Slurry digestion is increasingly being proposed for energy crops such as herbaceous and woody species provided in dedicated feedstock supply systems (Clausen et al. 1979).

Biogas in Developing Countries

In both India and China, very large-scale implementation projects for biogas production from animal, human, and plant residue materials have been carried out for individual homes and villages. Smil (1983) has discussed the situation in China extensively and notes that although there has been large-scale deployment, the use of individual units has not been an overwhelming success—in part because most of the units were in Szechuan, which is climatically unsuited for year-round operation of biogas digesters. The small scale of the family digester, the unreliability of the single family's livestock in times of drought, and the relative difficulty of managing a complex biological process have contributed to a new perspective on biogas production since Smil's analysis. Currently, village-scale units are being developed that seem at first sight to offer much better energy and environmental performance, albeit at the cost of increased social organization to ensure success.

The analysis of the Pura Village system, which provides electricity both to homes and to a water supply, shows that decentralized village-scale systems are competitive with the grid in rural areas of India (Rajabapaiah et al. 1992). Electricity distribution and use is not the only strategy for the decentralized system. In an analogue to the Town Gas systems of Europe and America that were in use until natural gas was widely distributed, several proposed schemes would distribute the biogas to homes and industries. The Town Gas system distributed a medium-energy-content gas that was produced by coal gasification. In the proposed systems, a medium-energy-content gas from anaerobic digestion would be distributed by a small-scale local grid (Tasdemiroglu 1991). In either case, the economies of scale at the digester and waste-handling system levels demonstrate that distribution is far superior to individual unit operation.

High Solids Digestion Systems

The anaerobic bioconversion process for solid wastes, including MSW, must take into account the economics of competing technologies for solid waste disposal. Incineration and landfilling will continue into the near future, with additional changes being made to meet more stringent environmental mandates. Potentially, similar requirements will be dictated for any disposal process, including those involving biological treatment. Biological treatments, although desirable in their natural sense of carbon cycling and coproduct production (compost), are often time consuming. Insufficient contact time for microbial biodegradation, especially for cellulose, results in incomplete digestion, which reduces the net energy production and compost product quality. Conventional low solids anaerobic fermentation systems have been used successfully in the digestion of biomass, animal manures, and MSW (Clausen et al. 1979; Jewell 1980; Isaacson et al. 1987). However, because of the relatively slow conversion rates and long contact times, these reactor systems are large and capital intensive.

The RefCom Project in Pompano Beach, Florida, was a pioneer project in the slurry treatment of MSW. DOE funded this project, which was based on studies by the University of Illinois at Urbana-Champaign and the Dynatech R&D Co. of Cambridge, Massachusetts. The project was operated intermittently during the period from 1978 to 1985. The 100 t d^{-1} system sorted and processed the organic fraction to two large-capacity CSTR digesters of about 1250 m^3 capacity. Although it was not economically successful, RefCom confirmed the technical feasibility of sorting and recycling MSW with anaerobic digestion of the easily hydrolyzable organic fraction (Isaacson et al. 1987).

Economic Criteria for Solid Waste Process Development

In preliminary economic evaluations of anaerobic digestion processes for producing fuel gas from solid wastes, reactor capital costs were identified as an important cost factor. If the reactor volume could be reduced significantly and power use maintained or decreased, the economics of the anaerobic digestion process would improve. Increasing the solids concentration within the reactor would be particularly beneficial in this respect because a decreased reactor volume is possible while maintaining the same solids loading rate and retention time. However, high solids slurries are very viscous and resemble solid materials more closely than typical fluids. Therefore, conventional mixers such as those employed in CSTR systems do not ensure homogeneity within the reactor, and problems develop in providing adequate dispersion of substrate, intermediates, and microorganisms while minimizing power requirements.

The Technology of High Solids Digestion Systems

High solids anaerobic bioreactor technology development has employed a variety of designs including non-mixed (or packed) batch-operated reactors (generally with liquid recycle, [Ghosh 1985; Goebel 1983; Hall et al. 1985; Jewell 1980; Lin 1983; Molnar and Bartha 1988; Snell Environmental Group 1983; Wujcik and Jewell 1979]) as well as mixed or partially mixed reactor designs (Begoven et al. 1988; de Baere and Verstraete 1984; Gaddy and Clausen 1985; Goldberg et al. 1981). In general, mixing has been viewed as a requirement for effective anaerobic fermentation as a means of increasing the accessibility of the consortium to the substrate. In conventional low solids systems, various agitation systems, including impeller agitators, recirculating pumps, and gas injection, have been used successfully in the anaerobic treatment of municipal sewage. However, low solids mixing systems must be modified substantially in order to obtain mixing at high solids levels.

The use of packed bed systems operated in a batch mode is enhanced with a passive mixing system involving the recycle of free liquid (see Figure 5). These systems may approximate semi-continuous operation by using staged operation as in the Sebac process (O'Keefe et al. 1993). The passive mixing of solids through pumping action is demonstrated through the use of the biofunnel (see Figure 6), in which material must flow over an expanding bed (Goldberg et al. 1981). However, the biofunnel requires the use of lower solids materials to ensure a minimum level of plasticity for effective movement of materials within the reactor system (i.e., <13%). The Valorga system utilizes gas mixing to develop zones of mixing similar to low solids "air-lift" fermentation systems (see Figure 7). However, mixing high solids materials with gas injection requires substantial pressures (i.e., 8 bar overpressure). Materials flow through the system based on a central baffle and removal is enhanced by operating the reactor at slight overpressure. Mechanical mixing of high solids materials may also be achieved using either internal or external mixers. The Dranco system uses external mixing of most of the sludge with a smaller amount of fresh feed and reintroduction to the unmixed reactor to accomplish external mixing (see Figure 8). The NREL high solids system utilizes a conventional internal mixer similar to a pug-mill to provide mixing in a horizontally positioned reactor (see Figure 9). All of these designs affect in some way the fermentation efficiency, capital costs, operating and maintenance costs, and overall process complexity. Additionally, with at least one mixing system, the biofunnel, the level of solids is limited for effective movement of materials within the reactor.

The mixing systems described are representative of selected designs for mixing high solids materials. Representative data from these systems are listed in Table 3 for comparison with conventional low solids systems. This review of fermentation data is limited to systems

Table 3. Analysis of High Solids Reactor System Fermentation Performance with a Conventional Low Solids System

System	Solids (% sludge)	Temp. (°C)	RT (d)	Scale	OLR kg VS/m^3•d	CH_4 Yield SCM/kg VS added	Reference
CSTR	2.7–6.3	60	6–27	2 × 1274 m^3	3–9.6	0.13–0.30	Issacson et al. 1987
Packed Bed	30–40	35	90	0.5 m^3	1.12	0.21	Ghosh 1984
Dranco	30–35	50	20	56.6 m^3	16	0.28	deBaere et al. 1987
Valorga	35	37	15	400 m^3	15	0.2	Bonhomme 1987
NREL	28–35	35	14–20	0.02 m^3	18.5	0.33	Rivard 1993

operated on RDF (refuse derived fuel) feedstocks. RDF is a mixed residential waste that has been size-reduced and subjected to a separation process to remove inert materials and plastics.

The data indicate that when using an RDF as the feedstock, organic loading rates on the order of 15-19 kg VS/m^3 • d may be achieved while operating the anaerobic fermentation at sludge total solids levels exceeding 30%. The data for the high solids systems, including Dranco, Valorga, and NREL, are comparable with the exception of methane yield.

Several conclusions may be drawn about the advantages that high solids operation afford to the anaerobic process. When comparing low solids systems to a representative high solids system, significant advantages in relative reactor size are gained by reducing the level of process water, thus increasing the sludge total solids. Additionally, the high solids system is capable of significantly higher organic loading rates while maintaining overall anaerobic bioconversion yields, which further reduces the required size of the reactor system. The combination of reduced process water content within the reactor and increased organic loading rate is shown in Figure 10. This combination effects a dramatic reduction in the size of reactor needed to treat the same volume of waste, compared to the conventional low solids reactor system.

Conclusions

Gasification technology is now reaching the marketplace as part of systems that generate secondary and transportable energy forms. The thermal gasification processes for biomass are emerging from previous attempts to treat biomass as rather poor coal. As a result, high-throughput systems are being scaled up to the engineering scale. Biological gasification nearly always has a dual function, meeting environmental needs as well as generating energy. One of the most promising applications of anaerobic digestion is in the mixed treatment of dilute organic wastes in conjunction with the organic fraction of MSW in engineered systems. However, despite the extensive RD&D of the last two decades, the largest biomass gasification source remains landfill gas. The potential market for products from medium-energy-content gas (such as is produced in oxygen-fed authothermal gasification, allothermal systems, or by anaerobic digestion) is far greater than that for low-energy-content gas from air gasification, which is likely to be limited to uses such as IGCC and direct firing of processes. The medium-energy-content gases can be converted to SNG, ammonia, and liquid fuels, in addition to their applications in electricity production.

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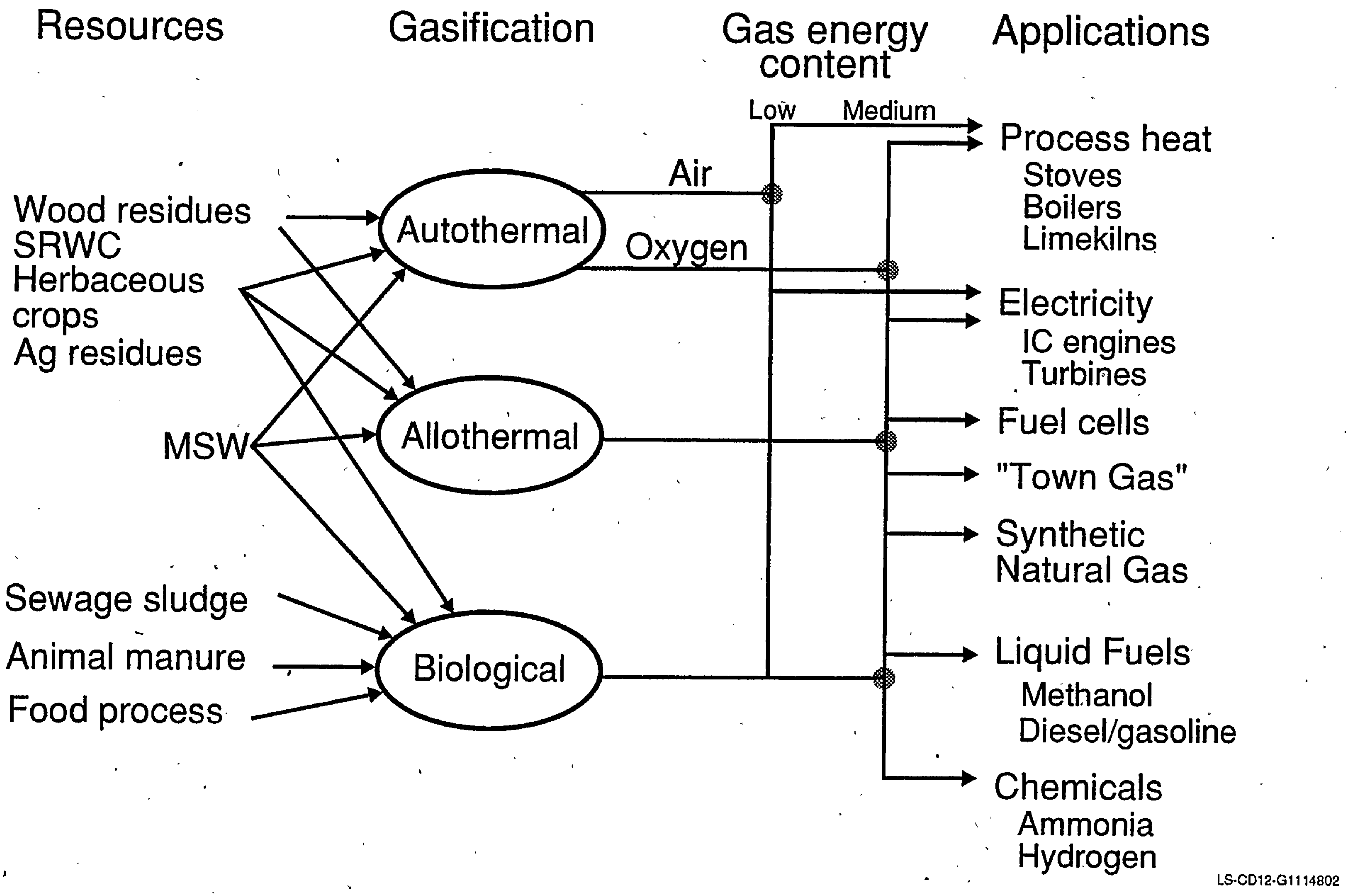

Figure 1. **Gasification pathways**

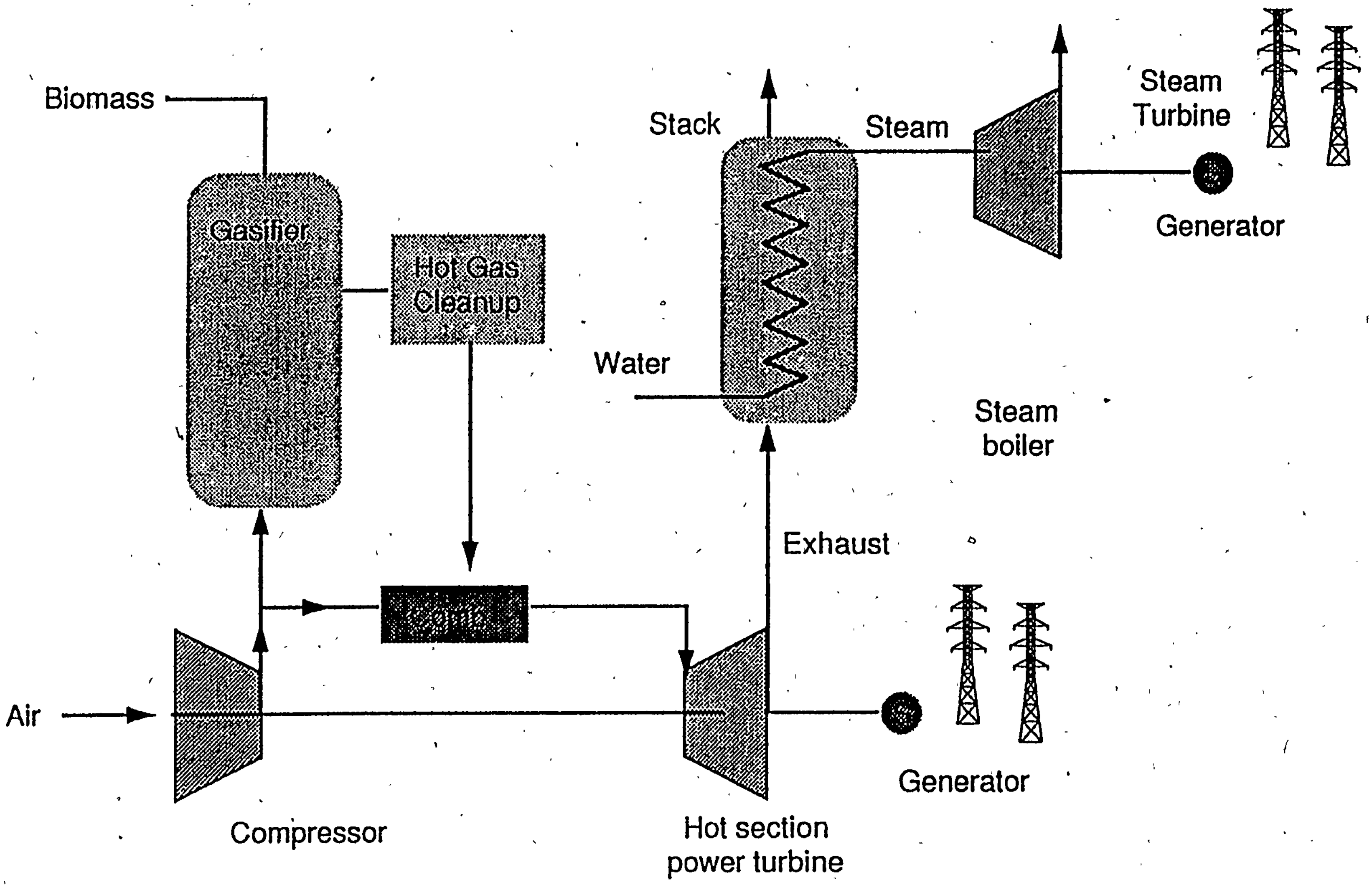

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Figure 2. Integrated gasifier combined cycle (IGCC)

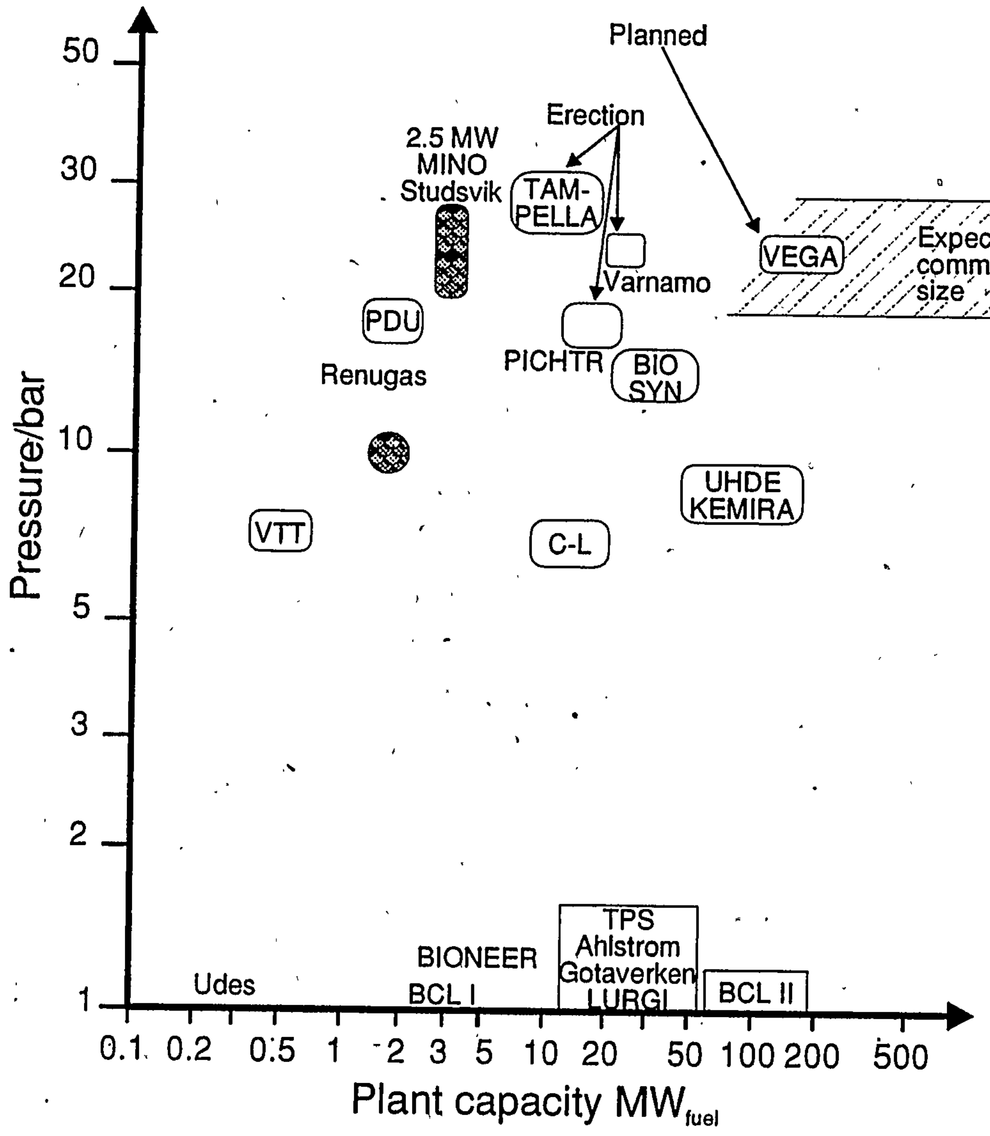


Figure 3. **Gasification performance map**

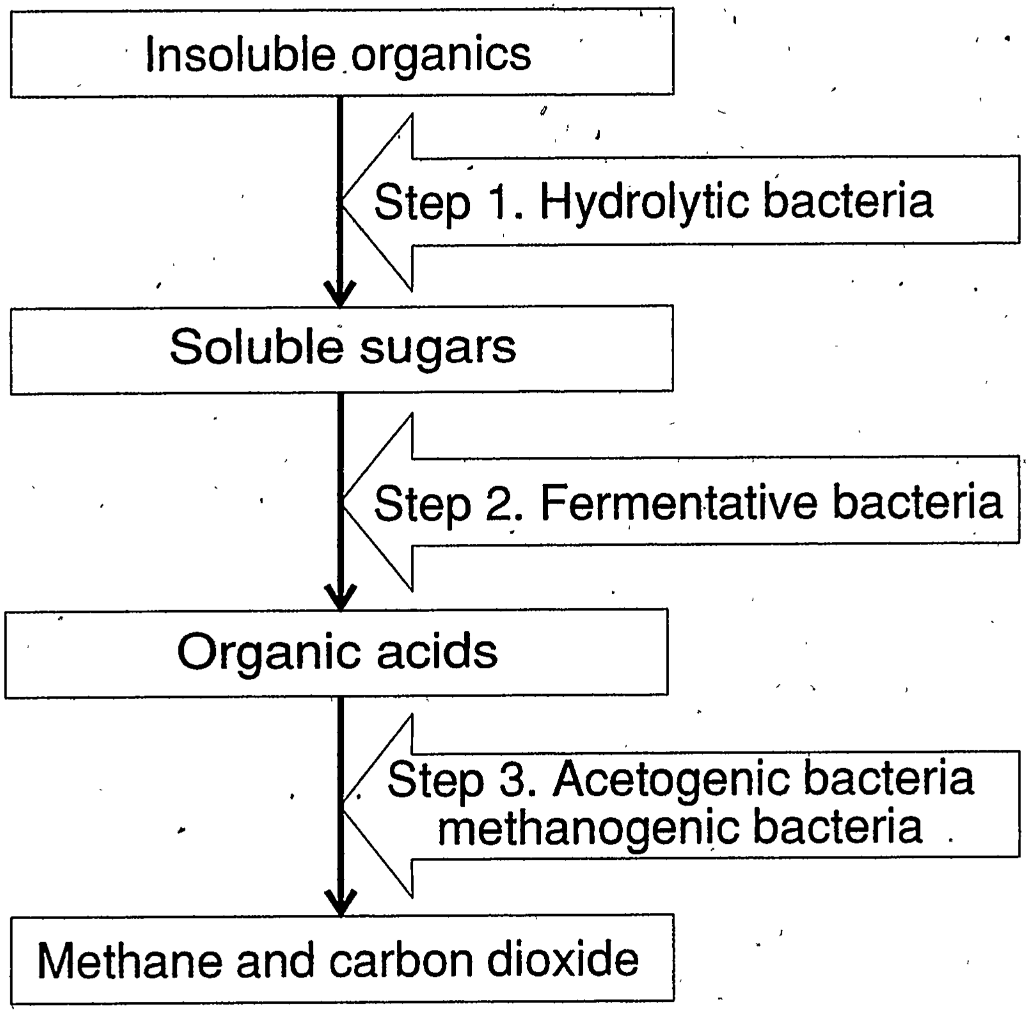


Figure 4. **Biological pathway for anaerobic digestion**

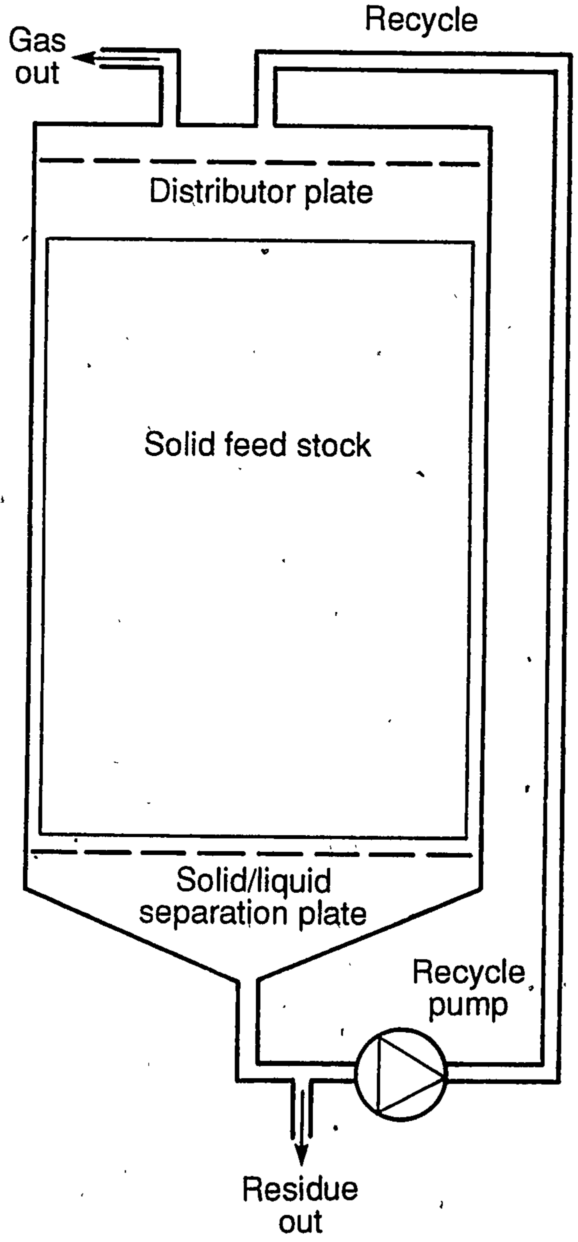


Figure 5. **Packed bed system**

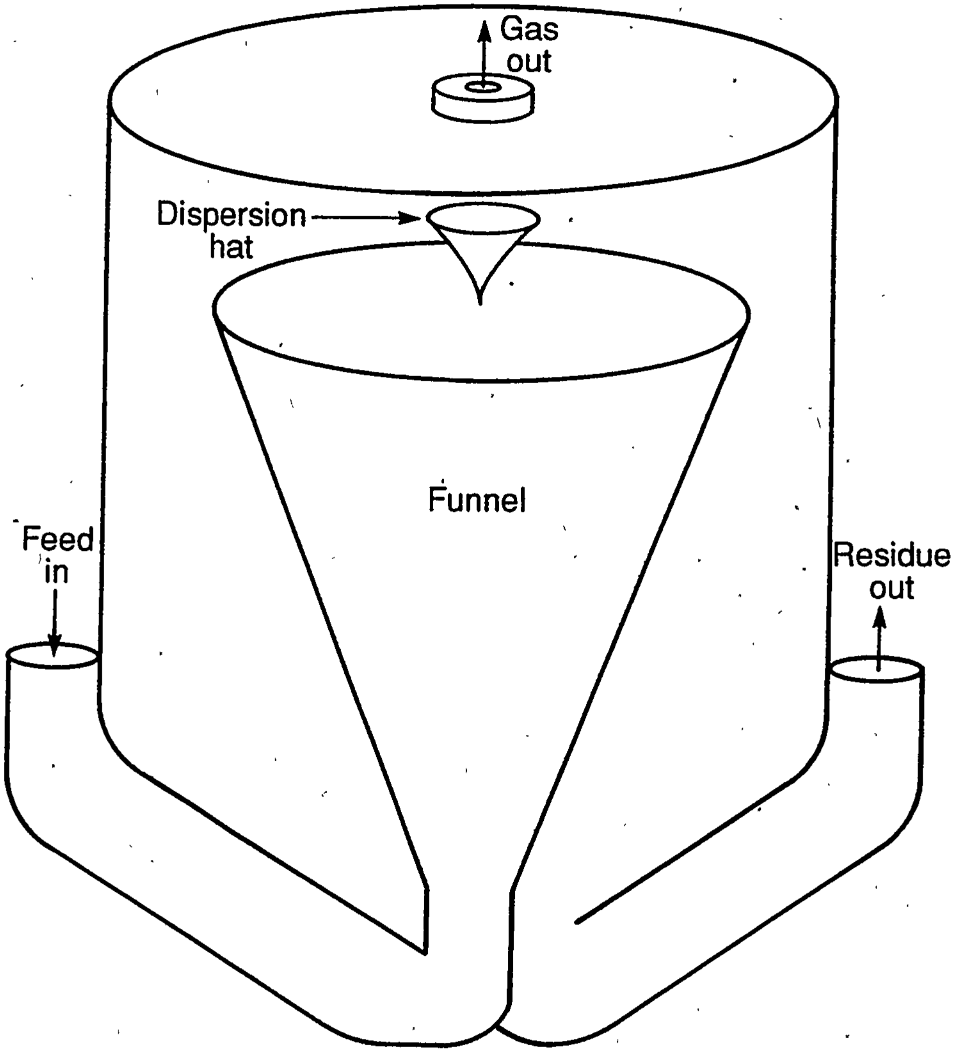
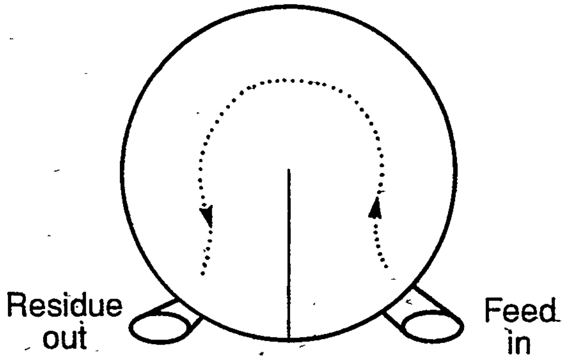


Figure 6. **Biofunnel system**



Plan view of solids movement

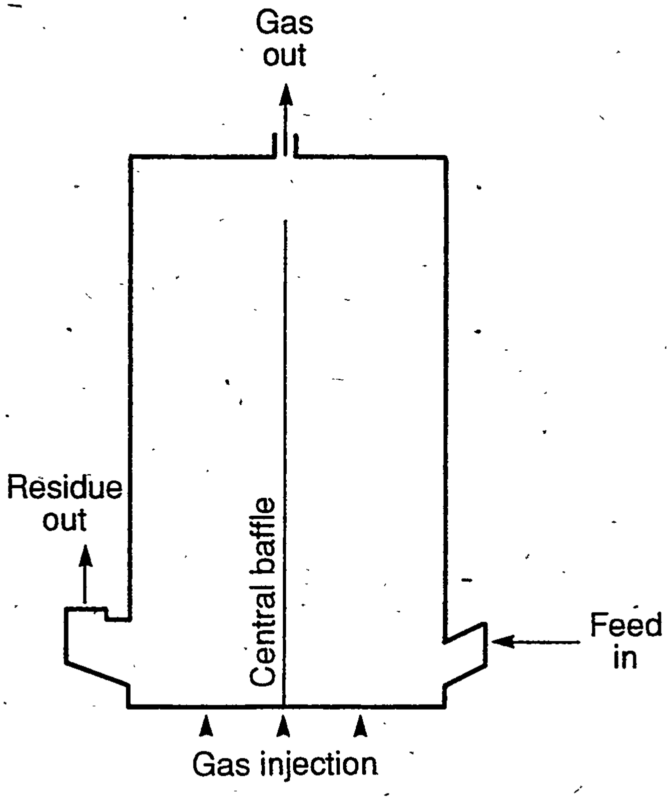


Figure 7. **Valorga system**

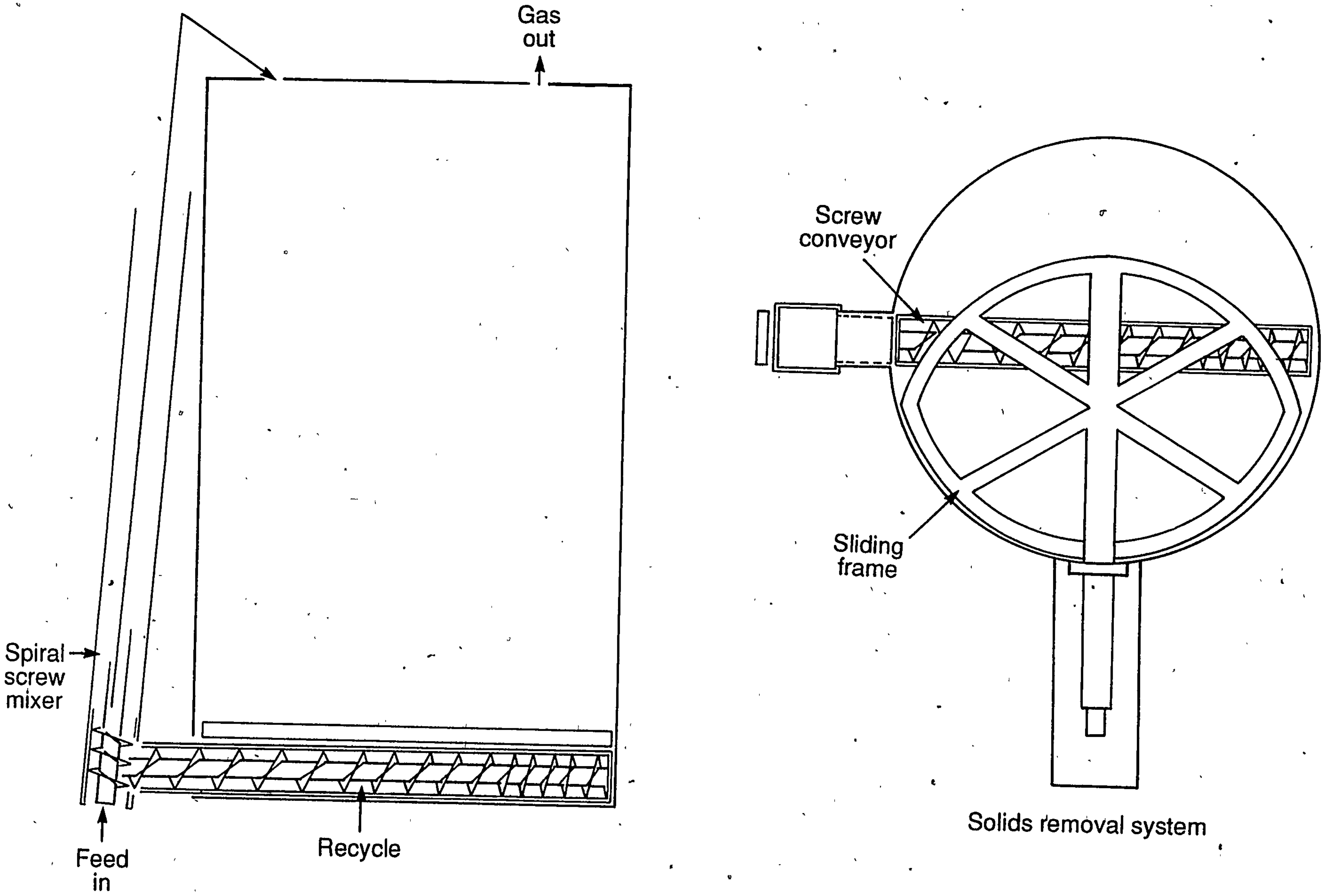


Figure 8. Dranco system

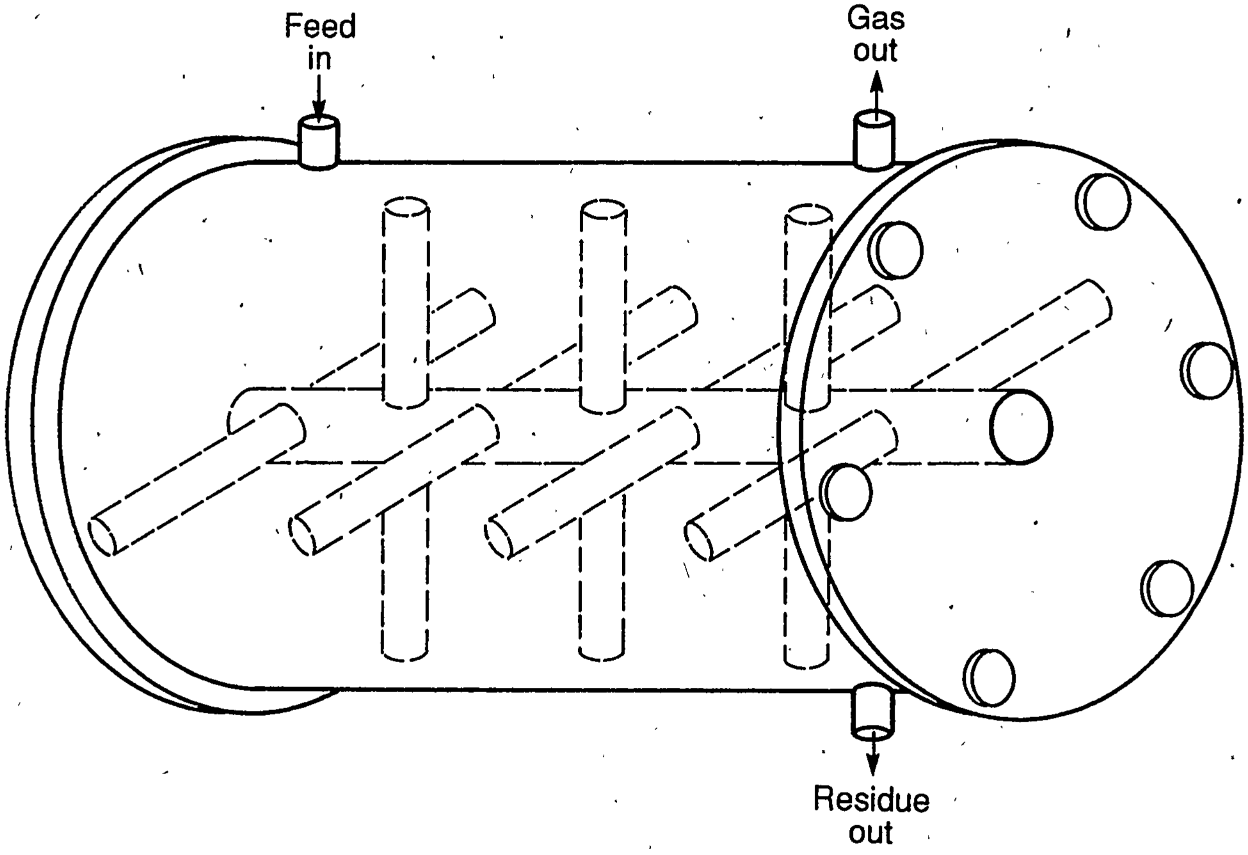


Figure 9. Mechanically mixed system

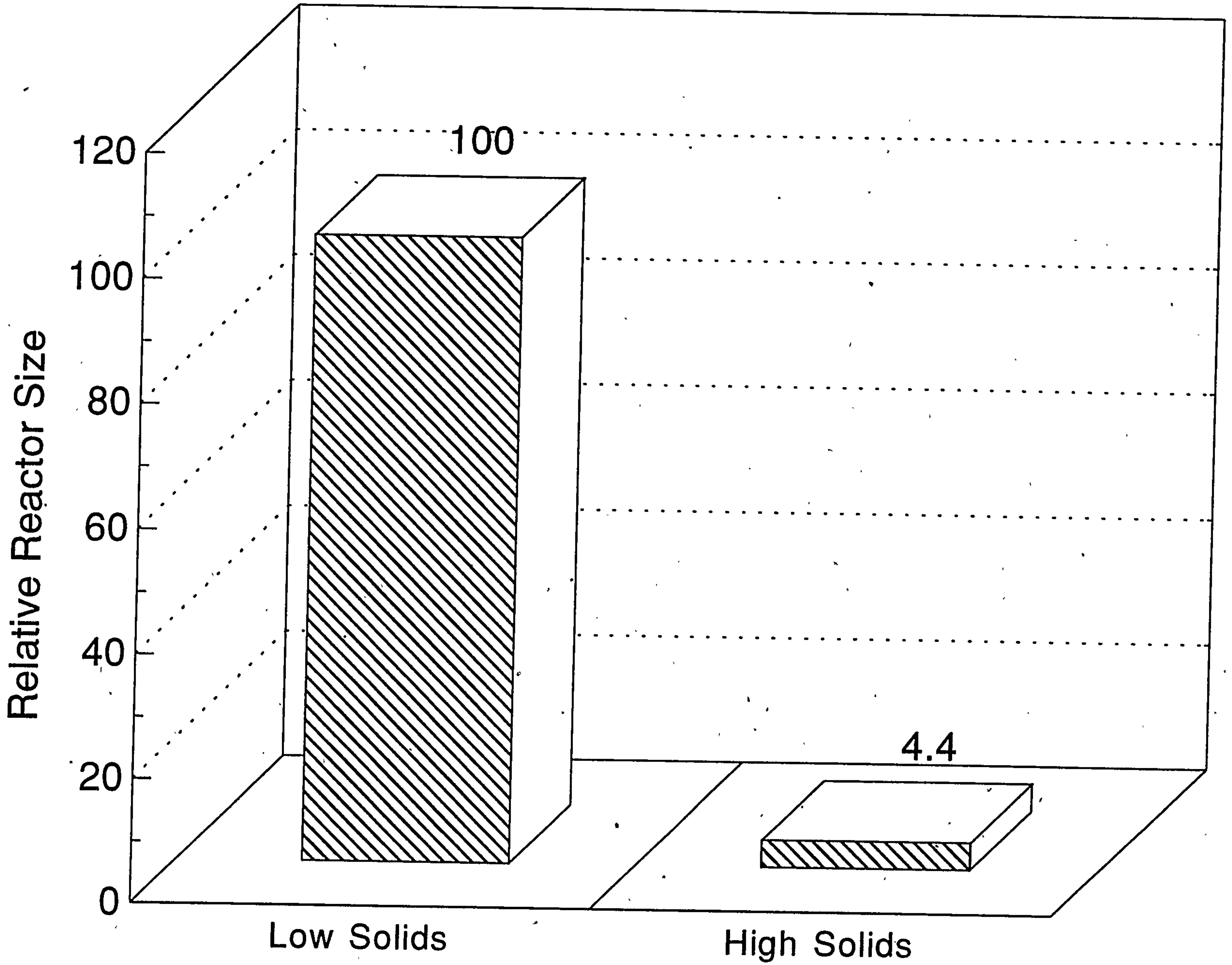


Figure 10. Combined effects of high solids and enhanced rates on relative reactor size

Pilot Scale Testing of Biomass Feedstocks for use in Gasification/Gas Turbine Based Power Generation Systems

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Abstract

A biomass gasification pilot program was performed at the GE Corporate Research and Development Center using two types of biomass feedstock. The object of the testing was to determine the properties of biomass product gas and its' suitability as a fuel for gas turbine based power generation cycles. The test program was sponsored by the State of Vermont, the U. S. Environmental Protection Agency, the U. S. Department of Energy and Winrock International/U. S. Agency for International Development.

Gasification of bagasse and wood chip feedstock was performed at a feed rate of approximately one ton per hour, using the GE pressurized fixed bed gasifier and a single stage of cyclone particulate removal, operating at a temperature of 1000 F. Both biomass feedstocks were found to gasify easily, and gasification capacity was limited by volumetric capacity of the fuel feed equipment. The biomass product gas was analyzed for chemical composition, particulate loading, fuel bound nitrogen levels, sulfur and alkali metal content.

The results of the testing indicated the combustion characteristics of the biomass product gas are compatible with gas turbine combustor requirements. However the particulate removal performance of the pilot facility single stage cyclone was found to be inadequate to meet turbine particulate contamination specifications. In addition, alkali metals found in biomass based fuels, which are known to cause corrosion of high temperature gas turbine components, were found to exceed allowable levels in the fuel gas. These alkali metal compounds are found in the particulate matter (at 1000 F) carried over from the gasifier, thus improved particulate removal technology, designed specifically for biomass particulate characteristics could meet the turbine requirements for both particulate and alkali loading.

The paper will present the results of the biomass gasification testing and discuss the development needs in the area of gas clean-up and turbine combustion.

Pilot Scale Testing of Biomass Feedstocks for use in Gasification/Gas Turbine Based Power Generation Systems

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Background/Objective

The General Electric Research and Development Center has been actively involved in pilot scale research in the area of coal gasification and gas clean-up technology since 1975. The majority of this research has addressed coal gasification and clean-up of coal gas for use in a gas turbine combined cycle power generation systems. This technology known as integrated gasification combined cycle (IGCC), offers plant efficiencies in the range of 42%-45% and capital costs competitive with conventional coal fired plants. The most recent technology developed under this program, high temperature coal gas clean-up technology, is currently being scaled-up for commercial demonstration at a 265 MW integrated coal gasification combined cycle power plant located in Polk County Florida. As a result of these coal gasification and gas clean-up programs, GE-CRD has develop an integrated pilot plant facility consisting of a fixed bed gasifier, gas clean-up system and a turbine combustor simulator capable of gasifying and combusting a wide range of fuels.

Although IGCC power generation technology has been developed with the aim of utilizing coal as a fuel, it represents a potentially cost-effective, highly efficient approach for utilizing other solid fuels, such as forest and agricultural wastes for power generation. Since biomass contains negligible amounts of sulfur ,the clean-up of the product gas will be much simpler than the process required for coal based systems. The resulting combustion of the clean product gas in the gas turbine/combined cycle will have low emission of conventional pollutants such as SO2 and particulate. Due to the presence of fuel bound nitrogen compounds in biomass gas, the ability to achieve ultra low (less than 10 ppm) NOx emissions will require some additional development. In addition to the high efficiency and excellent environmental performance of a biomass IGCC system, the use of biomass harvested on a renewable basis will result in a "greenhouse gas" neutral approach to power generation. Hence a biomass IGCC plant will not increase the net carbon dioxide to the atmosphere, further increasing the environmental attractiveness of the technology.

As a result of interest in the potential of biomass IGCC, GE-CRD performed gasification testing of biomass feedstocks, in a program sponsored by the Vermont Department of Public Service, the U. S Environmental Protection Agency, the U.S Department of Energy, the U. S Agency for International Development and the Winrock International Institute for Agricultural Development. The objective of the program was to demonstrate gasification of biomass fuels in the GE fixed bed gasifier, and based on a simple low cost approach to gas clean-up, evaluate the suitability of the resulting fuel gas for use in a gas turbine/combined cycle power generation power plant.

Initially three biomass fuels were to be supplied by the program sponsors; bagasse, wood chips and switch grass. Each of the three fuels was to be prepared (pelletized, chipped, briquetted) in a form compatible with the fuel feed system of the GE gasifier. No major gasifier feed modifications were to be made. Ultimately, only bagasse and woodchips were provided for testing, and gasification and evaluations were performed on these two fuels.

IGCC Process

The IGCC process is shown schematically in Figure 1. In its simplest form an IGCC system consists of a gasifier, a gas clean-up system and a gas turbine combined cycle power generation system. The gasifier, which may utilizes one of several technologies, gasifies a solid fuel, using steam, air, or oxygen in some combination. Based on the composition of the fuel and the type of the gasifier, the raw fuel gas contains contaminants such as ash and coal particulate, sulfur compounds, ammonia and other nitrogen compounds. These contaminants are removed in a gas clean-up system, resulting in a clean, low to medium BTU content gas. The fuel gas is then burned in a conventional gas turbine, using a modified combustion system designed to accommodate the BTU content of the fuel. Power is produced by the gas turbine, and the hot exhaust gases produced by the gas turbine are used to raise steam in a heat recovery steam generator (HRSG). The steam is them expanded through a conventional steam turbine to produce additional power, further improving the efficiency of the process. In some IGCC processes, a portion of the steam may be used in the gasification process if required.

Preliminary evaluations indicate the cost of gathering and transporting biomass fuels may limit the practical size of these plants to less than 50 MW thus indicating that an aeroderavitive gas turbine or small industrial gas turbine would be best suited to this type of application.

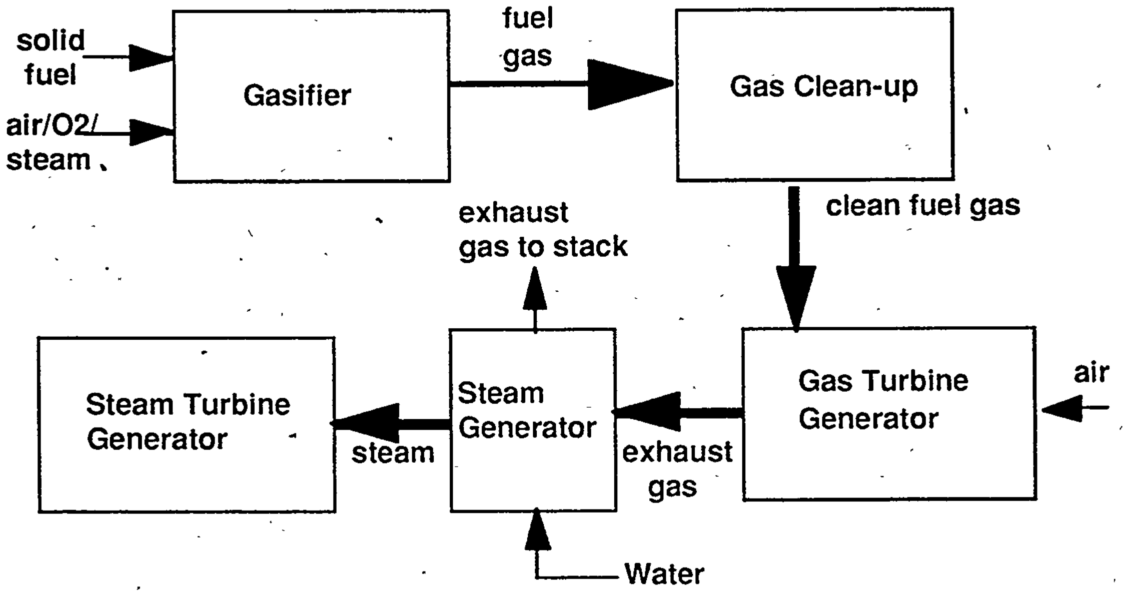

Figure 1 IGCC Process

GE-CRD Pilot Gasification Facility

The pilot gasification facility is located at the GE Research and Development Center (GE-CRD) in Schenectady, New York. The facility is sized to process approximately one ton of coal per hour, producing 8000 lbs per hour of fuel gas. This test facility includes an advanced fixed-bed gasifier, a full-flow, high-temperature gas cleanup system, a full flow gas turbine combustor simulator and an advanced, computerized data acquisition, analysis, and control system. Auxiliary systems include a high-flow, high-pressure process air supply, indirect air preheaters, a high-pressure steam boiler to supply process steam, and an extensive gas and particulate sampling system.

Figure 2 presents a schematic diagram of the gasifier/hot gas cleanup facility. The gasifier vessel is mounted in a 6-story building. Feedstock is fed from the main storage bin or portable feeder via elevator into the weigh bin, and then into one of two lockhoppers that feeds the gasifier via a pressurized auger. Blast steam and air enter at the base of the gasifier, under the rotating grate, and ash is removed from the gasifier through the ash lockhopper. The hot raw gas exits from the top of the gasifier counter current to the incoming coal. The gas can be sent directly to a roof-mounted flare, or it can be processed through a particulate-removing cyclone. Once through the cyclone the raw gas can be directed to the flare or to the hot gas sulfur-removal facility located adjacent to the gasifier tower. For the purpose of the biomass evaluation, the raw gas flowed directly through the primary cyclone and then was burned in the flare. Gas turbine combustion evaluations were not performed because the gas turbine simulator was not available at the time of the testing.

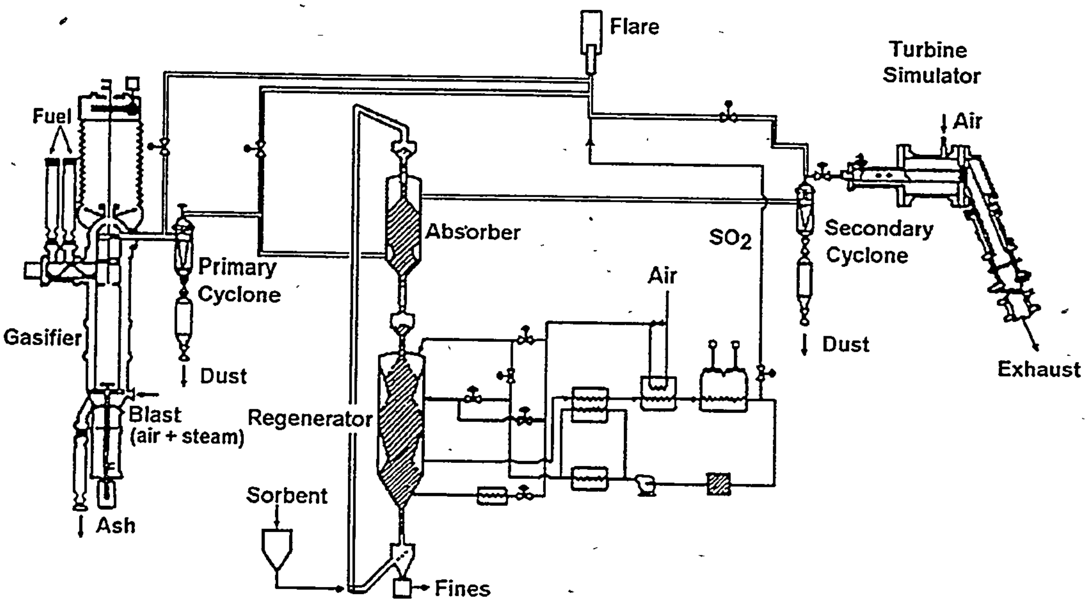

Figure 2 GE CRD Gasification/Hot Gas Clean-up Facility

TEST PROGRAM RESULTS

Fuel Handling Development

Prior to the gasification trials, cold flow testing was performed to determine the properties of bagasse and wood chips to enable them to be fed into the gasifier through the existing coal feed system.. A target flowrate of 4000 lb/hr was chosen in the off-line trials to attain a minimum operational fuel flow of approximately 2000 lb/hr, when the time allowed for lockhopper pressurization and depressurization during system feed operation is taken into account.

Cold flow testing of bagasse and wood chips was necessary for two major reasons. (1) Since the existing feed system was designed for relatively free-flowing coal, some of the flow angles and equipment sizes might not be compatible with fuels having generally poor flow characteristics such as wood chips. (2) Bagasse and wood chips have a much lower density than coal, as shown in Table 1 and therefore require larger volumetric flowrates to process a given weight and BTU content.

Table 1 Comparison of Feedstock Density

Fuel	Density, lb/ft^3
Coal	55
Bagasse	34
Wood chips	15

Wood Chips

Several different wood chip feedstocks were evaluated, resulting in the selection of wood chips from LaBranche Lumber Co., Inc, in Newport, Vermont. The chips were produced from air-dried mixed hardwood, then over- and under-screened to a 0.25"x1.25" size. The sample chips were very uniform and clean and contained no foreign material. The moisture content exceeded 20%. This wood feedstock was found to flow well through lockhopper B, but would not flow through the smaller lockhopper A. However, as the wood chips dried, dramatic improvement in flow properties was noted (Figure 3). On the basis of these results, this feedstock dried to 10% or less moisture, was selected for gasification testing. Modifications were also made to the feed augur to provide higher drive speeds.

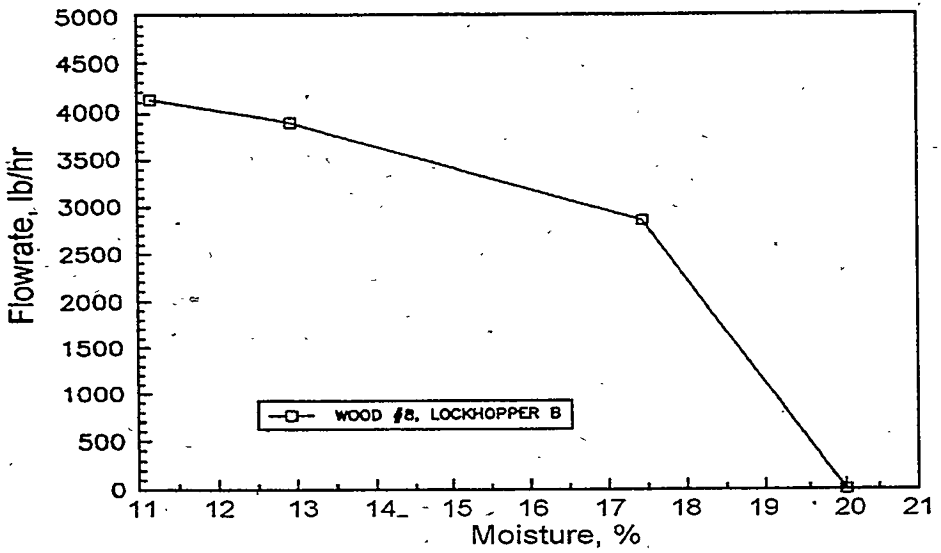

Figure 3 Flow rate of Wood Chip Sample #8 during various stages of drying

It should be noted that although it was necessary to select the gasification feedstock carefully, the wood chips that were finally selected were prepared by conventional means. No extraordinary chipping or drying requirements were needed to achieve an acceptable feedstock.

Bagasse

The bagasse pellets were supplied by Winrock International, and manufactured by Fiber Resources, Inc., Pine Bluff, Arkansas. They were produced using a standard wood pelletizing system. The pellets were cylindrical, 0.25 inch in diameter and approximately 1 inch long. They were compact and very uniform and passed the flow tests through the weigh bin, lockhoppers, and auger easily. A feed rate of 2928 lb/hr was obtained at the original auger gearing set for coal (max 1.4 rpm). Because bagasse fed at a higher rate for a given rpm than wood, an intermediate drive ratio of 2.3:1 was installed, which increased the maximum auger speed to 3 rpm. At this setting a throughput of 6100 lb/hr was obtained, exceeding the target rate of 4000 lb/hr by a comfortable margin.

The feed system was also modified by the installation of air-operated vibrators on both lockhoppers, and increasing the storage bin feeder angles. If bridging did occur, the vibrators could be operated to help break up the blockage and allow continued operation. Additional nuclear level detectors were installed just above the lower valves in the lockhopper cone area to enable confirmation that the lockhoppers were completely empty. If the fuel bridged in the lockhopper, the nuclear detector would continue to indicate "full" and prevent overfilling on the next cycle.

Experimental Results: Bagasse

The physical characteristics of the bagasse fuel as tested is summarized in Table 2, and the composition of the pelletized bagasse is listed in Table 3. The high volatile and oxygen content, coupled with a low fixed carbon are typical of biomass fuels and contribute to the fuel's high reactivity. The low percentage of sulfur results in low sulfur emissions. The fusion temperature of the ash is relatively high and the spread between softening and fluid quite broad. A high fusion temperature is desirable in fixed bed gasification because it reduces the quantity of steam required in the blast for temperature control, resulting in improved thermodynamic performance.

Table 2 Characteristics of Bagasse Pellets

Source	Winrock International; Pelletized by Fiber Resources, Inc., Pine Bluff, Arkansas
Process	dewatered; dried; roll pelletized
Storage	cardboard boxes
Size	1.0" x 0.25" dia
Avg. Moisture	8.5%
Density	34.3 lb/ft^3
Uniformity	good
Comments	dusty; some broken pellets; some "fluff"

Bagasse pellets were gasified at a pressure of 290 psig for a period of approximately 32 hours, consuming 42.5 tons of fuel, which was the total supplied by Winrock International for the test. The bagasse test was initiated on October 8 1991 following a 12-hour stabilization period in which the gasifier was brought up to 50% load and 290 psig on charcoal. Problems were immediately encountered with feeding of the bagasse pellets into the gasifier. The pellets became “sticky” in the fuel lockhoppers and would not feed into the fuel metering auger located at the bottom of the lockhopper. To overcome this problem the feed system was operated in a “batch” feeding mode to minimize the residence time in the lockhopper. This proved satisfactory although it resulted in variation in gasifier flow and outlet temperature.

No problems were encountered with discharge of ash from the system throughout the run. The grate was generally run continuously with speed adjusted to maintain a stationary temperature profile in the reactor. The ash was granular in consistency, with some clinker up to 3 to 4 inches in diameter occasionally mixed in. Torque requirements on both the grate and stirrer were well within design limits throughout the run, indicating no unusual formations in the bed.

Sampling of gas and solids was performed throughout the run. No unusual problems were encountered with sampling of the hot fuel gas in spite of the increased hydrocarbon content. Hot particulate sampling was performed at the outlet of the primary cyclone. Because of the relatively short duration of the test, only a limited number of samples were obtained.

Mechanical performance of the cyclone and associated equipment was satisfactory throughout the test. The dust lockhopper was discharged at 1-hour intervals, generally yielding from 25 to 35 lbs of a dry, fluid-like dust. An air-driven vibrator was cycled automatically during the blowdown cycle to ensure complete discharge of the lockhopper. No problems were experienced with deposition in the dust lockhopper or blowdown piping, in spite of the relatively cool temperatures in these areas (~400 °F) and the low density of the dust. Post test inspection of the cyclone discharge showed no signs of erosion and only minor buildup of particulate on the walls.

Table 3 Composition of Bagasse Pellets

Proximate Analysis		
	average	range
Btu/lb	6960	6761-7159
% Moisture	8.47	8.40-8.54
% Ash	7.78	5.90-9.65
% Volatile	69.89	69.39-70.38
% Fixed Carbon	13.87	12.56-15.18
% Sulfur	0.06	0.05-0.08

Ultimate Analysis		
	average	range
% H_2O	8.47	8.40-8.54
% C	42.13	41.12-43.14
% H	5.66	5.27-6.05
% N	0.87	0.76-0.97
% S	0.06	0.05-0.08
% Ash	7.78	5.90-9.65
% O (diff)	35.04	34.54-35.53

Fusion Temperature of Ash, °F		
Ash Phase	reducing	oxidizing
Initial Deformation	2225	2250
Softening	2375	2500
Hemispherical	2520	2630
Fluid	2700+	2700+

Percentage of Selected Elements in Dry Fuel	
Element	percentage (weight)
Na	0.09
K	0.52

Experimental Results: Wood Chips

Table 4 summarizes the physical properties of the wood chips used for gasification. Table 5 summarizes the composition

Table 4 Characteristics of Wood Chips

Source	State of Vermont; Chipped by LaBranche Lumber Co., Inc; Dried by Bob Foster, Vermont
Process	chipped/wood hog screened rotary-drum-dried
Storage	covered pile
Size	2.0" x 0.5" x 0.25"
Avg. Moisture	5.6%
Density	15.0 lb/ft^3
Uniformity	excellent
Comments	very low fines very clean

Table 5 Composition of Wood Chips

Proximate Analysis		
	average	range
Btu/lb	7983	7800-8232
% Moisture	5.6	4.9-7.3
% Ash	0.9	0.52-1.24
% Volatile	79.6	78.4-80.8
% Fixed Carbon	13.9	13.1-14.9
% Sulfur	0.04	0.01-0.09

Ultimate Analysis		
	average	range
% H_2O	5.6	4.9-7.3
% C	49.1	44.0-50.6
% H	5.7	5.6-6.0
% N	0.45	0.43-0.45
% S	0.04	0.01-0.09
% Ash	0.91	0.52-1.24
% O (diff)	38.23	37.23-39.43

Fusion Temperature of Ash, °F		
Ash Phase	reducing	oxidizing
Initial Deformation	2200	2200
Softening	2230	2220
Hemispherical	2240	2240
Fluid	2260	2330

Percentage of Selected Elements in Dry Fuel	
Element	percentage (weight)
Na	0.02
K	0.05

As with bagasse, the wood chips have a high volatile content indicating high reactivity. The ash level of less than 1% is extremely low compared with bagasse and coal. The ash fusion temperature spread between the initial softening point and fluid point is extremely narrow, i.e., 60 °F. This suggests that temperature control in the oxidation zone of the gasifier is extremely critical in order to prevent ash fusion and resultant clinker formation.

Approximately 84 tons of wood chips were gasified over a period of 80.5 hours at pressures of 200 and 290 psig. The gasifier was prepared for operation using the same startup procedure as for bagasse. Approximately 12 hours were allowed to bring the system to a hot, pressurized standby mode on charcoal

The feed auger was operated at 65% speed for an average throughput of 2130 lb/hr. Approximately 13 lockhopper cycles per hour were required to maintain this rate, compared to 4 or 5 for coal; the difference was due to the lower density and fuel value of the wood. No problems were encountered throughout this period with flow of material through the lockhoppers.

While gasifier operation was generally smooth throughout the 40-hour period, problems were experienced with discharge of dust from the cyclone lockhopper system. Hourly blowdown of the dust lockhopper yielded only a minimal discharge of very light carbonaceous material, considerably less than would be expected based on fuel and gas flowrates. As with the bagasse, an air-driven vibrator was cycled automatically during the letdown cycle but apparently was ineffective in promoting solids discharge. To determine whether dust was being removed from the gas but hanging up in the lockhopper system, a modified blowdown procedure was adopted in which the lockhopper was discharged at pressures slightly above atmospheric. This pressurized blowdown resulted in a significant discharge of dust, indicating that the cyclone was removing at least some particulate from the gas stream but the dust was either too light or too sticky to be discharged simply by gravity through the lockhopper. Unless the dust is periodically removed from the lockhopper, it will eventually become re-entrained in the gas stream, thereby lowering overall cyclone efficiency significantly. This problem continued throughout the test run.

During the wood chip testing, the gasifier pressure was lowered from 290 to 200 psig in an attempt to increase the wood chip throughput by reducing the vent/pressurize cycle times of the lockhoppers at lower pressure. This 200 psig data is included in the following data.

Biomass Fuel Gas Comparisons

Table 6 compares the gasifier operating parameters on bagasse, wood chips, and Illinois 6 bituminous coal at the same operating pressure, 290 psig, and steam-to-air ratio, 0.4. The difference in reactivity and oxygen content of biomass vs. coal is reflected in the higher quantity of air required on a lb/lb fuel basis to gasify bituminous coal. As a result of the additional air requirements and higher fixed carbon and lower volatile content of coal, approximately 45% more raw fuel gas, on a lb/lb basis, is produced from coal; however, the dry higher heating value is between 5% and 10% lower than the biomass fuels. Because of the higher moisture content in the fuel gas of the biomass, the wet higher heating values of the three fuels are approximately the same, 130-140 Btu/scf. The fuel gas moisture is the sum of unreacted steam from the blast, surface moisture on the incoming fuel, and chemically bound water released during devolatization and gasification. Biomass fuels tends to release larger quantities of pyrolysis water than coal; hence the reason for higher overall fuel gas moisture levels at approximately the same steam-to-air ratio and incoming fuel moisture.

Table 6 Comparison of Gasifier Operating Parameters (290 psig)

	Bagasse	Wood Chips	Coal
Raw Fuel, lb/hr	4000	2240	1860
Air Flow, lb/hr	3780	2520	4320
Steam Flow, lb/hr	1480	1008	1728
Steam/Air Ratio, lb/lb	0.4	0.4	0.4
Specific Throughput, lb dry fuel/ft^2-hr	535	305	240
Fuel Moisture, %	8.5	5.5	9.0
Raw Gas, lb/hr	8770	5680	6300
Gasifier Outlet Temperature, °F	1000	1115	1084
Cyclone Exit Temperature, °F	950	1050	1025
Air/Dry Fuel, lb/lb	1.0	1.2	2.6
Raw Gas/Dry Fuel, lb/lb	2.4	2.7	3.7
TAO, wt% dry fuel	4.1	3.7	3.0
Gas HHV, Btu/scf (dry)	172	179	160
Gas Water Content, vol %	29.4	27.0	18.5
Particulate (Cyclone Exit), ppmw	30-100	150-300	-----*
* Cyclone not run at 0.4 S/A ratio; Particulate 30-100 ppm typical			

The specific throughput of bagasse was twice that of coal and 1.75 times that of the wood chips, producing a higher total output of fuel gas. When corrected for the lower fuel heating values of biomass, the Btu input for the bagasse test was approximately 20% higher than on coal and 22% lower for wood gasification compared with coal. This underscores the issue of handling large volumes of low-density fuel, and puts a premium on densification and fuel drying, particularly in pressurized systems. The wood chips are approximately one quarter the density of coal and, therefore, required more frequent lockhopper cycles to obtain the same specific throughput.

There is approximately 35% more tar in the biomass fuel gas than in coal gas. This difference does not directly affect gasification operations as long as the system is kept hot and the tar remains in vapor phase. On a hot basis, gasification efficiency is not adversely affected either as credit is taken for the heating value contained in the higher order hydrocarbons.

Biomass Fuel Gas Composition

Table 7 compares the gas compositions of bagasse at 290 psig and wood chips at 290 psig and 200 psig. The gas concentrations are similar for bagasse and wood chips at 290 psig, with wood chips yielding a slightly higher wet higher heating value as a result of the lower moisture content in the fuel gas. The wood chips also produced 22% less H_2S at both pressures, due to a lower percentage of sulfur in the incoming fuel. The wood chips gasification at 200 psig produced a gas with a lower heating value than the fuel gas produced at 290 psig, due in part to the higher outlet gas temperature and higher water content at the lower pressure. The concentration of NH_3 is lower at reduced pressure, potentially leading to lower NO_x emissions at the turbine.

Table 7 Gas Composition Comparison (mole % wet) – Cyclone Exit

	Bagasse (290 psig)	Wood Chips (290 psig)	Wood Chips (200 psig)
N_2	27.7	28.9	30.4
CO_2	11.4	12.8	12.0
CO	15.2	14.8	14.8
H_2	12.2	10.9	9.2
CH_4	3.5	4.93	4.5
H_2S, ppmv	130	28	27
NH_3, ppmv	850	710	485
H_2O	29.4	27.0	29.0
TAO	0.28	0.23	0.09
Alkali, ppmw	0.285	0.516	1.035
Temperature, °F	950	1050	1075
HHV, Btu/scf (wet)	133	143	125

Bagasse Fuel Gas Contaminants

Particulate

Measurements of cyclone dust catch and hot isokinetic gas samples indicated the average particulate loading of the bagasse fuel gas entering the cyclone was 3400 parts per million by weight (ppmw), and that of the clean fuel gas was 40 ppmw. This yields an overall particulate removal efficiency for the cyclone of nearly 99% in the selected steady-state mass and energy balance period on bagasse.

Based on the observed particulate loading and particle size measurements, as well as the particulate chemical analyses, it is possible to estimate the characteristics of particulate entering the turbine. If it is assumed that the volatiles, carbon and moisture in the particles entering the combustor are completely burned/vaporized so that only ash exits from the combustor (the fuel gas particulate was 13% ash), and if it is also assumed that the ash particles do not agglomerate, then the particle loading entering the turbine will be approximately 1 ppmw and the average size less than 2 microns. At these sizes and concentrations, particulate erosion should not be of concern.

Thus, from a purely physical standpoint, a single cyclone is an effective cleanup device for gasified bagasse. It should be noted, however, that for other types of gasifiers and for other forms of bagasse feedstock, particulate capture requirements may be different.

Alkali Metals

Based on chemical analysis of the particulate, potassium comprises 5.9%, and sodium 1.1% (as oxides) of the mineral matter in bagasse fuel gas leaving the cyclone. If all of the potassium and sodium in the bagasse fuel were to pass into the turbine, severe hot corrosion would be expected. During gasification, the bulk of the alkali metals are removed with the gasifier bottom ash. However, some alkali metal is carried out of the gasifier condensed on the particulate. Because of the low outlet temperature of the fixed bed gasifier, no vapor phase alkali metal species will be present in the fuel gas. Thus the effectiveness of the particulate removal device dictates the effectiveness of alkali metal control.

As noted, sodium and potassium analyses were performed on particulate captured from the fuel gas stream exiting the cyclone. These results, summarized in Table 8, indicate that the alkali metal loading in the fuel gas is approximately 285 parts per billion (ppb) by weight. The major contribution comes from alkali contained in the particulate. At this level, approximately 50 ppb of alkali would exit the combustor and enter the turbine. Current gas turbine specifications require that the products of combustion contain less than 20 ppb of alkali. This specification was based on sodium-containing liquid fuels. Since potassium, in combination with sodium, is likely to form a more corrosive deposit than sodium alone, alkali metal specifications for potassium-containing fuels may be more stringent.

To meet the alkali metal level requirement for the fuel gas, improved particulate removal or, possibly, water scrubbing will be needed. However both of these approaches are within the current state of the technology.

Table 8 Alkali Distribution – Bagasse

Dry Fuel	3735 lb/hr	Fuel Gas (wet)	8771 lb/hr
Na	3.502 lb/hr	Na	0.0004 lb/hr
K	19.360 lb/hr	K	0.0020 lb/hr
Steam Flow	1476 lb/hr	Condensate/TAO	2112 lb/hr
		Concentration*	24.1 wt %
		Ash*	0.06 wt %
		Na*	3.2 ppbw
		K*	1.5 ppbw
		Total Alkali*	4.7 ppbw
Air Flow	3780 lb/hr		
Gasifier Ash Discharge	278.5 lb/hr	Particulate	0.35 lb/hr
Na	2.91 lb/hr	Concentration*	39.9 ppmw
K	17.30 lb/hr	Ash*	5.4 ppmw
		Na*	0.05 ppmw
		K*	0.23 ppmw
		Total Alkali*	0.28 ppmw
Cyclone Dust Discharge	30.1 lb/hr	Total Alkali (condensate and particulate):	0.285 ppmw
Na	0.068 lb/hr		
K	0.347 lb/hr		
		*All concentrations are of wet Fuel Gas.	

Fuel-Bound Nitrogen

Table 9 shows the FBN content of gasified bagasse and the FBN content for gasified Illinois #6 coal for comparison. Also shown are estimates for total NO_x emissions resulting from the conversion of FBN to NO_x and thermal NO_x production in conventional gas turbine combustors.

Table 9 Fuel-Bound Nitrogen – Bagasse and Coal

	Bagasse	Illinois # 6 Coal
Fuel-Bound Nitrogen, wt % as N	0.9	1.5
Fuel Gas ppmv as N		
NH_3	850	6000
non NH_3	2100	437
Estimated NO_x, ppmv at 15% O_2	175-280	

Unlike the FBN in gasified coal, the FBN contained in gasified bagasse is largely non-ammonia. Based on the chemical composition of the bagasse fuel gas, it is likely that the non-ammonia FBN compounds are in the form of hydrogen cyanide (HCN), amines, such as methyl amine (CH_3NH_2), and pyridines such as (C_5H_5N).

There is extensive technical literature exploring the conversion of these non-ammonia FBN species to NO_x in both premixed and non-premixed (diffusion flame) flames. (Sarofim et. al. 1975) The literature concludes that the conversion of these FBN compounds to NO_x is relatively insensitive to the form of the nitrogen compound. Therefore estimates regarding the production of NO_x from bagasse product gas containing non-ammonia FBN will be based on GE experimental data for the conversion of ammonia to NO_x in experimental low-Btu lean diffusion flame combustors.

The conversion data indicates that FBN conversion is expected to be in the range of 30% to 50%. In addition to NO_x produced by conversion of FBN, it is estimated that the thermal NO_x production at these temperatures and fuel composition will be approximately 10 ppm (at 15% oxygen). It should be noted that the overall NO_x emission estimates, shown in Table 5.4, are speculative and highly dependent on specific combustor design. Combustion testing will be required to establish actual emission levels. The requirement for NO_x emissions from gas turbines will be dependent on the location of the plant site, with emissions as low as 9 ppm required for some areas such as Southern California, and higher limits (up to 75 ppm) in other areas, again dependent on state and local regulations. Thus, it appears that improvement in technologies to reduce the NO_x from biomass IGCC will be required for plants located in the United States.

Currently GE and other organizations are developing low NO_x combustors for fuels containing FBN. One approach to this problem is the use of rich-quench-lean (RQL) technology. This is a staged combustion approach with a rich first stage and a rapid quench using secondary air followed by a lean burnout stage. Theoretical predictions indicate that RQL combustion can achieve FBN conversion rates as low as 10%. It should be recognized that this technology is in its early stage of development and will require substantial additional development before it can be offered as a commercial product.

A more speculative approach to reducing the FBN in the fuel gas is the use of catalytic materials to promote the reduction of FBN species to their equilibrium levels. These species are generally produced by gasifiers at levels that are much higher than their equilibrium value. Thus, by bringing the composition of the fuel gas to chemical equilibrium, the concentration of FBN can be reduced. This approach will require development of advanced catalytic materials that are insensitive to the "poisons" contained in fuel gas at low levels such as H_2S and chlorides. This technology is not available commercially.

Alternately, post combustion NO_x cleanup technologies, such as selective catalytic reduction (SCR), are commercially available. SCR can reduce NO_x levels in the exhaust gas products by 90%. However this approach is expensive, has a moderate performance penalty associated with the addition of back pressure to the gas turbine, and requires the use of ammonia, which is released to the environment in small quantities.

A more conventional approach to reducing FBN in the bagasse fuel gas is to cool the product gas and water scrub to remove particulate materials as well as the FBN compounds. This approach removes all of the particulate material and the associated alkali metal contaminants as well. However this approach would create several other problems including a reduction in plant efficiency resulting from the loss of the sensible energy of the fuel gas (estimated at approximately 5% reduction in plant efficiency). Scrubbing the fuel gas also removes the tars and oils and their associated heating value from the fuel gas (which could amount to 10% of the heating value of the fuel). Safe disposal of the contaminated scrubber water represents an environmental problem, requiring additional plant equipment. Although the process of cooling and water scrubbing the fuel gas will remove contaminants from the fuel gas, the resulting impact on plant efficiency and plant capital cost will be detrimental.

In summary, many solutions exist to reduce NOx emissions from biomass IGCC plants; however a detailed systems tradeoff study must be undertaken to identify the best solution for a specific plant site. It should be noted that the results of similar tradeoff studies for coal gasification plants indicate that the cost and efficiency benefits of hot gas cleanup outweigh the capital cost and efficiency penalties of competing approaches.

Sulfur

Bagasse contains 0.06% sulfur on the average, which results in fuel gas containing only 130 ppm of H_2S (Table 10). This low value can be compared with a typical medium-sulfur coal content of 1.6% S, which results in 3000 ppm of H_2S in the fuel gas. Because of the low sulfur content, the SO_x emissions from bagasse-based gas turbine power generation will be less than those of a typical coal-burning steam plant with a high-efficiency flue gas scrubber. Details of the distribution of sulfur in the solids, tars, oils, and condensate can be found in Table 10. Closure of the sulfur balance around the system is within the variances found in the individual process streams.

Table 10 Sulfur Distribution – Average Values for Bagasse

Dry Fuel Sulfur in Fuel: Average Range	3735. lb/hr 2.45 lb/hr (2.04–3.26 lb/hr)	Fuel Gas (wet) H_2S-S	8771 lb/hr 1.51 lb/hr ±.02
Steam Flow	1476 lb/hr	Condensate/TAO S*	2112 lb/hr 0.40 lb/hr ±.10
Air Flow	3780 lb/hr		
Gasifier Ash Discharge S	278.5 lb/hr 0.04 lb/hr	Particulate S*	0.35 lb/hr 0.001 lb/hr
Cyclone Dust Discharge S	30.1 lb/hr 0.05 lb/hr	Total Sulfur (condensate + particulate): 1.91 lb/hr ± .10 217 ppmw	
		*All concentrations are of wet Fuel Gas.	

Wood Chip Gas Stream Contaminants

Particulate

Substantially larger quantities of particulate were measured in the gasified wood chip fuel gas downstream of the cyclone than for bagasse or coal. Particulate levels in the product fuel gas were 290 ppmw for 290 psig operation and 280 ppmw at 200 psig. Since the estimated particulate loading for the fuel gas leaving the gasifier was approximately 2000 ppm, cyclone efficiencies were only of the order of 85%. One reason for poor cyclone efficiencies is the low density of the particulate.

Bulk density measurements indicated the density of the particulate associated with wood chips was low compared with bagasse and coal. Since cyclones are inertial separation devices, it is not surprising that particulate removal efficiencies were lower for the wood chip gasification run.

Another cause of poor cyclone performance was the difficulty of removing captured particulate from the cyclone due to their low density and poor flow properties. Since captured particulate were not being discharged from the cyclone properly, it is possible that some particulate were being re-entrained into the fuel gas stream, thereby lowering overall removal efficiency.

Clearly, more effective means for particulate removal will be required for a wood-chip gasification system. Options include more effective cyclones specifically designed for this type of particulate, barrier filters, or water scrubbing.

Alkali Metals

The alkali metal content of the wood particulate remaining in the gas stream is approximately one-fourth that for bagasse. However, because of the high particulate loading of the fuel gas, the total alkali metal level is twice that for bagasse, as indicated in Table 11. Like bagasse, the ratio of potassium to sodium is high. Improved particulate control, which will be required to reduce particulate loading at the turbine inlet, will also reduce alkali metal concentrations. At the level of 0.516 ppmw total alkali measured for the wood gas at 290 psig, about 90 ppb of alkali would exit the gas turbine combustor and enter the turbine, as compared to the current gas turbine limit of 20 ppb alkali.

Table 11 Alkali Distribution – Wood Chips (290 psig)

Dry Fuel	2127 lb/hr	Fuel Gas (wet)	5680 lb/hr
Na	0.338 lb/hr	Na	0.0005 lb/hr
K	1.029 lb/hr	K	0.0024 lb/hr
Steam Flow	1008 lb/hr	Condensate/TAO	1220 lb/hr
		Concentration*	21.5 wt %
		Ash*	0.05 wt %
		Na*	8.1 ppbw
		K*	0.1 ppbw
		Total Alkali*	8.2 ppbw
Air Flow	2520 lb/hr		
Gasifier Ash Discharge	24.1 lb/hr	Particulate	1.65 lb/hr
Na	0.111 lb/hr	Concentration*	290 ppmw
K	0.974 lb/hr	Ash*	5.0 ppmw
		Na*	0.086 ppmw
		K*	0.422 ppmw
		Total Alkali*	0.508 ppmw
Cyclone Dust Discharge	12.2 lb/hr	Total Alkali (condensate + particulate): 0.516 ppmw	
Na	0.014 lb/hr		
K	0.069 lb/hr	*All concentrations are of wet Fuel Gas.	

Table 12 shows the alkali distribution at 200 psig gasifier operation. The overall wood chip throughput was increased; however, the gasifier ash discharge decreased, indicating that ash was being entrained in the fuel gas stream. As a result, only 45% of the alkali was removed in the gasifier ash discharge, the remainder exiting with the fuel gas due to the higher bed velocity. The ash content in the particulate at 200 psig operation was double the ash content at 290 psig operation. The alkali content in the fuel gas, therefore, also doubled. This would indicate that the upper limit on gasification throughput is dictated by entrainment of ash from the fuel bed rather than by the gasification reactions themselves. Running at lower steam-to-air ratios to produce a coarser, denser ash would help minimize carryover, although the operability window provided by the ash fusion properties is rather narrow.

Table 12 Alkali Distribution – Wood Chips (200 psig)

Dry Fuel	2338 lb/hr	Fuel Gas (wet)	6372 lb/hr
Na	0.418 lb/hr	Na	0.0011 lb/hr
K	1.273 lb/hr	K	0.0055 lb/hr
Steam Flow	1008 lb/hr	Condensate/TAO	1406 lb/hr
		Concentration*	22.1 wt %
		Ash*	0.04 wt %
		Na*	4.5 ppbw
		K*	0.1 ppbw
		Total Alkali*	4.6 ppbw
Air Flow	2952 lb/hr		
Gasifier Ash Discharge	17.1 lb/hr	Particulate	1.77 lb/hr
Na	0.079 lb/hr	Concentration*	278 ppmw
K	0.691 lb/hr	Ash*	10.1 ppmw
		Na*	0.174 ppmw
		K*	0.856 ppmw
		Total Alkali*	1.030 ppmw
Cyclone Dust Discharge	12.2 lb/hr	Total Alkali (condensate + particulate): 1.035 ppmw	
Na	0.014 lb/hr		
K	0.069 lb/hr	*All concentrations are of wet Fuel Gas.	

Fuel-Bound Nitrogen

Table 13 shows the FBN content of the gasified wood chips. Also shown are estimates for NO_X emissions resulting from the conversion of FBN to NO_X in conventional gas turbine combustors.

Table 13 Fuel-Bound Nitrogen – Wood Chips

Fuel-Bound Nitrogen, wt % as N	0.5
Fuel Gas ppmv as N NH_3 non NH_3	 710 1015
Estimated NO_x, ppmv at 15% O_2	100-160

Because of the lower level of nitrogen in the wood chips, FBN levels in the fuel gas are substantially lower than for bagasse. Consequently, NO_x emissions are expected to be lower. However, as in the case of bagasse, the conversion of FBN to NO_x during combustion is not well known and any emission estimates are highly speculative.

Sulfur

The wood chips contained 0.04% sulfur on the average. The variation between samples was relatively high, ranging from 0.01 to 0.09% (Table 14). The average H_2S content of the fuel gas at 290 psig was 28 ppmv (Table 4.14), significantly lower than the 130 ppmv obtained for bagasse, and orders of magnitude lower than the 3000 ppmv for gasified medium sulfur coal. Details of the specific distribution of sulfur in the solids and product gas are shown in Table 14. It should be noted that a larger contribution to total sulfur comes from the tars, oils and condensate than from H_2S. Also, the ratio of total sulfur in the fuel gas, including contributions from H_2S, particulate, higher order hydrocarbons and condensate, to that obtained from bagasse is approximately 0.6, or very nearly the ratio of sulfur contained in the parent fuels. The discrepancy in closure of the balance between sulfur entering in the fuel and that exiting in the gas is within the variation in sulfur content of the wood chips. Considering the total sulfur in the fuel gas, sulfur emissions in the form of SO_2 from the gas turbine exhaust would be expected to be in the range of 45 ppmv (corrected to 15% O_2, dry).

Table 14 Sulfur Distribution – Average Values for Wood Chips (290 psig)

Dry Fuel Sulfur in Fuel: Average Range	2127 lb/hr 1.06 lb/hr (0.22–2.01 lb/hr)	Fuel Gas (wet) H_2S-S	5680 lb/hr 0.21 lb/hr ±.02
Steam Flow	1008 lb/hr	Condensate/TAO S*	1220 lb/hr 0.49 lb/hr ±.36
Air Flow	2520 lb/hr		
Gasifier Ash Discharge S	24.1 lb/hr 0.009 lb/hr	Particulate S*	1.65 lb/hr 0.004 lb/hr
Cyclone Dust Discharge S	12.2 lb/hr 0.003 lb/hr	Total Sulfur (condensate + particulate): 0.71 lb/hr ± .36 125 ppmw	
		*All concentrations are of wet Fuel Gas.	

SUMMARY

Gasification tests were conducted on bagasse and wood chips in the fixed-bed coal gasification pilot plant located at the GE Research and Development Center in Schenectady, New York. Gasification runs in which 42.5 tons of bagasse pellets and 83.8 tons of dried wood chips were consumed were performed over periods of 32 hours and 81 hours, respectively. Gasification was performed at 20 atmospheres, and the fuel gas cleanup system consisted of a single cyclone. The following technical conclusions are based on results from feeding trials and gasification runs.

Feeding of biomass into a pressurized gasifier can be accomplished as long as either the biomass feedstock or the pressurization system is specified appropriately. The feedstock used in these gasification runs required careful selection and, in the case of bagasse, pelletization was needed because of the design of the lockhopper system, which was designed for free flowing coal. Although many wood chip samples were evaluated before an appropriate feedstock could be found, the final material was processed using conventional means.

Both biomass materials were highly reactive and easily gasified at substantially higher rates than can be achieved with coal. The biogas produced was slightly higher in heating value than coal gas, and its composition indicates that its combustion properties are compatible with gas turbine combustors. However, because of the low density, especially for wood chips, of the fine particles entrained in the product gas, the cyclone was unable to reduce particulate loadings to levels required by gas turbines. The alkali metals contained in these fine particles were at a level substantially in excess of the gas turbine fuel gas specification. Thus, improved particulate removal through cyclone modification, the addition of a filtration system, or wet scrubbing will probably be required. However, these more efficient particulate removal technologies are well within the state-of-the-art.

An extremely attractive feature of biomass is its potential for low emissions. Sulfur loadings are substantially lower than for low-sulfur coals. Indeed, the sulfur levels are lower than the levels for medium-sulfur coal burning facilities with high-efficiency flue gas desulfurization systems. Fuel bound nitrogen (FBN) levels, which are of concern because of the conversion of FBN to NO_x during combustion, are lower than for coal. However, the FBN distribution between ammonia, cyanides, and nitrogen-containing organics is quite different than for coal. In order to meet stringent NO_x emission requirements (less than 10 ppm), it may be necessary to implement one or more of the following technologies: (1) removal of FBN compounds by scrubbing, (2) catalytic decomposition, (3) advanced low NO_x combustion technology, (4) post combustion cleanup. Each of these approaches has a cost and efficiency impact, and the best approach can only be identified by system tradeoff studies based on the specific plant location, feedstock and plant equipment to be utilized.

One of the key reasons for interest in biomass as a power generation feedstock is that the emissions of CO_2, a greenhouse gas, are compensated by the absorption of atmospheric CO_2 by the biomass during its growth cycle, thus the use of biomass based IGCC based on sustainable harvesting of biomass can be considered greenhouse gas neutral.

It can be concluded that biomass is a viable feedstock for integrated gasification combined cycle power generation systems. The use of biomass feedstocks offers potential advantages both in terms of overall cost of electricity and environmental performance. However the specific economics of biomass IGCC will depend on both the ultimate cost of the biomass fuel and the specifics of the plant design. Implementation does not require development of breakthroughs in gasification or turbine technology. However, there are specific development needs related to gas clean-up and plant integration which could lead to reduced environmental impacts and improved plant costs and efficiencies.

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PRODUCTION OF 800 kW OF ELECTRICAL POWER USING MEDIUM CALORIFIC GAS FROM A BIOMASS GASIFIER INTEGRATED IN A COMBINED CYCLE

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Abstract

An allothermal fluidised bed biomass gasifier is under construction to operate at a pressure slightly above atmospheric to produce a gaseous fuel of medium heating value. The output of the gasifier is 2.5 x 10^6 kcal/h and will be attached to a gas turbine that is specifically modified to burn the gas produced. The amount of electricity to be generated will be 800 kW. The gasifying medium used is superheated steam at 2.5 bars and 400 °C and the amount needed will be 280 kg/h. The gasifier will have a cross sectional area of 2.1 m^2.with dimensions of 1 500 mm x 1 400 mm. There is a heat exchanger to provide the heat needed for the gasification reactions. The gasifier will operate at about 850 °C and the biomass throughput will be about 950 kg/h. The amount of gas that is to be produced will be about 1 300 kg/h or 1 900 Nm^3/h. Part of the gas obtained will be burned in an external combustor to provide the heat for the gasifier. The gas turbine to be employed is a single shaft turbine designed to drive 750 kVA electrical generator. The turbine combustion chamber is somewhat modified to allow for the lower heating value of the gas. However, there is no loss of efficiency in the turbine output due to lower calorific value of the fuel. The turbine inlet temperature is 900 °C and that of the exhaust will be 500 °C. The amount of gas to be used is about 745 Nm^3/h.

The paper reports the experimental results obtained from a pilot-scale gasifier operating under similar conditions. The results of test runs carried out with a gas turbine are also presented.

INTRODUCTION

For reasons of protecting the environment and achieving higher thermal efficiencies, direct combustion of biomass does not appear to be an attractive option to produce energy as the level of CO_2 formation in a conventional combustion cycle constitutes to be the highest for lowest efficiencies. Furthermore, the combustion process produces only heat which is then used for raising either hot water or steam. The steam generation could be coupled with electricity production. Furthermore, the use of solid fuels in industrial application is somewhat limited as many processes require clean fuels with little or no ash formation as this could cause impurities in the final product. Direct combustion of residues integrated in any industrial process thus create problems of ensuring the product quality.

Thermal conversion processes for producing liquid and gaseous fuels from residues could have advantages in overcoming the difficulties encountered with the direct combustion. Gasification appears to be at more advanced stage of development, in fact in some cases ready for full commercial exploitation. The gaseous fuel produced is easier to transport and pollutant free. In addition, its use in processes in which any contamination is to be avoided is more feasible.

The quality of the gas produced depends on the biomass type and operating conditions, such as temperature, pressure, heating rate, etc. The influence of these conditions need to be well understood to optimise the design of gasifiers for industrial applications.

The air gasification technology [1] is well understood and commercial units are in operation. However, the gas produced is very low in calorific value and its potential to substitute fuels with much higher heating values is not always feasible, particularly in those processes in which there is a need to achieve high temperature flames. Furthermore, the use of this gas in gas turbines is difficult. In addition, its transport over long distances is economically not viable if the gas is to be used as an industrial fuel in processes. The use of oxygen as a gasification agent is a solution to improve the heating value of the gas but this solution requires an oxygen plant which could be expensive for gasifiers with smaller outputs. Consequently, other systems of gasification need to be developed to produce medium calorific gas but with smaller levels of investment. There have previous studies to improve the heating value of the gas either through using steam [2-3] or through recycling of gas to supply the necessary heat for the gasification [4].

Studies have been undertaken in INETI to develop an allothermal gasifier operating with steam only to produce gas of reasonable quality and medium calorific value. These studies have been initiated first on a bench-scale fluidised bed gasifier equipped with continuous feeding system, using steam in order maximize the conversion to gas and to achieve higher gas quality. The work developed involves the influence of the following parameters on gasification reactions: i) Bed temperature, ii) Steam/biomass mass ratio, iii) Types of biomass, and vi) Particle size.

EXPERIMENTAL

The pilot plant used is a continuously-fed fluidised bed gasifier with a square cross section, each side 300 mm long. The height of the gasifier is 4 500 mm high. It is refractory coated and is fluidised by using superheated steam and by the recycled gases formed during the gasification reactions. There is a continuous feeding system directly linked with the screw feeder located on the side of the gasifier to supply biomass to the top of the bed at a height of 500 mm above the distributor plate. The gas formed passes through a cyclone specially designed to operate at high temperatures to recover particulates entrained from the bed. Part of the gas and the charcoal from the pyrolysis reactions is burned in an outside combustor to produce hot gases at about 1 100 ^{o}C which is then utilised in the gasifier to provide the heat to initiate the pyrolysis reactions. The rest of the gas produced is burned in an existing furnace at INETI employing a burner designed by the INETI group for this type of gas. The gas turbine studies were carried out in UK by a company contracted by INETI. Gas turbine steady state control and dynamic response was monitored to try to correlate with those of the gasifier. The quality of the gas produced was determined by on-line analysers that measure the levels of H_2, CO, CO_2, and O_2. Some of the gas produced was also collected in aluminium bags for analysis on a gas chromatograph equipped with a FID detector to measure the hydrocarbon amounts. The temperatures in the gasifier were monitored by thermocouples that were located along its height. The operating conditions used in this work are summarised in Table 1.

TABLE 1 - Range of Operating Conditions of the Atmospheric Gasification Studies

Gasification temperature (^{o}C)	900 - 1 100
Equivalence ratio,	0.15 - 0.35
Biomass,	
. Species	Pine, Holm-oak
. Particle size, (µm)	250 - 2 500
. Feed rate (kg/h)	up to 40
. Moisture (% - dry basis)	8 - 10
Fluidising velocity (m/s)	0.4 - 0.6
Steam supply temperature (^{o}C)	400
Steam pressure (bar)	2

RESULTS AND DISCUSSION

The results obtained from the gasification studies are given in Table 2.

TABLE 2 - The Results Obtained from Steam Gasification Studies of Biomass

i) Average Values for Pine

Temperature (^oC)	Equivalence ratio	Composition of Gas in Molar Basis CO	CO_2	H_2	CH_4	C_2H_4	Calorific Value((kJ/Nm^3)	Liquids % wt)
700	0.18	32	18	38	9	3	11 704	24
700	0.22	34	16	42	6	2	12 344	22
800	0.18	33	15	42	8	2	12 332	16
800	0.22	35	12	44	7	2	12 412	13
900	0.18	34	14	44	6	2	12 403	9
900	0.22	36	11	45	6	2	12 636	6

ii) Average Values for Helm-Oak

Temperature (^oC)	Equivalence ratio	Composition of Gas in Molar Basis CO	CO_2	H_2	CH_4	C_2H_4	Calorific Value (kJ/Nm^3)	Liquids (% wt)
700	0.18	34	16	38	10	2	12 104	21
700	0.22	34	18	39	7	2	12 184	24
800	0.18	36	14	41	9	2	12 546	19
800	0.22	36	12	44	7	2	12 448	12
900	0.18	35	13	44	6	2	12 423	10
900	0.22	36	11	45	6	2	12 636	9

The calorific values of the gas given above were calculated from the compositions obtained in test runs and were corrected for NPT conditions.

The gas composition was observed to be affected by both temperature and heating rate. The end composition and the yield levels were, however, found to be independent of the type of biomass used. Fig. 1 gives a comparison of CO and H_2 yields for the range of temperatures used.

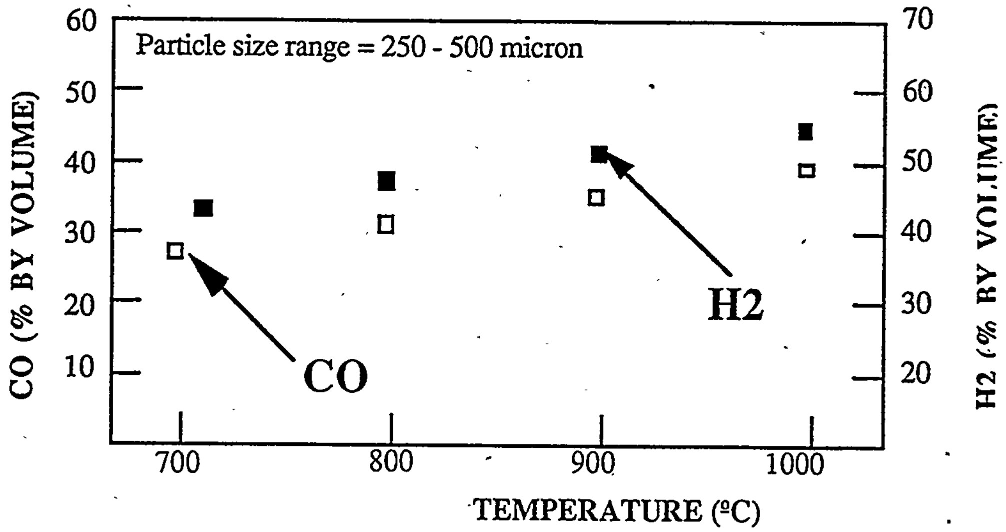

Fig. 1 - The Effect of the Temperature on the Yields of CO and H2 for Different Gasifications Conditions

The gasification process appeared to be primarily controlled by temperature and rate of heating. Smaller particles gave rise to higher gas yields because of higher heating rates, thus resulting in faster release of volatiles. Greater heating rates also caused higher particle temperatures, thus encouraging the cracking of volatiles even during the devolatilisation stage. This hence produced greater gas yield. Fig. 2 illustrates the effect of particle size on the gas yield for different temperatures. It was also observed that the effect of particle size on the gas yield was more pronounced for particles less than 1 mm.

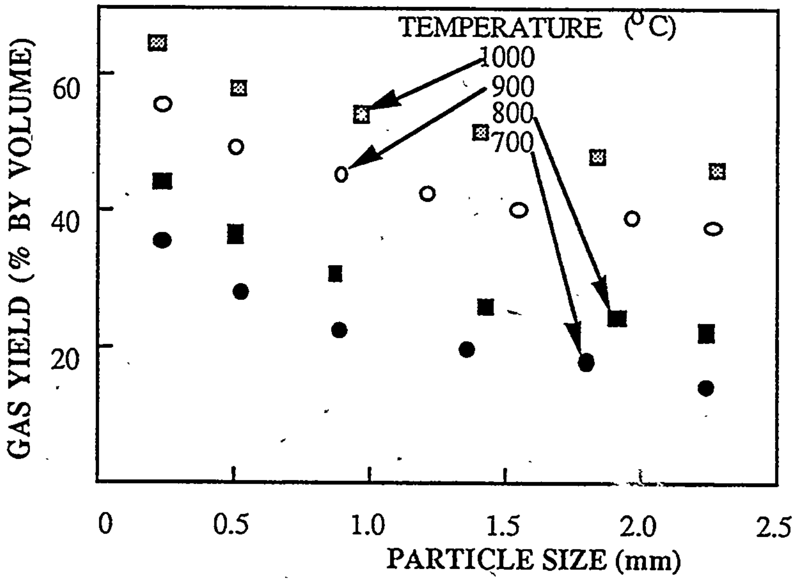

Figure 2 - The Effect of Particle Size on the Gas yield for Different Temperatures

The equivalence ratio (ER) is defined as the oxidant to fuel weight ratio divided by the stoichiometric ratio. It was found to have a stronger influence on the gas yield than the temperature. In steam gasification the product gas yield varied between 1.25 and 1.4 kg / kg of biomass for ER ratios of 0.15 and 0.30 respectively. Test runs carried out for the same ER showed that the range of variation in the gas yield with temperature was relatively small. This was found to be the case for all types of biomass used. Fig 3 illustrates the dependence of the gas yield on ER for different temperatures.

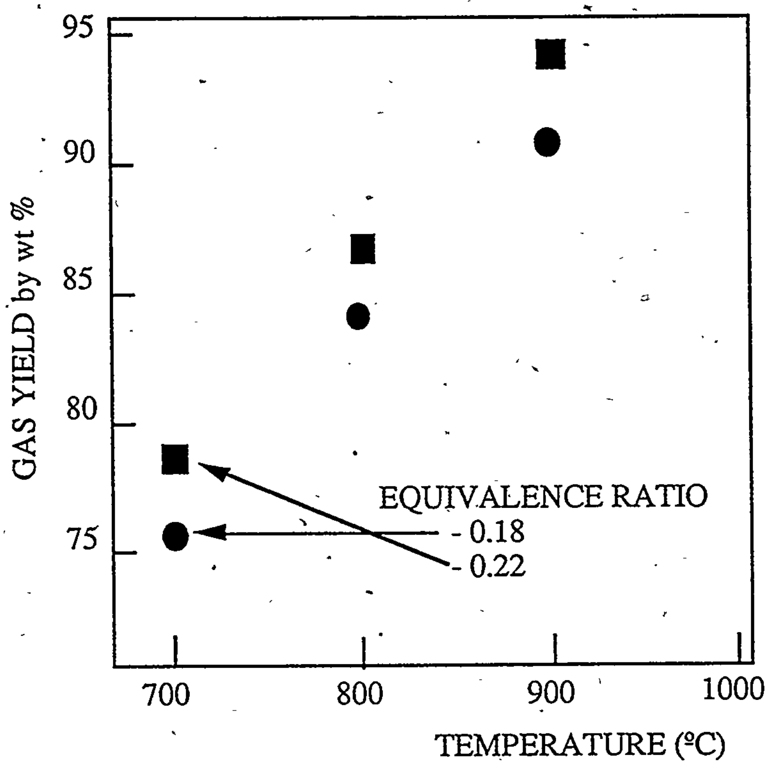

FIG. 3 - The Influence of Equivalence Ratio on the Gas Yield for Different Temperatures

It was observed that the CO content of the gas produced increased with the temperature. This was thermodynamically expected. The rate of increase was, however, found to be the highest with the steam gasification compared with air gasification studies that had been carried out separately.

In general, the equivalence ratio was found to have smaller influence on the production of liquids for the same temperature range as given in Table 2. It was observed, that the liquids production decreased with the increasing temperature until about 1000 °C with steam contrary to the observations with air gasification in which the liquid yield remained almost constant for temperatures above 800 / 820 °C. This could be due to the highly oxygenated nature of thebiomass so that the solid surface was highly saturated, thus preventing further adhesion of oxygen when air or oxygen is used as the gasification agent.

During gasification tests it was found that 5 to 10% of the biomass input was converted to char. This means that the overall conversion to liquids and gases is higher with air gasification. In fact with an adequate control of temperature it is possible to maximise the yield of gas when steam is used.

The calorific value of the gas produced was reasonable as demonstrated in Table 2. This could be due to higher levels of CO and H_2 present in the gas resulting from water/shift reaction. The gas was found to be suitable as a fuel to be used in gas turbines.

Environmentally, the gasification did not give rise to any problems with regard to gaseous pollutants like NO_x, SO_2, H_2S. The only pollutant for concern emerging from the gasifier was particulate matter which could be resolved using cyclones and filters. High efficiency cyclone that was used in the test facility was observed to be sufficient to reduce the concentrations of particles below the acceptable levels. The filters would be needed when the gas was to be used in the gas turbine.

Steam gasification appears to be a more attractive option for making gas from biomass in comparison with other gasification systems using air or oxygen. The gas obtained appears to of better quality and has higher heating value. The range of variations in parameters influencing stable operation appears to be wider with steam gasification and is easier to control to achieve the quality in end products.

A gas turbine with an output of about 400 kW was used to carry out some tests with the gas produced. The results were quite promising as relatively reasonable cycle efficiency could be achieved and specific output in kWs/kg followed the the usual pattern in such manner that the cycle efficiency fell with higher pressure ratios due to the fact that less fuel supply was used to maintain the inlet turbine temperature as demonstrated in Fig. 4. There were no problems associated with burning the gas, the ignition, flame stability and response to changes in load.

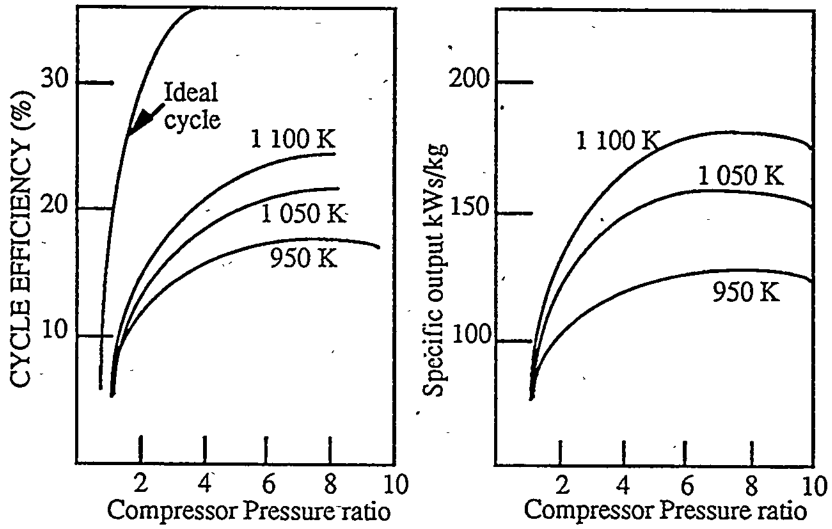

Figure 4 - The Cycle Efficiencies and Specific Outputs of the Turbine Used With the Gas Produced

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FUEL CONVERSION EFFICIENCY AND ENERGY BALANCE OF A 400 kW_t FLUIDIZED BED STRAW GASIFIER

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Abstract

A 400 kW (thermal) dual-distributor type fluidized bed gasifier developed for the energy recovery from cereal straw was used to investigate the effects of equivalence ratio (actual air-fuel ratio:stoichiometric air-fuel ratio), fluidization velocity and bed height on the fuel conversion efficiency from wheat straw. The energy balance was also performed on the system under those operating conditions. The results indicated that the equivalence ratio was the most significant parameter affecting the fuel conversion efficiency and the energy recovered from rhe straw in the form of gas. Both the fuel conversion efficiency and the energy recovery increased with increases in the equivalence ratio. The fluidization velocity and bed height had minimal effects on these parameters. A fuel conversion efficiency as high as 98 % was obtained at the equivalence ratio of 0.35. The energy recovered in the form of gas and the sensible heat of the produced gas were in the ranges of 40-70 % and 9-17 %, respectively. Unaccounted losses showed a dramatic increase at lower equivalence ratios and were in the range of 6-53 % depending on the operating condition.

Introduction

In most thermochemical conversion systems, high operating temperatures are desirable in order to achieve higher conversion efficiencies and lower emission of carbon monoxide (CO), dioxin ($C_4H_6O_2$) and unburned particles (Orth et al., 1982; and Rexen, 1980). Although, high fuel conversion efficiencies (over 99 %) have been obtained during the combustion of coal in conventional and circulating fluidized bed systems, it has always been a challenge to achieve high fuel conversion efficiencies during the combustion of biomass (especially agricultural residues) because of their high volatile contents (75-85 %) and low ash fusion temperatures (900-1000°C). Ergüdenler and Ghaly (1993), Salour et al. (1993) and Ghaly and AlTaweel (1990) suggested that operating temperatures in excess of 800-850°C should be avoided in thermochemical conversion systems utilizing straw. However, in practical operations, it is very difficult to keep the combustion temperature below the ash melting temperature because of the high content of volatiles in straw which burns at unfavorably high temperatures that can cause severe slag formation and operational problems (Carre et al., 1988; Whiteway et al., 1985; Wilen et al., 1985; and Whiteway and Caley, 1980).

The low softening temperature of straw ash leaves a rather narrow operating temperature range which makes optimal combustion of cereal straws almost impossible. Because of incomplete combustion and high flue gas temperatures, low straw combustion efficiencies of 50-70 % were reported by Strehler (1985), Orth et al. (1982) and Strehler (1980). Gasification was, therefore, proposed by several investigators as an alternative method to utilize agricultural crop residues (Ergüdenler and Ghaly, 1993; Ergüdenler and Ghaly, 1992; Corella et al., 1989; Walavender et al., 1986; Kaupp, 1984; and Groves, 1979). However, the temperature in the oxidation zone of fixed bed (or moving bed) gasifiers can exceed 1500°C (Carre et al., 1989; and Tuttle, 1984). Such a high temperature can melt the ash and produce slag that can cause serious operational problems (Hartiniati et al., 1989; Liinaki et al., 1985; and Lepori et al., 1983).

Reed (1981) reported that, unlike fixed bed gasifiers, fluidized bed reactors do not have a discrete reaction zone because of their mixing characteristics. A fluidized bed gasifier consists of an inert bed material such as sand, ash or char that acts as an effective heat transfer medium. In fluidized bed reactors, biomass mixes rapidly with the bed material and hence is almost instantaneously heated up to the bed temperature (Overend, 1982). The high heat capacity of the particles combined with their high mobility through the bed result in good heat transfer properties and a uniform temperature distribution in lateral and vertical directions of the bed. These promote relatively high fuel conversion efficiencies, thus, allowing a wider variety of the biomass to be utilized in fluidized bed gasifiers (Maniatis et al., 1982; and Groves, 1979). Another advantage of the fluidized bed gasifiers is that their temperatures can be easily controlled and maintained below the fusion temperature of the ash by varying the feed and/or air supply rates (Ergüdenler and Ghaly, 1992; and Dalvi and Brunett, 1982).

Objectives

The aim of this study was to investigate the effect of various operating parameters (bed height, fluidization velocity and equivalence ratio) on the fuel conversion efficiency of a dual distributor type fluidized bed gasifier operating on wheat straw and to perform energy balance on the system under these conditions.

Materials and Methods

Materials

Monopol variety winter wheat straw was used in chopped form (average size of 15 mm) as a feed-stock. To maintain a uniform straw composition, the straw was collected during the same harvesting season from a field at the Dyke View Farms in Port Williams, Nova Scotia in the form of small rectangular bales (0.46 m x 0.48 m x 0.70 m). The straw bales were placed in a drying system and dried by blowing warm air (35°C) before they were chopped, in order to obtain a consistent moisture content of the feed-stock. The moisture content of feed-stock was kept within the range of 9-11 percent. Some characteristics of straw are given in Table 1.

Alumina sand was used as inert bed material in the fluidized bed gasifier. It was obtained from Diamonite Products Ltd., Shreve, Ohio, USA. The alumina was white in colour and very spherical in shape. It was kiln fired at 1500°C. The main characteristics and chemical composition of the alumina sand are given in Table 2.

Experimental Apparatus

The fluidized bed gasification system used in this study is shown in Figure 1. It was made of 8 mm thick, 310 stainless steel cylinder of 22.5 cm diameter and 2.7 m total height. An enlarged disengagement section mounted on the top of the main fluidizing column was used to reduce the elutriation rate from the system. The height and diameter of the enlarged section were 39.5 cm and 35.5 cm, respectively. A cyclone was connected to the exit of the disengagement section to capture the solid particles (dust, bed material and ash/char) escaping from the bed. These particles were separated from the gas stream and collected in an ash collector placed at the bottom of the cyclone. A propane fired start-up system was used to raise the temperature of the bed material up to 600°C before starting to feed straw to the reactor. The fluidizing column and the cyclone were insulated using flexible Inswool-HP blanket to reduce the heat losses from the system.

A dual distributor type feeding mechanism was developed for feeding the low density fuel material (cereal straw) into the fluidized bed gasifier. It consisted of a main distributor plate, a secondary column, a secondary distributor plate and a feeding tube. Two identical air supply units (primary and secondary) were used to provide air to the fluidized bed gasifier. The primary air supply (from blower-1) was used to fluidize the bed material within the main fluidizing column, whereas the secondary air supply (from blower-2) was creating a jet of air within the secondary column which carried the bed material and the fuel (the chopped straw that is fed into this secondary column) to the main fluidizing column above the main distributor plate.

The temperature measurements were done using twelve special purpose thermocouple probes (Cole Parmer Type-K, Catalog No. N-08516-70) connected to a computer based data acquisition system. Dwyer slack-tube manometers (Model No. 1211-200) were used to measure the pressure drop at eleven locations in the gasifier. A gas sampling system, consisting of gas sampling probe, copper tubing, three-way switch valve, gas purifier, compressed air line, peristaltic pump, gas sampling bulb, pressure relief valve, pressure gauge, syringe and evacuated tubes was used to collect the gas samples. All the gas analyses were done using a Hewlett Packard Model 5890 Series II Gas Chromatograph. The gas production rate of the gasifier was measured using an especially designed orifice-plate. More detailed descriptions of the experimental apparatus can be found elsewhere (Ergüdenler and Ghaly, 1992).

Table 1. Some Characteristics of Wheat Straw.

Characteristics	Straw
Moisture content (%)	10-11
Average particle size (mm)	15x2x0.3
Bulk density (kg/m^3)	75-80
Lower heating value (MJ/kg)	18.71
Proximate Analysis* (%)	
Volatile matter	78.80
Fixed carbon	17.61
Ash	3.59
Ultimate Analysis* (%)	
C	45.97
H	5.78
O	44.15
N	0.55
S	0.12
Cl	0.02
Ash	3.41

* weight percentage on dry basis

Table 2. Main Characteristics of the Alumina.

Characteristic	Value
Particle Density (kg/m^3)	3450
Bulk Density (kg/m^3)	2000
Maximum Particle Size (μm)	500
Mean Particle Size (μm)	380
Minimum Particle Size (μm)	250
Minimum Fluidization Velocity* (m/s)	0.15
Chemical Composition (%)	
Alumina (Al_2O_3)	85.0-90.0
Silica (SiO_2)	8.0-10.0
Calcia(CaO)	0.5-2.0
Magnesia (MgO)	0.5-1.5
Soda (Na_2O)	0.1-0.4
Iron Oxide (Fe_2O_3)	0.1-0.3
Titania (TiO_2)	0.05-0.15
Potasia (K_2O)	0.01-0.05

* Minimum fluidization velocity was calculated for ambient conditions

Experimental Procedure

The feeder was filled with a known weight of chopped straw. The alumina sand was placed into the reactor to a bed height of 25.5 cm. The primary air supply was turned on to fluidize the sand particles in the main fluidizing column and the air flow rate was adjusted to 0.56 m^3/min (0.67 kg/min). The computer based data acquisition system was activated to monitor and record both the temperature, the pressure drop and the feed rate values. The temperature of the bed material was raised to 600°C by combusting the propane-air mixture. The start-up system was, then, shut down while keeping the primary air supply on to cool the bottom section (wind-box) of the gasifier before starting to feed the straw. When the temperature in the secondary column reached 500°C, the secondary air supply was turned on and adjusted to the minimum rate (0.56 kg/min) required to carry the sand particles from the secondary column into the main column. The feeder was turned on and the fuel feed rate was adjusted to allow excess air in order to achieve complete combustion of straw. The bed temperature was, thus, increased rapidly (to 750°C) by the energy released from the combustion of straw. The fuel feed rate and air flow rates were adjusted to the desired respective levels and the system was operated under this condition for half an hour to insure that the steady state condition was reached in the fluidized bed. Gas samples were then collected during the steady state operation. When sampling and data recording was completed, the feeder, secondary air supply and primary air supply were shut down. The ash collector was replaced by an empty ash collector. The same procedure was followed with all equivalence ratio-fluidization velocity combinations. The whole procedure was, then, repeated for the bed height of 12.5 cm. The equivalence ratio, as it was used in this study, was defined as follows:

$$\text{Equivalence Ratio} = \frac{\text{Actual Air-Fuel Ratio}}{\text{Stoichiometric Air-Fuel Ratio}} \qquad (1)$$

Analyses

All char samples were analyzed for volatile, fixed carbon, ash compositions and calorific values. Elemental and proximate analyses of the char samples were done at the Analytical Chemistry Laboratory of Nova Scotia Research Foundation Corporation. Elemental analysis was conducted on the char samples to determine the carbon, hydrogen, nitrogen, sulphur and oxygen compositions. The carbon, hydrogen and nitrogen contents were determined by using LECO CHN-Analyzer. Sulphur analysis were done on LECO S-Analyzer. The ash analysis was done according to ASTM D 3714-73. The oxygen content in the sample was found by difference. Volatile matter in the char sample was determined according to ASTM D 3175-77. Calorific analyses of the char samples were done at the Thermal Analyses Laboratory of the Technical University of Nova Scotia using Parr 1261 Calorimeter according to ASTM D 3286-85.

Results and Discussion

Straw char collected at the bottom of the cyclone at various operating conditions were analyzed for elemental compositions, higher heating value, volatile matter, fixed carbon and ash composition. The conversion efficiency calculations were based on the analyses of these char samples. The results are shown in Tables 3 and 4. The energy recovered in the form of gas, the sensible heat of the gas at the exit of the gasifier, the heat losses through the

Table 3. The Elemental Analysis and Higher Heating Value of Char.

Bed Height (cm)	Fluidization Velocity (m/s)	Equivalence Ratio	Elemental Composition (% dry basis)						Higher Heating Value (MJ/kg)
			C	H	N	O	S	Ash	
25.5	0.37	0.35	29.01	0.80	0.51	2.86	0.08	66.74	10.2
		0.25	47.64	1.38	0.78	1.25	0.10	48.85	16.5
		0.20	50.30	1.77	1.11	3.05	0.11	43.66	16.7
		0.17	56.80	1.48	0.88	9.51	0.13	31.19	17.1
	0.33	0.35	46.37	1.40	0.92	2.87	0.10	48.35	14.9
		0.25	49.07	1.45	0.93	3.33	0.11	45.11	15.3
		0.20	50.71	1.57	0.98	3.87	0.09	42.77	16.1
		0.17	52.88	1.71	1.96	8.01	0.10	36.11	17.1
	0.28	0.35	45.83	1.23	1.06	1.46	0.16	50.26	14.4
		0.25	47.29	1.30	1.07	6.31	0.06	43.97	15.7
		0.20	54.26	1.86	1.24	0.84	0.10	41.70	16.6
		0.17	57.18	1.97	0.97	0.52	0.10	39.27	19.5
12.5	0.37	0.35	-	-	-	-	-	-	-
		0.25	58.81	1.67	0.99	9.69	0.23	28.60	18.7
		0.20	62.96	1.72	0.86	10.29	0.12	24.05	20.0
		0.17	74.16	2.13	1.11	3.16	0.12	19.31	20.8
	0.33	0.35	-	-	-	-	-	-	-
		0.25	30.61	0.89	0.50	6.89	0.09	61.02	12.8
		0.20	53.99	1.40	0.89	4.85	0.07	38.80	16.0
		0.17	61.89	1.88	0.87	6.61	0.10	28.64	18.9
	0.28	0.35	39.53	1.02	0.72	1.73	0.11	56.88	12.7
		0.25	57.52	1.81	0.82	1.66	0.09	38.09	18.2
		0.20	57.11	1.71	0.87	5.43	0.12	34.76	18.5
		0.17	59.68	1.68	0.88	5.26	0.18	32.32	19.1

The values are the average of two analyses

Table 4. Proximate Analysis of Char and Fuel Conversion Efficiency.

Bed Height (cm)	Fluidization Velocity (m/s)	Equivalence Ratio	Proximate Analysis (% dry basis)			Fuel Conversion Efficiency (%)
			Volatile Matter	Fixed Carbon	Ash	
25.5	0.37	0.35	11.80	21.47	66.74	98.1
		0.25	17.32	33.83	48.85	96.1
		0.20	16.73	39.61	43.66	95.2
		0.17	20.79	48.02	31.19	91.8
	0.33	0.35	10.78	40.87	48.35	96.0
		0.25	11.36	43.53	45.11	95.5
		0.20	13.56	43.67	42.77	95.0
		0.17	14.29	49.60	36.11	93.4
	0.28	0.35	10.61	39.13	50.26	96.3
		0.25	10.87	45.16	43.97	95.3
		0.20	13.87	44.43	41.70	94.8
		0.17	18.81	41.92	39.27	94.2
12.5	0.37	0.35	-	-	-	-
		0.25	20.23	51.17	28.60	90.7
		0.20	21.91	54.04	24.05	88.2
		0.17	16.49	5.20	19.31	84.4
	0.33	0.35	-	-	-	-
		0.25	15.23	23.75	61.02	97.6
		0.20	15.56	45.64	38.80	94.1
		0.17	12.90	58.46	28.64	90.7
	0.28	0.35	9.76	33.36	56.88	97.2
		0.25	16.23	45.68	38.09	93.9
		0.20	17.91	47.33	34.76	93.0
		0.17	19.02	48.66	32.32	92.2

* The values are the average of two analyses

gasifier walls and the unaccounted losses are summarized in Table 5.

Elemental Composition of Char

At the bed height of 25.5 cm, the fluidization velocity did not have any significant effect on the carbon and ash contents of the char. However, reduced ash contents and increased carbon contents in the char were observed at all levels of fluidization velocity when the equivalence ratio was decreased. The decrease in the carbon content and the increase in the ash content of the char with the increases in the equivalence ratio were due to the higher bed temperatures achieved at higher equivalence ratios. Corella et al. (1989) and Walawender et al. (1986) reported similar results.

At the bed height of 12.5 cm and the fluidization velocities of 0.33 and 0.37 m/s, it was not possible to operate the gasifier at the equivalence ratio of 0.35 due to the agglomeration of the bed material. Higher levels of carbon and lower levels of ash contents were obtained in char at this bed height as compared to those observed at the bed height of 25.5 cm. The lowest ash content and the highest carbon content were obtained at the highest fluidization velocity (0.37 m/s)-lowest equivalence ratio (0.17) combination due to a low reactor temperature combined with a low residence time.

Higher Heating Value of Char

The higher heating value of char was increased when the equivalence ratio was decreased, at all levels of fluidization velocity and bed heights. The decreases in the carbon content and the increases in the ash content of the char with increases in the equivalence ratio were the reasons for the decreases in the higher heating values of char. The lowest higher heating value of char (10.2 MJ/kg) was observed at the highest levels of bed height (25.5 cm), fluidization velocity (0.37 m/s) and equivalence ratio (0.35). Higher heating values obtained at the bed height of 12.5 cm were higher than those obtained at the bed height of 25.5 cm. No distinct trend was observed for higher heating value with respect to the fluidization velocity.

Proximate Analysis of Char

At the bed height of 25.5 cm, the volatile matter and fixed carbon contents of char increased whereas the ash content decreased when the equivalence ratio was decreased. This was due to the decrease in the gasifier temperatures which resulted in a poor fuel conversion.

At the bed height of 12.5 cm, the fixed carbon content of char showed a decreasing trend when the equivalence ratio was decreased. However, there was not any distinct trend for the volatile matter with respect to the equivalence ratio. Generally, higher levels of volatile matter and fixed carbon were observed at the bed height of 12.5 cm as compared to those at the bed height of 25.5 cm. The very high levels of volatile matter and fixed carbon observed at the maximum fluidization velocity (0.37 m/s) were good indications of poor fuel conversion primarily because of short residence times experienced at those operating conditions.

Table 5. Energy Balance.

Bed Height (cm)	Fluidization Velocity (m/s)	Equivalence Ratio	Energy of Gas (MJ/kg fuel)	Energy of Gas (%)	Sensible Heat (MJ/kg fuel)	Sensible Heat (%)	Heat Losses (MJ/kg fuel)	Heat Losses (%)	Unaccounted Losses* (MJ/kg fuel)	Unaccounted Losses* (%)
25.5	0.37	0.35	12.71	67.9	2.82	15.1	0.89	4.8	2.29	12.2
		0.25	10.56	56.4	2.25	12.0	0.59	3.2	5.31	28.4
		0.20	9.29	49.7	2.05	12.0	0.43	2.3	6.94	37.1
		0.17	7.54	40.3	1.71	9.1	0.33	1.8	9.13	48.8
	0.33	0.35	10.70	57.2	2.88	15.4	1.00	5.3	4.13	22.1
		0.25	10.41	55.6	2.28	12.2	0.69	3.7	5.33	28.5
		0.20	8.95	47.8	1.95	10.4	0.46	2.5	7.35	39.3
		0.17	6.77	36.2	1.71	9.1	0.36	1.9	9.87	52.8
	0.28	0.35	12.84	68.6	3.16	16.9	1.23	6.6	1.48	7.9
		0.25	12.83	68.6	2.42	12.9	0.79	4.2	2.67	14.3
		0.20	9.75	52.1	2.01	10.7	0.55	2.9	6.40	34.2
		0.17	7.42	39.7	1.66	8.9	0.43	2.3	9.20	49.2
12.5	0.37	0.35	-	-	-	-	-	-	-	-
		0.25	10.74	57.4	2.25	12.0	0.61	3.3	5.11	27.3
		0.20	9.61	51.4	1.96	10.5	0.46	2.5	6.68	35.7
		0.17	9.00	48.1	1.81	9.7	0.36	1.9	7.54	40.3
	0.33	0.35	-	-	-	-	-	-	-	-
		0.25	11.16	59.6	2.39	12.8	0.65	3.5	4.51	24.1
		0.20	9.23	49.3	2.01	10.7	0.52	2.8	6.95	37.1
		0.17	8.57	45.8	1.77	9.5	0.38	2.0	7.99	42.7
	0.28	0.35	13.10	70.0	3.24	17.3	1.23	6.6	1.14	6.1
		0.25	12.83	68.6	2.52	13.5	0.81	4.3	2.55	13.6
		0.20	10.20	54.5	2.01	10.7	0.59	3.2	5.91	31.6
		0.17	9.12	48.7	1.79	9.6	0.47	2.5	7.33	39.2

* tar, unburned carbon in char and water vapor

Conversion Efficiency

Ash, as the inert portion of straw and straw char, formed the basis of the conversion efficiency calculations. Ash in straw was assumed to leave the gasifier as was introduced without being subjected to any change. Ash in the char and the degradable (remaining) portion of char were normalized by bringing the ash in char to the same level as that of straw and, then, the fuel conversion efficiency was calculated as follows:

$$Fuel\ Conversion\ Efficiency(\%) = \frac{DPS - DPC}{DPS} \times 100 \qquad (2)$$

where:

DPS is the degradable portion of straw (%)
DPC is the degradable portion of char (%)

The degradable portions of straw and char were calculated as follows:

$$DPS = (100 - PAS) \qquad (3)$$

$$DPC = (100 - PAC) \times \frac{PAS}{PAC} \qquad (4)$$

where:

PAS is the percent ash in straw (%)
PAC is the percent ash in char (%)

The effects of the equivalence ratio, fluidization velocity and bed height on the fuel conversion efficiency are presented in Figure 2. The fuel conversion efficiency increased when the equivalence ratio was increased at all levels of bed height and fluidization velocity. The highest conversion efficiency values (96.1-98.1 %) were obtained when the gasifier was operated at the equivalence ratio of 0.35. The increases in the fuel conversion efficiencies were the results of the increases in the bed temperature that resulted in higher carbon conversions. The decrease in the carbon content and the increase in the ash content of the char with the increase in the equivalence ratio were also good indications of better carbon conversion.

Lower conversion efficiencies were observed at the bed height of 12.5 cm as compared to those at the bed height of 25.5 cm, especially at the fluidization velocity of 0.37 m/s. The lowest conversion efficiency (84.4 %) was observed at the bed height of 12.5 cm, the fluidization velocity of 0.37 m/s and the equivalence ratio of 0.17 combination which corresponded to the lowest bed temperature (caused by a low equivalence ratio and a short residence time due to low bed height and high fluidization velocity).

The fuel conversion efficiency experienced in this study was relatively higher than those reported by Walawender et al. (1986) for corn (63 %) and sorghum stovers (74 %). High fuel conversion efficiencies experienced in this study were mainly because of the very high volatile matter content of straw and high reactivity of its char combined with the increased residence time of fuel achieved by an effective feeding system adopted to the fluidized bed gasifier.

Energy Balance

The energy balance of the gasifier at various equivalence ratios, fluidization velocities and bed heights are shown in Figures 3 and 4. A sharp increase in the energy content of the produced gas was observed when the equivalence ratio was increased from 0.17 to 0.25 at all levels of bed height and fluidization velocity. However, the energy content of the produced gas did not vary much between the equivalence ratios of 0.25 and 0.35. The higher energy recovery in the form of gas (55.6 to 70.0 %) per unit weight of straw, observed at these equivalence ratios, was due to higher gas yields and higher conversion efficiencies owing to higher gasifier temperatures. At lower equivalence ratios (0.17 and 0.20), a drastic decrease in the energy recovery was observed due to the increased tar yield and the unburned carbon in the char. A higher percentage of the energy content of the produced gas was obtained when the gasifier was operated at the lowest fluidization velocity (0.28 m/s), primarily because of the higher residence time achieved at that fluidization velocity. The bed height, however, did not have any significant effect on the energy content of the gas.

Increasing the equivalence ratio increased the amount of sensible heat and the heat losses through the gasifier walls at all levels of bed height and fluidization velocity. Higher percentages of sensible heat in gas (15.1 to 17.3 %) and heat losses (4.8-6.6 %) were observed at the highest equivalence ratio (0.35) because of higher gasifier temperatures experienced at that equivalence ratio. The lowest fluidization velocity (0.28 m/s) yielded the maximum percentages of the sensible heat (17.0 %) and the heat losses (6.6 %) at the highest equivalence ratio for both bed heights. The bed height had a very slight effect on the sensible heat and the heat losses because both of these parameters were directly affected by the gasifier temperature which showed slight increases when the gasifier was operated at the lower bed height (12.5 cm). The sensible heat in gas and the heat losses experienced in this study ranged from 8.9 to 17.3 % and from 1.8 to 6.6 % of the energy value of straw, respectively. The sensible heat in gas reported by Maniatis et al. (1982) ranged from 11.7 to 20.3 % for cacao pellets and from 11.3 to 14.5 % for wood shavings.

The unaccounted losses (in the form of tar, unburned char, water vapor, etc.) showed a substantial increase when the equivalence ratio was reduced from 0.35 to 0.17. This was mainly due to the increased tar yield and the unburned carbon in the char owing to lower gasifier temperatures at lower equivalence ratios. The unaccounted losses ranged from 6.1 to 52.8 % of the energy value of straw. Slight decreases in the unaccounted losses were detected when the gasifier was operated at a lower bed height (12.5 cm). However, no clear trend was observed with respect to variations in the fluidization velocity.

The thermal efficiency of the gasifier (based only on the energy recovered in the form of gas) ranged from 36.2 to 70.0 %. Very similar values of thermal efficiency were obtained at the equivalence ratios of 0.25 and 0.35 for all fluidization velocities. When the sensible heat in gas was included in the energy recovered, thermal efficiencies as high as 81.5-87.3 % were obtained at the fluidization velocity of 0.28 m/s for the equivalence ratios of 0.25 and 0.35 at both bed heights. The energy balance analyses reported by Chern et al. (1989) for a down-draft gasifier operated on wood chips showed a thermal efficiency of 52.9 % based on the dry gas only and 55.4 % considering the sensible heat in gas at a temperature of 700 K. The thermal efficiency reported by Maniatis et al.(1982) ranged from 26.1 to 56.3 % and 43.2 to 50.2 % for fluidized bed gasification of cacao pellets and wood shavings, respectively. The study by McDonald et al. (1983) on fluidized bed gasification of saw dust reported thermal efficiencies of 59.7-66.3 %. Maniatis et al. (1989) reported 65 % thermal efficiency for the fluidized bed gasification of chopped wood.

Conclusions

A 400 kW$_t$ dual-distributor type fluidized bed gasifier, developed for the energy recovery from cereal straw, was used to investigate the effects of equivalence ratio, fluidization velocity and bed height on the fuel conversion efficiency of wheat straw. The energy balance was also performed on the system at those operating conditions. The fuel conversion efficiency increased with increases in the equivalence ratio. Higher fuel conversion efficiencies (96.2-98.2 %) were achieved when the gasifier was operated at the higher equivalence ratio (0.35). The energy recovery (in the form of gas) increased with increases in the equivalence ratio. The energy content of the produced gas reached its maximum value (70.0 %) when the gasifier was operated at the bed height of 12.5 cm, fluidization velocity of 0.28 m/s and equivalence ratio of 0.35. Drastic decreases in the thermal efficiency of the gasifier were observed at the lower equivalence ratios (0.17 and 0.20). At the equivalence ratios of 0.25 and 0.35, thermal efficiencies as high as 82-87 % were obtained when the sensible heat in the gas was included in the energy balance.

Acknowledgments

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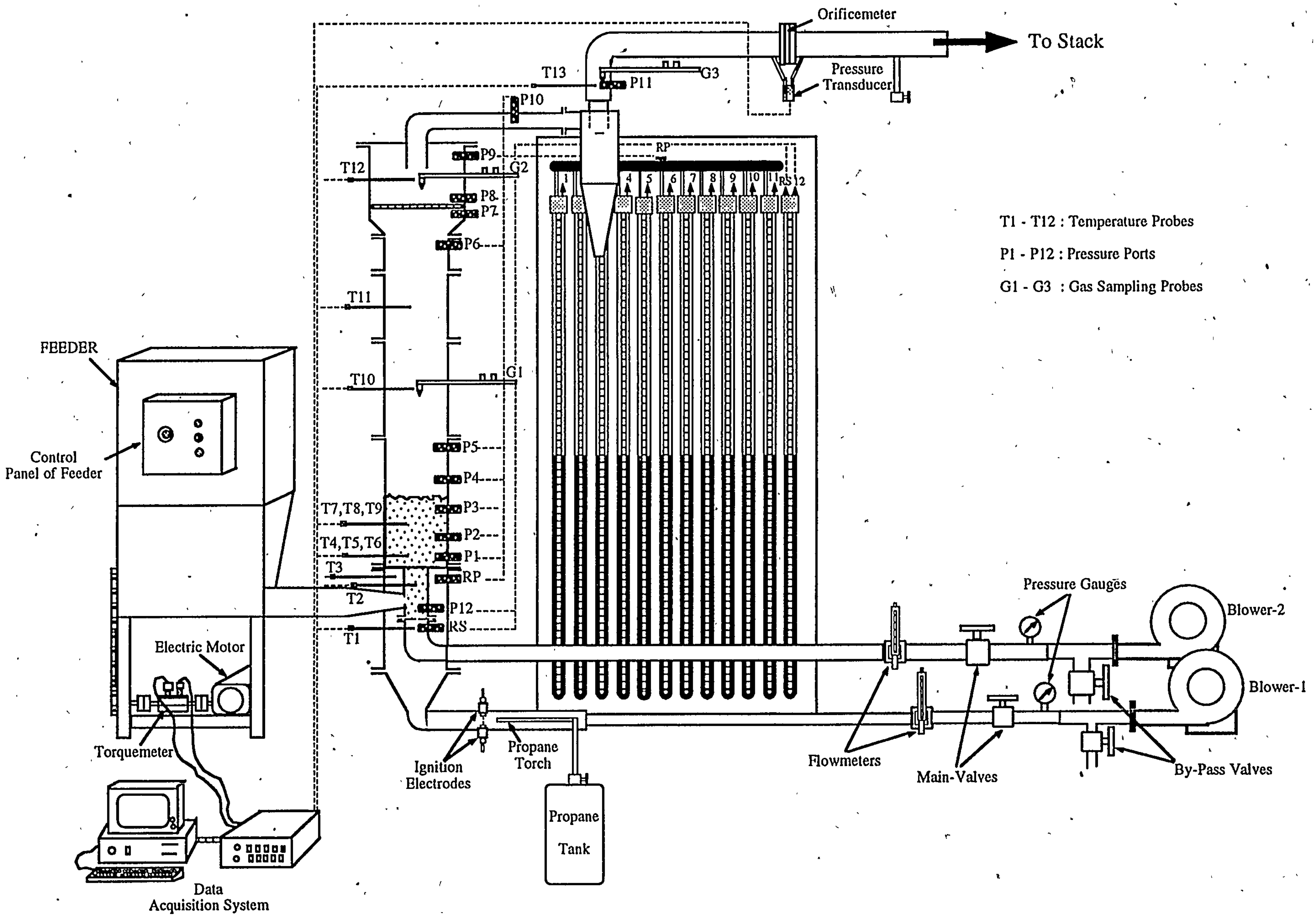
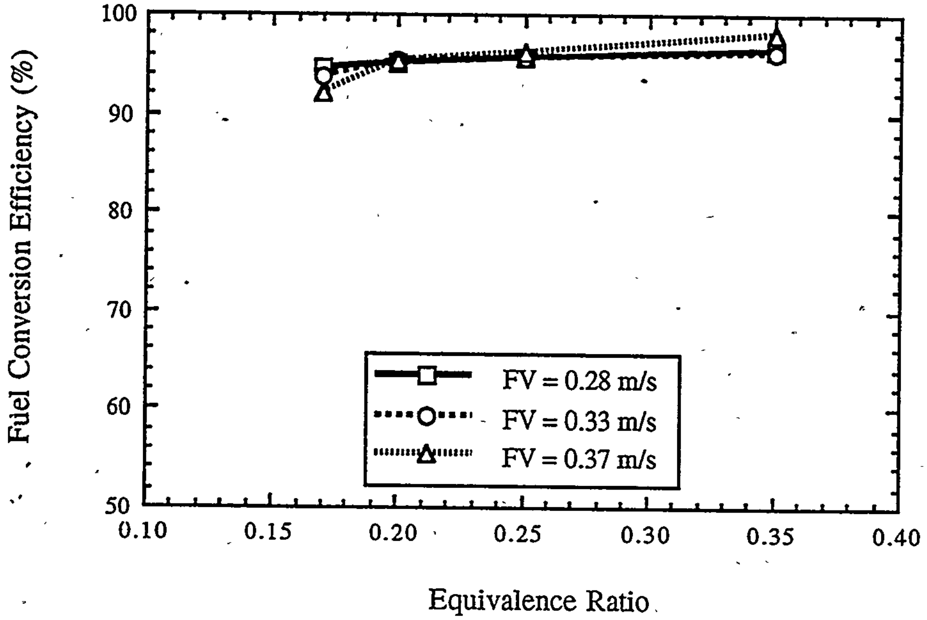
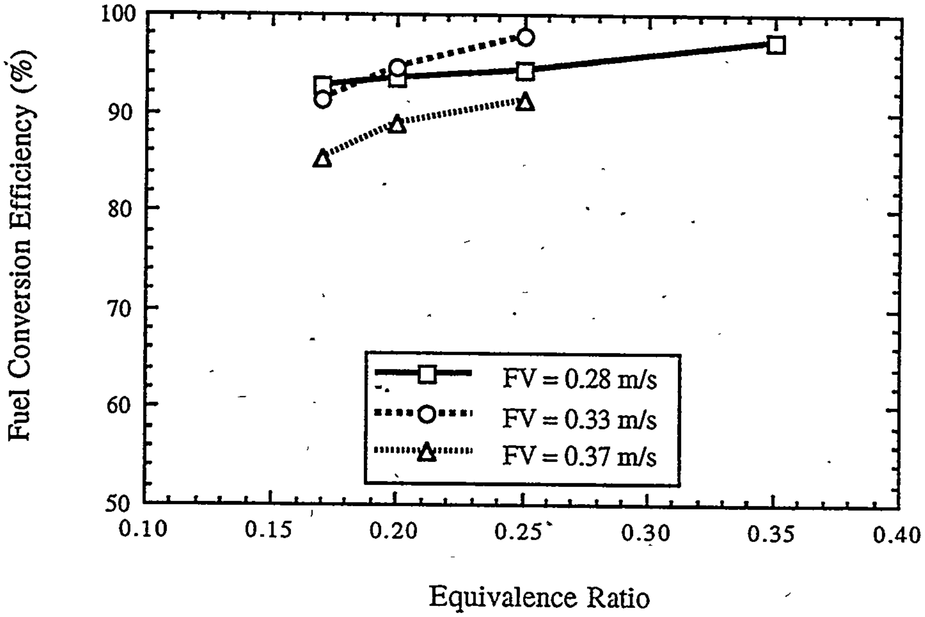


Figure 1. Experimental Apparatus.

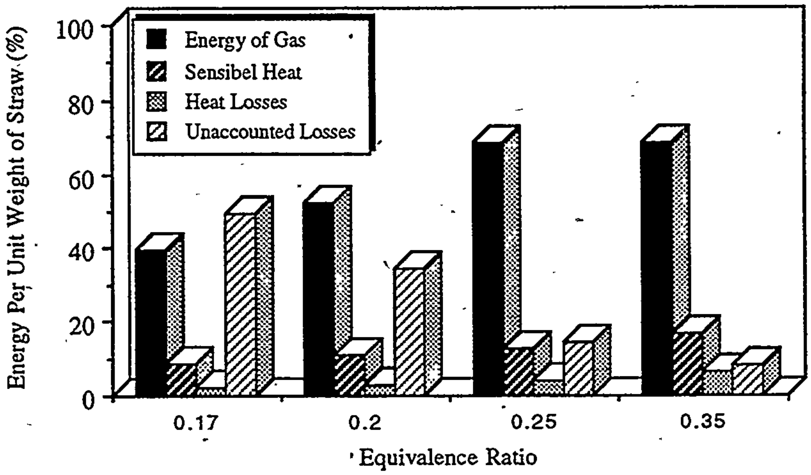


(a) Bed Height = 25.5 cm

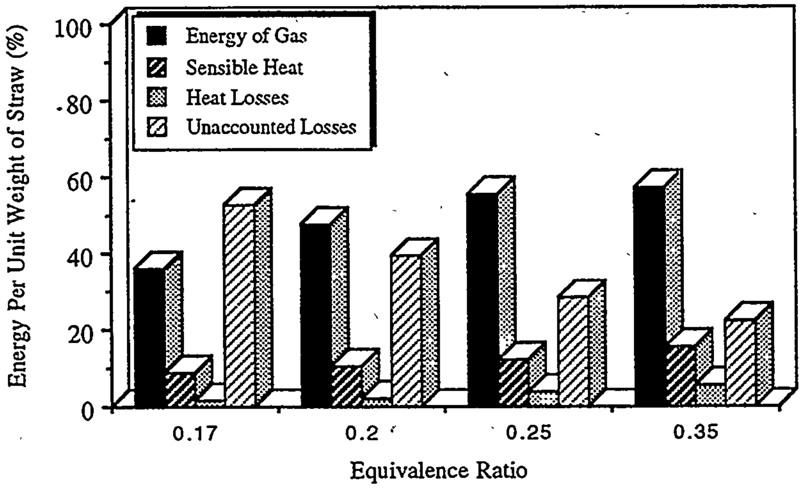


(b) Bed Height = 12.5 cm

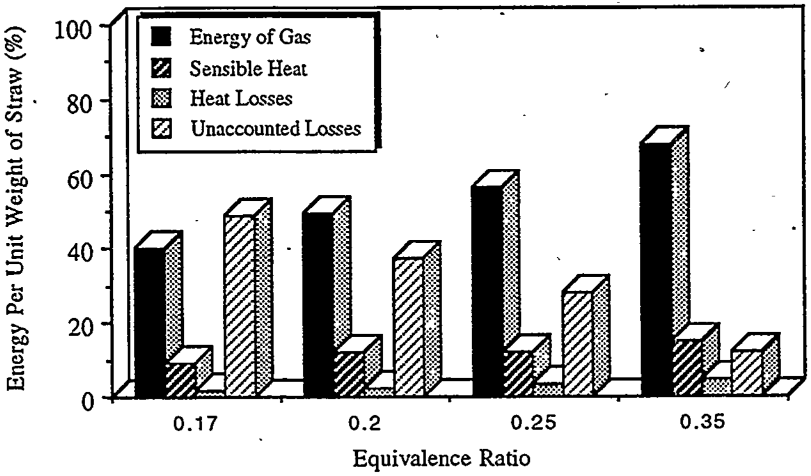
Figure 2. Fuel conversion efficiencies at various equivalence ratios, fluidization velocities and bed heights.



(a) Fluidization Velocity = 0.28 m/s

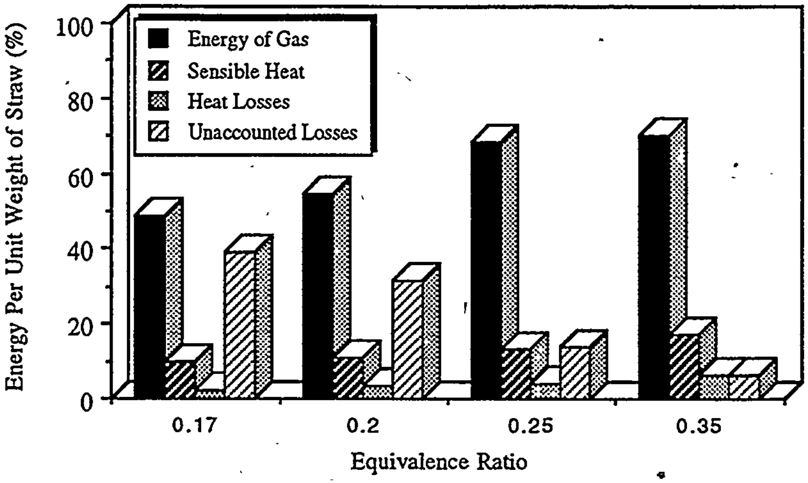


(b) Fluidization Velocity = 0.33 m/s

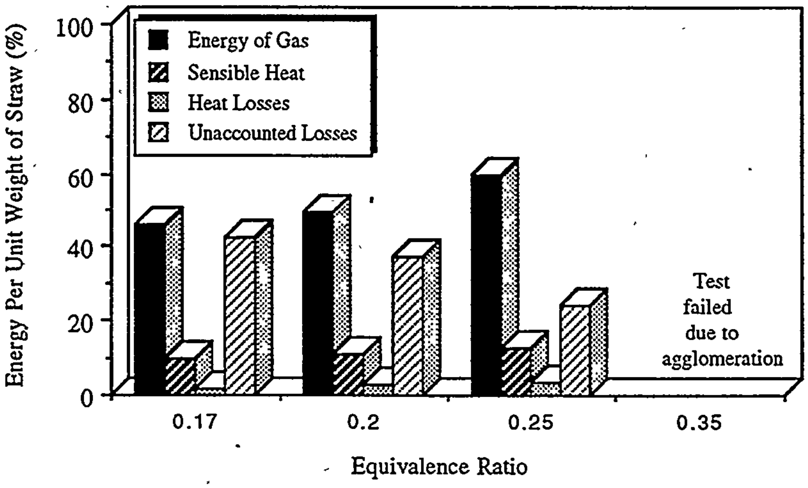


(c) Fluidization Velocity = 0.37 m/s

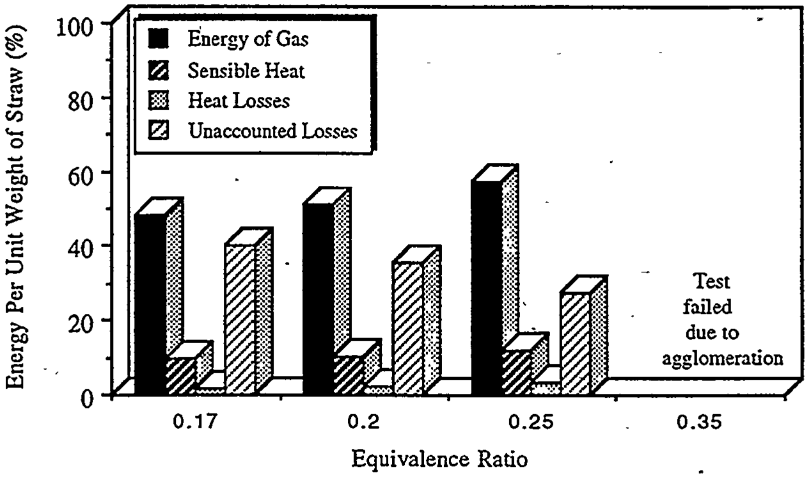
Figure 3. Energy balance of the gasifier at various equivalence ratios and fluidization velocities at a bed height of 25.5 cm.



(a) Fluidization Velocity = 0.28 m/s



(b) Fluidization Velocity = 0.33 m/s



(c) Fluidization Velocity = 0.37 m/s

Figure 4. Energy balance of the gasifier at various equivalence ratios and fluidization velocities at a bed height of 12.5 cm.

EVALUATION OF ENERGY PLANTATION CROPS IN A HIGH-THROUGHPUT INDIRECTLY HEATED BIOMASS GASIFIER

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Abstract

Experiments were run in Battelle's 10 ton per day Process Research Unit (PRU) gasifier using two high-growth, energy plantation crops--hybrid poplar--and an herbaceous biomass crop--switch grass. The results show that both feedstocks provide gas production rates, product gas compositions, and heating value similar to other biomass feedstocks tested in the Battelle gasification process.

The ash compositions of the switch grass and hybrid poplar feedstocks were high in potassium relative to previously tested biomass feedstocks. High growth biomass species tend to concentrate minerals such as potassium in the ash. The higher potassium content in the ash can then cause agglomeration problems in the gasification system. A method for controlling this agglomeration through the addition of small amounts (approximately 2 percent of the wood feed rate) of an additive could adequately control the agglomeration tendency of the ash.

During the testing program in the PRU, approximately 50 tons of hybrid poplar and 15 tons of switch grass were gasified to produce a medium Btu product gas.

Introduction

Biomass resources are an important alternative to conventional fossil fuels. Biomass resources currently supply over 3 quads to the nation's energy supply and are projected to provide between 17 and 55 quads of the nation's energy needs in the future. Biomass resources provide a means to reduce the net quantity of carbon dioxide (CO_2) emitted to the atmosphere since CO_2 is used in the growth cycle of the biomass feedstocks.

The U.S. Department of Energy has been developing a number of alternative, high-efficiency technologies to utilize these renewable energy resources. One of these promising technologies is gasification. In gasification, the biomass is converted into a mixture of gases that can later be used as a clean, gaseous fuel for heating, power generation, or as a feedstock for chemical synthesis. Chemical synthesis generally requires the use of a medium-Btu (non-nitrogen diluted) gas with minimal contaminants for optimum conversion to chemicals. Medium-Btu gas containing primarily CO and H_2 can be generated using oxygen as the gasifying medium in a single-vessel system, but the costs of pure oxygen are high. Alternatively, the gas can be generated by heating the biomass materials indirectly by using a circulating heat carrier. The resulting gas is nitrogen free, as in the oxygen blown case, but with a heating value that is slightly higher (about 500 Btu/scf).

Battelle has developed an indirectly heated biomass gasification process. Development efforts on the Battelle High Throughput Gasification Process were initiated in 1977. Detailed process development activities were initiated in 1980 with the construction and start-up of a process research unit (PRU) at Battelle's West Jefferson Laboratory. These PRU investigations, conducted during the mid-1980s demonstrated the technical feasibility of the gasification process and provided the basis for a detailed process conceptual design to be generated. Recently, testing has focused on the use of energy plantation crops as feedstocks.

The PRU design was such that the inherently high reactivity of biomass feedstocks could be exploited. Conventional reactor systems, i.e., fixed bed and bubbling fluid bed gasification processes could not provide sufficient throughput of the biomass materials to take advantage of the biomass reactivity.

The Battelle process employs a circulating fluid bed gasifier to provide sufficiently high throughputs of biomass material. Heat necessary for the gasification reactions is provided from a stream of circulating sand which passes between the gasifier and an associated combustion reactor. The process is shown schematically in Figure 1. A small amount of char is produced as a result of the gasification reactions (typically 20 percent of the feed material). This char provides the fuel for the combustor to reheat the circulating sand. The combustor like the gasifier is a circulating fluid bed reactor and also is capable of high throughputs.

Experimental data were generated in the PRU in gasifiers of 6 in. diameter and 10 in. diameter. Data from these two reactors showed that extremely high throughputs (up to 4000 lb/hr-ft^2) could be achieved. A wide range of feed materials has been tested in the system including:

- Hardwood and Softwood Chips
- Shredded Bark
- Sawdust
- Whole Tree Chips
- Shredded Stump Material

These tests demonstrated the flexibility of the system to handle a variety of biomass forms with little or no preparation. This flexibility in feedstock acceptance provides improved process economics compared to many competing processes.

As an additional process benefit, the product gas heating value is consistent regardless of the moisture or ash content of the feed material tested.

The Battelle process was found to have the following important benefits, shown in Table 1, when compared to other available technologies.

Process Description

The Basic Concept

The Battelle biomass gasification process produces a medium-Btu product gas without the need for an oxygen plant. The process schematic in Figure 1 shows the two reactors and their integration into the overall gasification process. This process uses two physically separate reactors: (1) a gasification reactor in which the biomass is converted into a medium Btu gas and residual char and (2) a combustion reactor that burns the residual char to provide heat for gasification. Heat transfer between reactors is accomplished by circulating sand between the gasifier and the combustor.

The Battelle Process provides a cooled, clean, 450-500 Btu/scf product gas with wood as the feedstock. Waste heat from the combustor flue gas can be used to preheat incoming air and then to dry the incoming feedstock. Although these unit operations are not required, they provide a means of increasing product yield by returning waste heat to the process. The condensed organic phase scrubbed from the product gas is separated from the water, in which it is insoluble, and injected into the combustor. As Figure 1 indicates, the products from the process are the cooled cleaned product gas, ash, and treated waste water.

Potential Applications of the Technology

Medium-Btu gas has many potential industrial applications. Among these options is the use of the gas as an industrial fuel to directly replace natural gas or distillate oil. The consistent heating value of the product gas from the Battelle system allows conventional combustion controls to be utilized without modification. Single vessel, direct gasification systems will supply a gas whose heating value varies with variations in feedstock, thus complicating the control of combustion processes. Another potentially important use of the gas is for power generation. Here, as in the case of direct combustion, the consistent heating value of the gas provides a means to readily control the fuel gas supply to the turbine generation system. A third important potential use for the product gas is as a synthesis gas for the production of valuable chemical or fuel products such as methanol.

To realize the potential of any of these applications, a consistent, reliable supply of biomass feedstock must be available. Waste wood or chipped wood from current supplies serve as reasonable sources for biomass energy, however to provide a sustainable, reliable energy supply dedicated energy crops must form the basic feedstock supply. The US DOE has been supporting the development of such energy crops, but thus far the research has focused on the production aspects alone. The ultimate

Table 1. Features/Benefits of the Battelle High Throughput Gasification Process

High Throughput

- Reduced Investment
- Modularized Construction

No Oxygen Plant Required

- Low Operating Costs
- Reduced Plant Investment

Separation of Gasification/Combustion Zones

- High Energy Density Product Gas -- Directly Substitutes for Oil or Natural Gas
- High Temperature Flue Gas Valuable for Heat Recovery
- Product Gas Heating Value Independent of Feed Moisture

No Significant Byproduct Production

- Process/Environmental Simplicity

Ability to Handle Wide Range of Feedstocks Without Preparation

- Minimized Feed Costs
- Increased Flexibility

usefulness of these crops depends not only on a reliable supply, but also on their acceptability as feedstocks in conversion processes.

Experiments were run in Battelle's 10 ton per day Process Research Unit (PRU) using two high-growth, energy plantation crops. Those selected represented both woody biomass -- hybrid poplar -- and an herbaceous biomass crop -- switch grass. The results of these tests are presented in this paper and show that both of these feedstocks provide gas production rates, product gas compositions, and heating value similar to other biomass feedstocks tested in the Battelle gasification process.

Experimental Equipment

Experimental operation for this program phase was conducted in the Battelle Biomass Gasification PRU. A schematic of this facility is shown in Figure 2 and a photograph of the unit is found in Figure 3. The PRU integrates all the critical unit operations required to convert biomass to a medium-Btu gas including:

- Automated transport of the feedstock from storage to a lock hopper feeder system.
- Continuously monitored feeding of the feedstock into the gasifier.
- Gasification with continuous transfer of circulating solids and char into the gasifier.
- Char combustion with circulation of hot solids back to the gasifier controlled by an L-valve.
- Scrubbing of medium-Btu product gas and continuous analytical monitoring of the product gas composition.

The PRU consists of a 10 inch diameter circulating fluidized bed gasifier coupled to a 40 inch diameter combustor. Heated sand flows from the combustor through an L-valve into the gasifier where it provides the heat necessary for the gasification reactions. The nominal throughput of the gasifier is 10 tons per day but throughputs over 12 tons per day have been achieved during the previous process development efforts.

The PRU feed system consists of a 15-ft diameter storage silo from which the feedstock is transported using a screw auger mounted so as to feed from the center of the floor of the silo. The auger feeds into a 10 HP blower which pneumatically transports the feedstock into a lock hopper assembly which is mounted on load cells to provide a constant recording of the hopper assembly plus the contained feedstock. The metering bin of the lock hopper system is mounted directly over four 4-in. metering augers which carry the feedstock into a 9-in. horizontal auger which empties into the bottom of a 9-in. vertical auger. From the top of the vertical auger the feedstock falls, by gravity, down a 6-in. diameter pipe at 20 degrees from vertical into the bottom of the gasifier. At the bottom of the gasifier the feedstock contacts the incoming hot sand and the feedstock/sand suspension is transported up the height of the gasifier.

The transport of feedstock to the hopper assembly, charging of hoppers, pressurizing of hoppers, valve operation and auger operation are automatically controlled electronically by level sensing probes in the hoppers. The lock hopper cycle time is approximately 2 minutes.

Feedstock Selection

Two high growth, energy plantation crops that show promise for wide application were evaluated during the experimental program. *Hybrid poplar* represents a woody biomass energy crop. The poplar tested was supplied to Battelle by Domtar Forest Products in Cornwall, Ontario. The trees were planted in early 1983 and harvested in February of 1992. They had been grown from 10 inch unrooted cuttings taken from 2 year old trees grown in the Ontario Provincial Government nursery. No fertilizer was used in during the growing cycle for the trees, but a herbicide was applied during the first three years to control weeds and grass. The average size at harvest was 6 inches diameter and an overall height of approximately 45 feet. The green weight was about 100 pounds per tree. Whole tree chips (~ 1.5 inch maximum) including branches, leaves, and heart wood were shipped to Battelle for testing.

The second feedstock tested, *switch grass*, is an herbaceous energy crop. *Switch grass* was obtained from Osenbaugh Grass Seeds in Lucas, Iowa. This material is grown primarily as a rotational crop and is used as cattle feed. The potential for *switch grass* as an energy crop lies in the potentially high yields of the material from currently idle farmland. The *switch grass* consisted primarily of "leaf" material rather than straw material. Some size reduction of the *switch grass* through a pug mill with a 1/2 inch screen was necessary to provide a reliable feed into the gasifier during testing. The final particle size was approximately 3/4 inch maximum. Earlier attempts to feed the as received material caused plugging in the feed screws.

Experimental Results

During this testing program, 26 tests were run in the PRU Of these 26 tests, 15 were run with hybrid poplar as the feedstock and 9 were run with switch grass as the feedstock. The following sections describe the data and results generated during this testing. These tests add to the previous data base of over 150 tests with other biomass materials.

Feedstock Evaluations - Hybrid Poplar

An important measure of the suitability of a feedstock for gasification is the amount of the feed carbon converted to gaseous products in the gasifier. This measurement provides both an indication of the relative reactivity of the feedstock and an initial measure of the efficiency of the gasification process. As expected, the conversion results from the hybrid poplar feedstock tests were consistent with previous data generated in the system with other types of wood. These previous results have been discussed in detail in DOE reports. [1,2] Product gas generation rates and composition were likewise similar to the previous results. Gasifier temperature again proved to be the most important variable in determining carbon conversion rates as shown in Figure 4. In this figure, the carbon conversion values generated with hybrid poplar are compared to the least squares fit of the data generated with other wood species. The data here shows that carbon conversion with hybrid poplar is essentially the same as that with other woody biomass. The similarity becomes even more striking when the complete data set is shown, Figure 5. The data points generated with hybrid poplar are indistinguishable from those generated during previous testing in the PRU, showing that hybrid poplar is an acceptable feedstock for gasification.

The product gas heating value, an important measure of the usefulness of the product gas, was also the same as that generated with other wood species and had a consistent heating value of about 450 Btu/scf.

An analysis of the hybrid poplar feedstock is found in Table 2. When compared to other woody biomass tested, the poplar has a higher ash content, (2.7 percent versus 1 percent or less); a higher nitrogen content, (0.6 percent versus 0.2 percent), and a lower volatile content, (12.5 percent versus 15 to 18 percent). Some of the differences can be explained by the fact that the hybrid poplar feed material was whole tree chipped material while the other wood feedstocks were cleaned chips.

Ash Constituents

Both the hybrid poplar and the switch grass feedstocks tested during this phase of the program has ash components that caused some difficulty in operation of the PRU system. High growth species generally concentrate certain compounds in their ash. These are represented by the more soluble alkaline earth materials which are found as alkaline earth oxides in the ash analysis. When the ashes of the hybrid poplar and switch grass were analyzed, high levels of potassium and phosphorous and lower levels of silica relative to previous wood feedstocks tested were found. Table 3 shows the results of these analyses for the hybrid poplar and switch grass ashes.

During two of the initial PRU tests with the hybrid poplar feed material, some instability in sand circulation through the L-valve was noticed. This instability was determined to be the result of agglomeration in the combustor sand bed to form "sand babies" caused by low melting constituents in the ash.

An examination of the ash analysis showed the ash to be 95.0 percent basic. Hence, the first thoughts concerning agglomeration centered on the possible fluxing of the acidic bed material by the basic ash. However, agglomeration of ash-CaO mixtures in DTA tests discounted ash fluxing of the sand bed as the likely cause of the agglomeration.

The presence of low-melting species initially was thought to be inconsistent with the reported ash fusion temperatures, all above 2700 F. However, it was realized that some species, such as the potassium, may have been volatilized during the ashing process so that the reported ash fusion values may represent potassium-free ash.

The "sand babies" formed during the PRU tests were submitted for scanning electron microscopic examination. These photomicrographs show that the sand particles had been glued together with a low melting material. Electron microprobe analysis showed that the "glue" between the sand particles consisted of 64.61 percent Si, 13.6 percent K, 0.94 percent Ca, 6.56 percent Ti, and 14.29 percent Fe. Similarly, analysis of the surface coating on the particle showed the same metallic species in the same general ratios.

The results of these analyses showed that the fused material did not contain sulfur. Most of the previous work on ash agglomeration from biomass species has focused on the presence of sulfur and on the resulting formation of low melting sulfates as the primary cause of agglomeration. The agglomeration found in the PRU combustor, based on the microprobe analyses, was not caused by the formation of sulfates, but appears to result from the formation of compounds such as alkali-silicates.

Differential Thermal Analysis (DTA) of the ash materials showed that two primary endothermic peaks were present in each of the samples. These peaks occur at approximately 500 C and 770 C. The melting point of potassium tetra-silicate, which is suspected as the troublesome compound, is 770 C. The formation of potassium silicate must then be prevented or the silicate must be modified after forming in order to prevent agglomeration in the bed.

In an attempt to inhibit the agglomeration tendency of the ash, additives such as kaolin clay, CaO, and MgO were tested in the DTA either with wood ash alone or with a 1:1 mixture of wood ash and bed sand. The kaolin clay was ineffective in preventing agglomeration. Therefore, it was concluded that the reaction rates for the formation of potassium silicate are sufficiently high to effectively prevent the potassium from combining with another acidic oxide (such as alumina) as a means of preventing the agglomeration. Substituting a basic oxide for the sand as the bed material would then provide the means to limit the formation of the low melting silicates to that which can be formed by the components of the ash itself. In the case of the hybrid poplar ash, the low concentration of silica in the ash would be expected to limit the quantity of silicate that can form, however, in a silica sand bed, the level of silicates that can form may still be troublesome.

Table 2. Hybrid Poplar Wood Analysis Results

Proximate Analysis		
	As Received	Dry Basis
Percent Moisture	6.89	xxxxx
Percent Ash	2.51	2.70
Percent Volatile	78.97	84.81
Percent Fixed Carbon	11.63	12.49
	100.00	100.00
Btu/lb	7615	8178
Percent Sulfur	0.02	0.02
MAF Btu		8405
Ultimate Analysis		
Percent Moisture	6.89	xxxxx
Percent Carbon	46.72	50.18
Percent Hydrogen	5.64	6.06
Percent Nitrogen	0.56	0.60
Percent Sulfur	0.02	0.02
Percent Ash	2.51	2.70
Percent Oxygen (diff)	37.66	40.44
	100.00	100.00
Percent Chlorine	0.01	0.01

Table 3. Ash Analyses

Mineral Component	% By Weight Pine Ash	% By Weight Switch Grass Ash	% By Weight Hybrid Poplar Ash
SiO_2	32.46	69.92	2.59
Al_2O_3	4.50	0.45	0.94
TiO_2	0.40	0.12	0.26
Fe_2O_3	3.53	0.45	0.50
CaO	49.20	4.80	47.20
MgO	0.44	2.60	4.40
K_2O	2.55	15.00	20.00
Na_2O	0.44	0.10	0.18
SO_3	2.47	1.90	2.74
P_2O_5	0.31	2.60	5.00
SrO	--	0.04	0.13
BaO	--	0.22	0.70
Mn_2O_4	--	0.15	0.14
Total Oxides	96.30	98.35	84.78
Carbon Dioxide, CO_2			14.00

Testing then focused on more basic oxides such as CaO and MgO. The CaO showed a slight improvement in agglomeration, while MgO resulted in a near elimination of the agglomerates in the DTA samples.

The remaining tests during the experimental program phase utilized a co-feed of MgO to control the agglomeration in the combustor bed. MgO was added at a rate approximately equal to the ash composition in the feed material or about 2 percent of the wood feed rate. Although a parametric evaluation of the minimum MgO addition rate was not conducted, qualitatively the 2 percent addition level was necessary to control agglomeration. With MgO added to the combustor bed, no restriction of combustion temperature was necessary during testing.

The potassium content in the circulating sand bed was measured at the end of each of the tests with hybrid poplar and switch grass. The potassium content stabilizes in the combustor bed at approximately 0.6 percent with the hybrid poplar and 0.5 percent with switch grass. In both cases, the maximum concentration of MgO at the end of the tests was about 3.5 percent. Such a level of MgO in the bed would provide a reasonable target concentration for control of agglomeration in a commercial gasification facility.

Feedstock Evaluations - Switch Grass

Seven tests were run in the PRU using switch grass, a candidate energy plantation crop that can easily be grown in many regions of the country. An initial shakedown test was run using switch grass that was straw-like and chopped to approximately 3 inches in length. The remaining tests were with a switch grass supply that consisted more of the leaf material and physically was more like hay to handle. This hay-like material had to be chopped to approximately 3/4" particles to provide a reliable feed rate to the PRU.

The PRU tests run confirmed the suitability of switch grass as a viable gasification feedstock. Conversion levels and gas production rates were slightly lower than with the woody biomass species, as shown in Figure 6, but were generally within the scatter for the complete data set as shown in Figure 5. The switch grass exhibited a low bulk density (approximately half that of wood) which restricted the achievable feed rates to approximately 600 pounds per hour. A typical switch grass analysis is found in Table 4. As shown, the ash content of the switch grass is nearly 5 times higher than that of the hybrid poplar, yet the gasifier performance as expressed in terms of carbon conversion, is very much in line with the results generated with the hybrid poplar. The extremely high heat up rates and the separation of gasification and combustion zones in the Battelle gasification system are the probable reasons for this result. Some of the carbon in switch grass, like that in some other herbaceous feed materials such as rice hulls, tends to be enclosed in a silica matrix. In some conversion systems, this can restrict the availability of the carbon and can therefore lower overall conversion levels.

Table 4. Switch Grass Analysis Results

Proximate Analysis		
	As Received	Dry Basis
Percent Moisture	12.05	xxxxx
Percent Ash	8.89	10.11
Percent Volatile	63.02	71.65
Percent Fixed Carbon	16.04	18.24
	100.00	100.00
Btu/lb	6808	7741
Percent Sulfur	0.09	0.10
MAF Btu		8612
Ultimate Analysis		
Percent Moisture	12.05	xxxxx
Percent Carbon	42.03	47.79
Percent Hydrogen	5.07	5.76
Percent Nitrogen	1.03	1.17
Percent Sulfur	0.09	0.10
Percent Ash	8.89	10.11
Percent Oxygen (diff)	30.84	35.07
	100.00	100.00
Percent Chlorine	0.12	0.14

The gas composition and heating value is approximately the same as that generated with hybrid poplar as shown in Table 5.

Table 5. Typical Product Gas Compositions With Energy Plantation Crops

	Baseline	Hybrid Poplar	Switch Grass
H_2	17.5	26.1	24.0
CO	50.4	37.8	39.6
CO_2	9.4	15.2	15.9
CH_4	15.5	14.7	14.2
C_2H_4	6.1	5.2	5.3
C_2H_6	1.1	0.4	0.3
Heating Value Btu/scf	493	455	449

Conclusions

The results of this program have shown that the Battelle Biomass Gasification process has significant potential as a candidate for commercial application because of the ability to effectively process a range of feedstocks and efficiently produce a medium Btu gas. The large data base available helps reduce the risk in moving from PRU scale to commercial scale operation.

Operation with energy plantation crops such as hybrid poplar and switch grass shows that these materials have significant potential as feedstocks for the generation of medium Btu gas. There are differences between the energy plantation crops and other forms of biomass that will require engineering design changes and/or slight changes in operating conditions. The tests at Battelle have identified some of these operating issues and have shown that the changes are relatively minor and should not have a negative impact on process operation or economics.

Engineering design changes such as the use of an additive to control agglomeration or a different preparation method for the feedstock are common practice in energy conversion systems. In coal combustion processes, for instance, such changes are made to provide a boiler operator with the flexibility to fire a range of coals without significant slagging or fouling. The changes in a biomass conversion system necessary to utilize energy plantation crops are of a similar nature.

The engineering solutions developed significantly improve the potential for operation of gasification based biomass energy plantations. Assuming adequate production of these feedstocks at reasonable costs, gasification of these crops can provide a sound basis for the development of integrated energy plantations.

Acknowledgements

The authors wish to acknowledge the technical support and guidance of Ralph Overend and Rich Bain of NREL and Tom Miles for his valuable help in feeding diverse materials such as switch grass.

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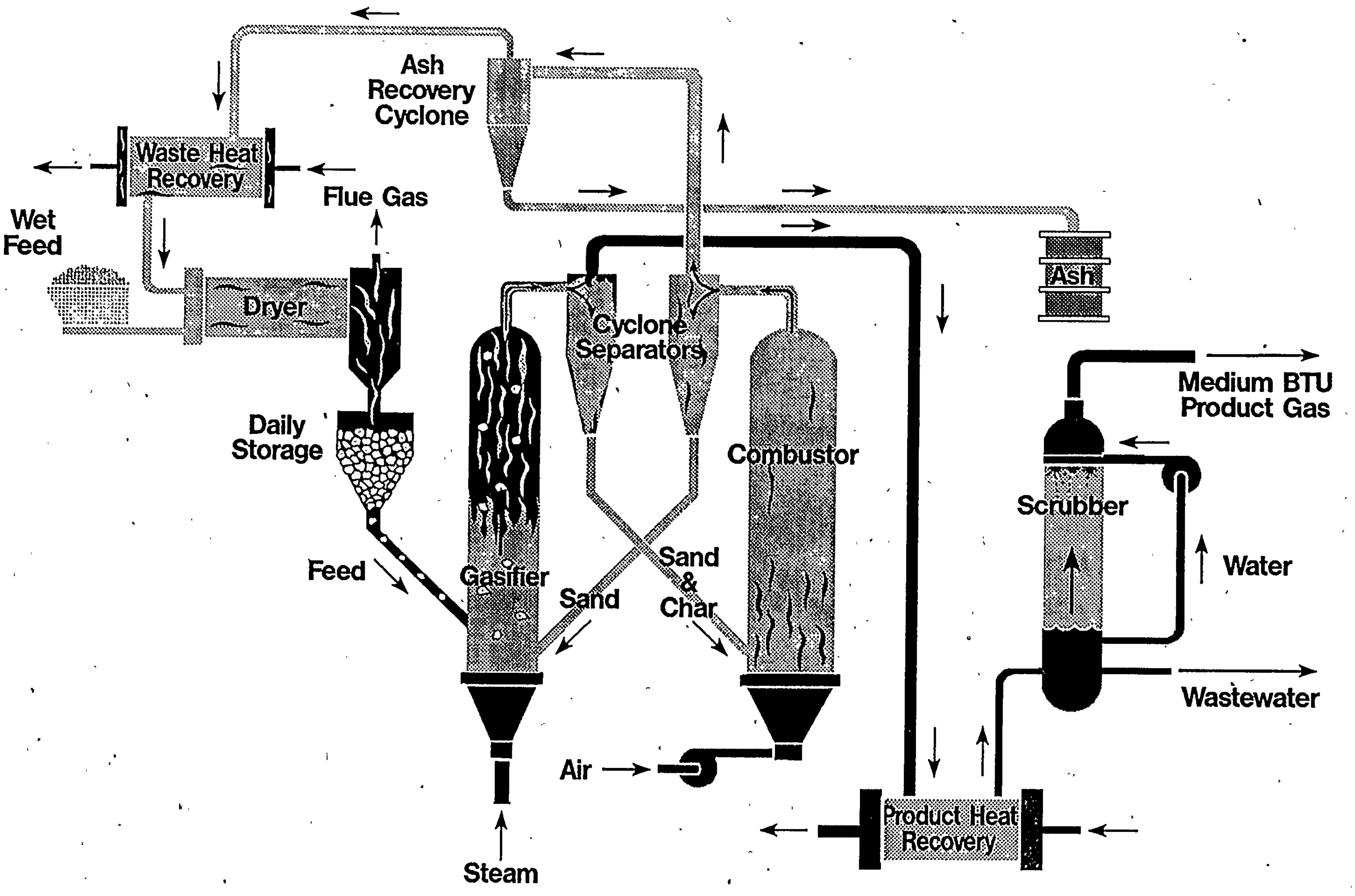

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Figure 1. The Battelle High Throughput Gasification Process

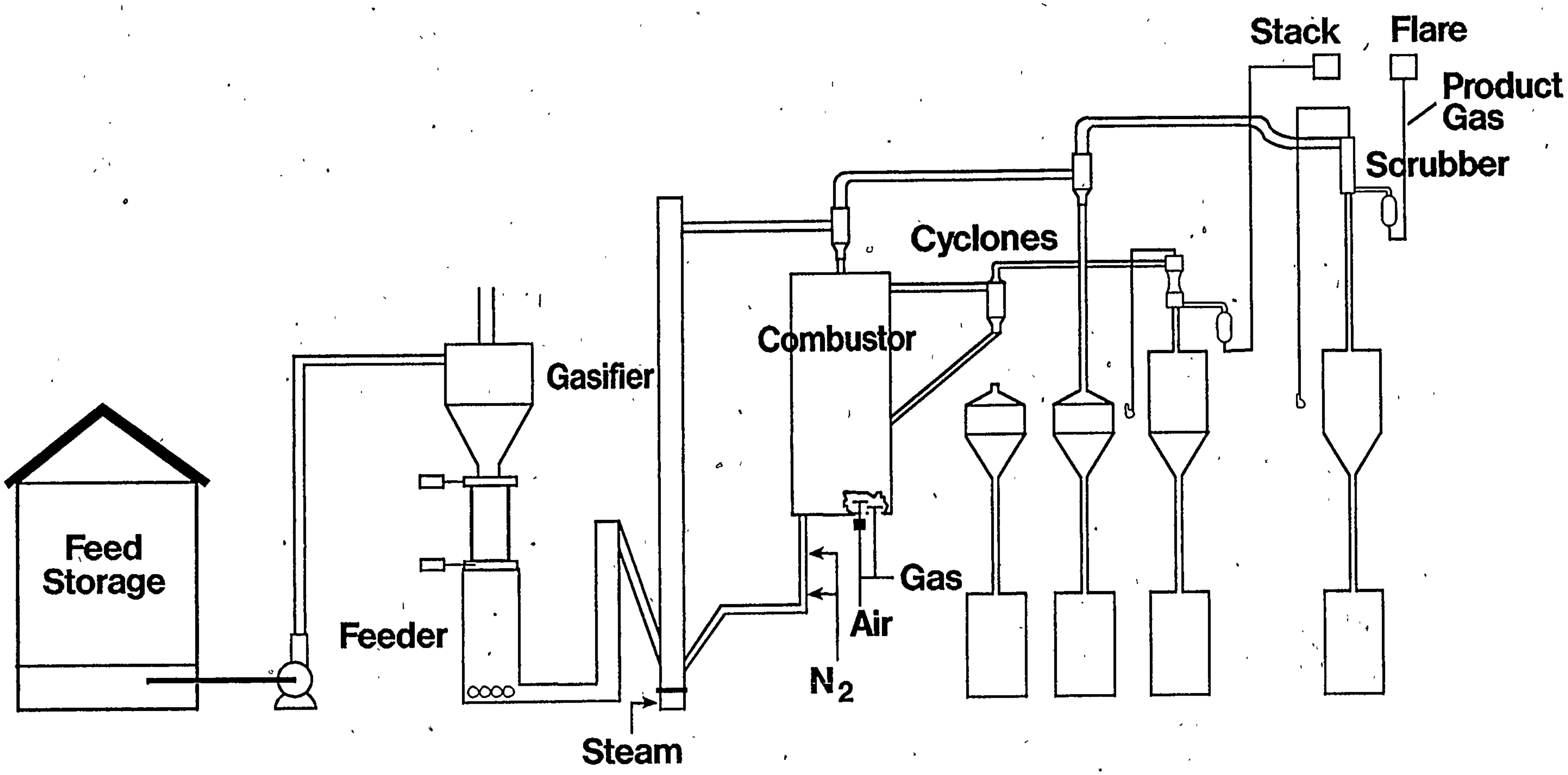

Figure 2. Battelle's Biomass Gasification PRU

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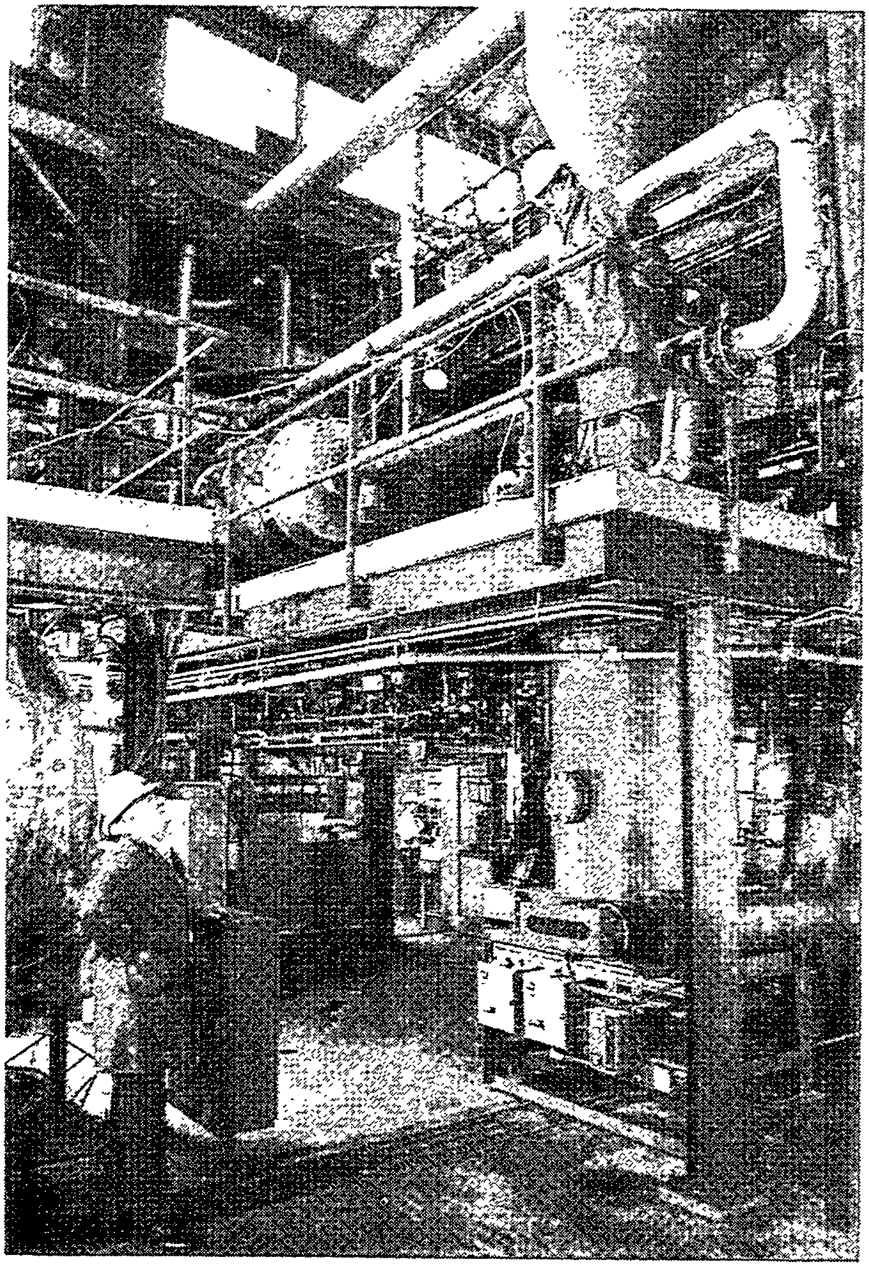

Figure 3. Photograph of Battelle's Biomass Gasification PRU

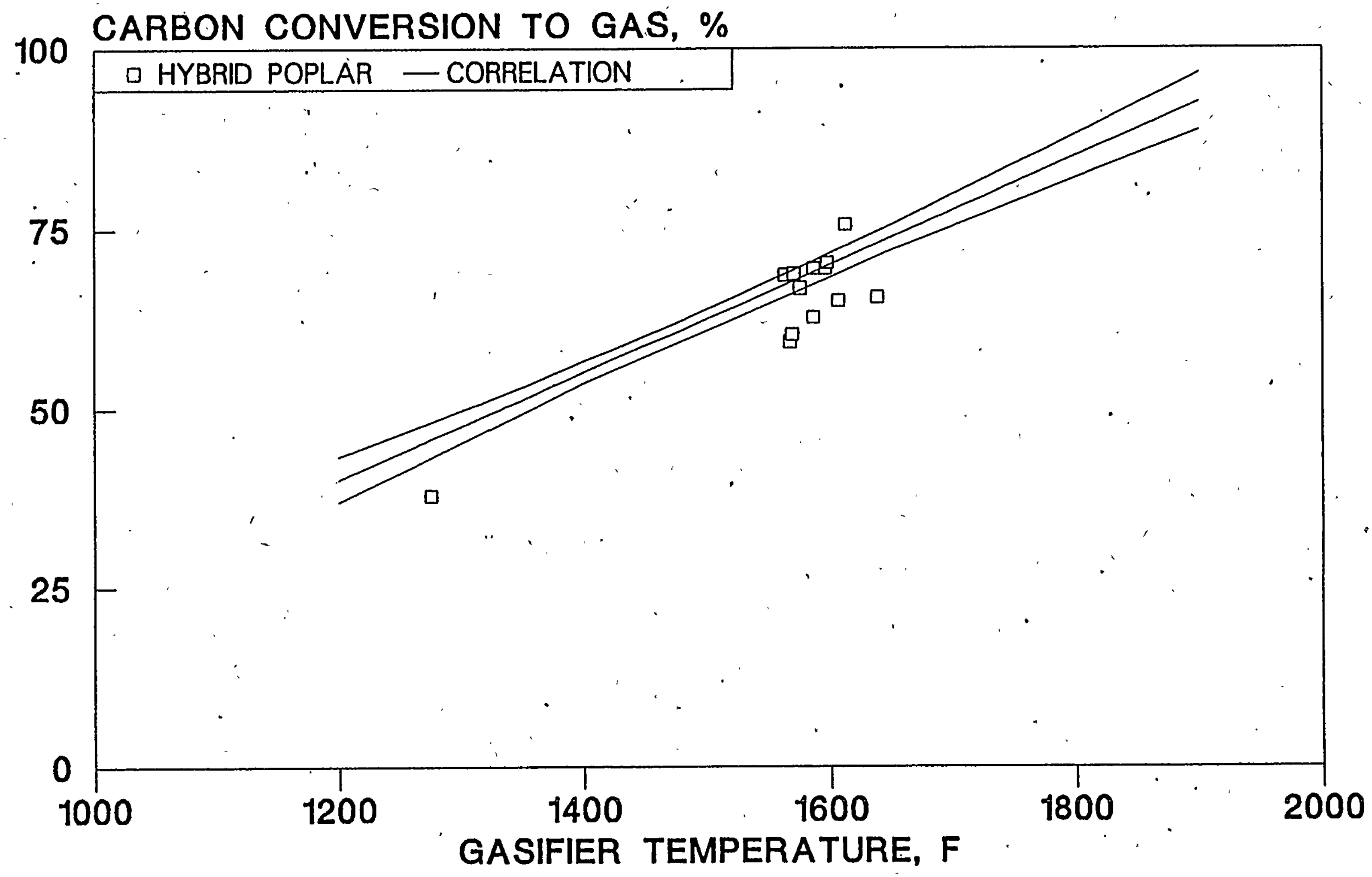

Figure 4. Carbon Conversion to Gas Hybrid Poplar Data

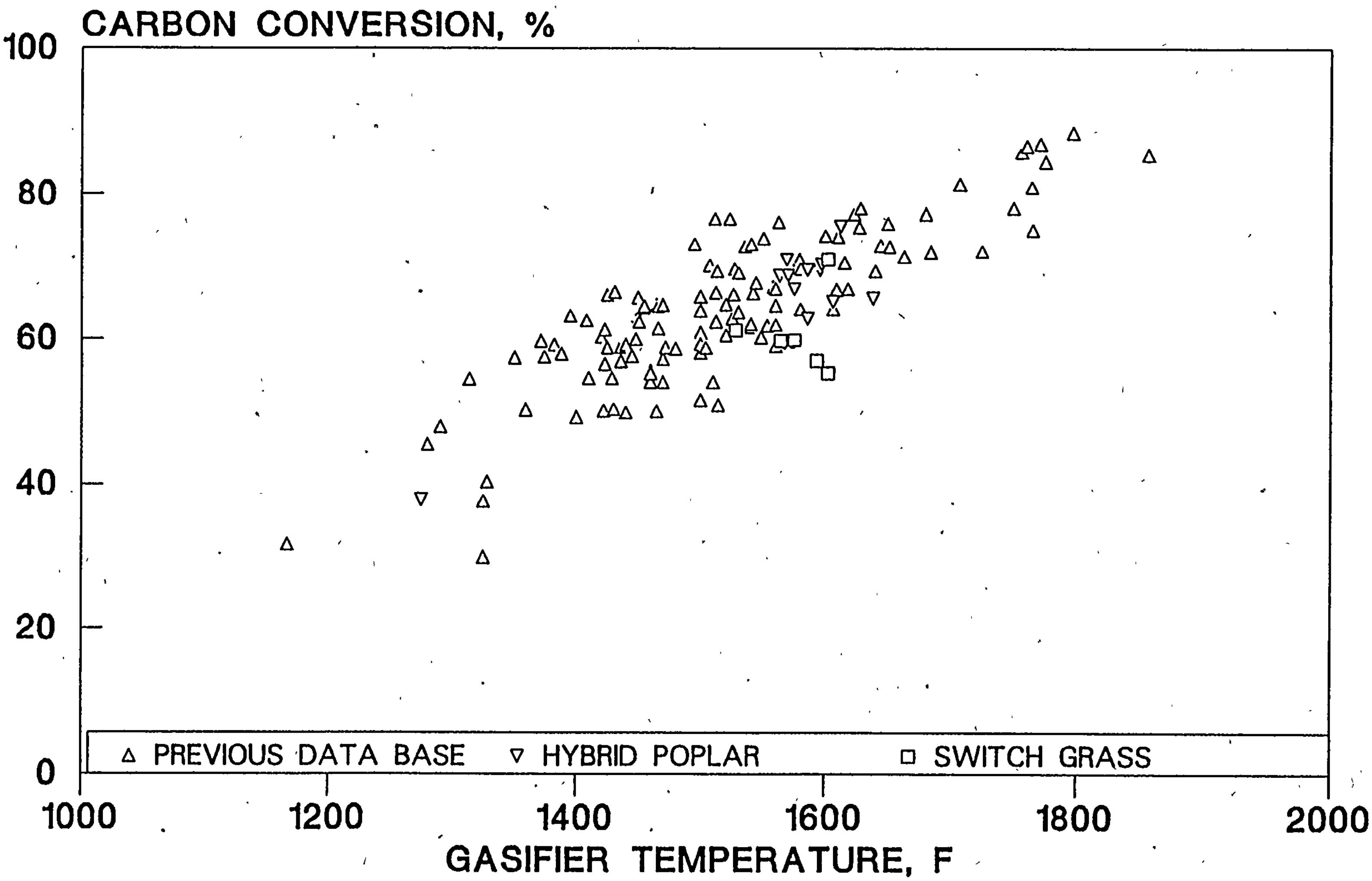

Figure 5. Biomass Gasification Carbon Conversion Hybrid Poplar and Switch Grass Compared to Previous Data Base

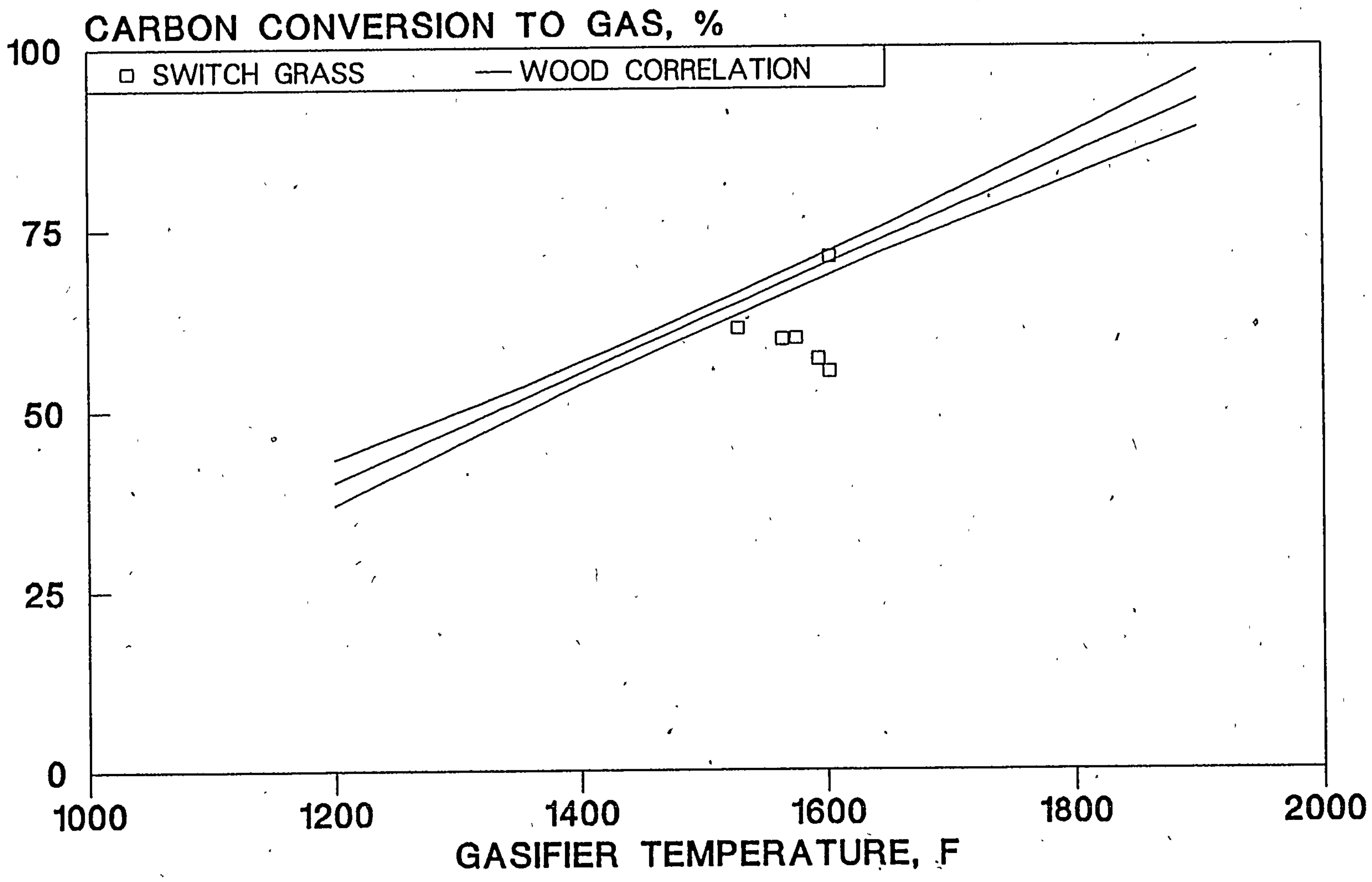

Figure 6. Carbon Conversion to Gas Switch Grass Data

Development of a Catalytic System for Gasification of Wet Biomass

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Abstract

A gasification system is under development at Pacific Northwest Laboratory that can be used with high-moisture biomass feedstocks. The system operates at 350°C and 205 atm using a liquid water phase as the processing medium. Since a pressurized system is used, the wet biomass can be fed as a slurry to the reactor without drying. Through the development of catalysts, a useful processing system has been produced.

This paper includes assessment of processing test results of different catalysts. Reactor system results including batch, bench-scale continuous, and engineering-scale processing results are presented to demonstrate the applicability of this catalytic gasification system to biomass. The system has utility both for direct conversion of biomass to fuel gas or as a wastewater cleanup system for treatment of uncoverted biomass from bioconversion processes.

By the use of this system high conversions of biomass to fuel gas can be achieved. Medium-Btu gas is the primary product. Potential exists for recovery/recycle of some of the unreacted inorganic components from the biomass in the aqueous byproduct stream.

Introduction

A pressurized catalytic gasification process, operated at low-temperature, is available under the trade name TEES® (Thermochemical Environmental Energy System, a registered trademark of Onsite*Ofsite, Inc., Duarte, California). It is effective for treating wet biomass streams to address both environmental cleanup and energy recovery goals. Through a liquid-phase, heterogeneously catalyzed process operated at nominally 350°C and 205 atm, TEES produces a methane/carbon dioxide product gas from water solutions or slurries of organics. This biomass gasification process was specifically developed for processing high-moisture biomasses (high-growth grasses, marine and aquatic biomass, and food processing residues), which are not efficiently gasified in conventional, low-pressure thermal systems (Elliott and Sealock 1985; Sealock et al. 1988) . Later studies applied the technology to the destruction of hazardous organic chemical wastes and organic chemical manufacturing wastewaters (Baker and Sealock 1988) as well as biomass feedstocks (Elliott et al. 1991).

Part of the continuing development of the TEES technology has involved studies on catalyst efficiency and integrity. Nickel catalysts have been used in the system throughout its development and scaleup. This paper discusses experiments conducted and catalysts formulated for the purpose of maintaining high conversion and longer catalyst lifetimes in the subcritical, high-temperature, liquid-phase water operating environment of the TEES process. Many conventional catalysts developed for steam reforming, hydrogenation, and methanation, (the chemical mechanisms involved in TEES) have been evaluated. Many of these catalysts were found to be active for converting organics to methane and carbon dioxide but were not satisfactory for long-term operation. Experiments are described here which were used to evaluate a wide range of catalyst materials and support compositions.

In addition, this paper describes test results from the reactor systems which have been constructed to develop TEES for wet biomass applications. Most of our recent results are from continuous-flow reactor studies with a fixed bed of catalyst in a tubular reactor. These tests demonstrate the scale-up of a useful reactor configuration for industrial application of the TEES technology.

BACKGROUND

The use of high-pressure liquid water at elevated temperatures as a processing environment has recently been reviewed (Sealock et al. 1993). One application of this processing environment is for catalytic gasification of biomass. In this application, which we call TEES, catalysts accelerate the reaction of biomass with water and produce methane and carbon dioxide from the pyrolysis intermediates. TEES has been reported both as a means of recovering useful energy from wet biomass and other organics in water and as a water treatment system for more dilute hazardous organic contaminants. Batch reactor test results have demonstrated process applicability to a wide range of organic components (Sealock et al. 1988; Baker and Sealock 1988; Elliott et al 1993b). Development of catalysts for this processing environment has also been an important factor in making this processing technology viable (Elliott et al. 1993a).

TEES processing involves relatively complex chemistry including pyrolysis, steam-reforming, hydrogenation, methanation and water-gas shift. Specific chemistry varies with the feedstock type. For the biomass carbohydrate feedstocks used in the experiments described here, various reaction pathways are suggested by the products that have been identified:

$C_6H_{10}O_5 + H_2O \rightarrow 6CO + 6H_2$	steam-reforming
$CO + 3H_2 \rightarrow CH_4 + H_2O$	methanation
$CO + H_2O \rightarrow CO_2 + H_2$	water-gas shift

The overall stoichiometry approximates:

$$C_6H_{10}O_5 + H_2O \rightarrow 3CH_4 + 3CO_2$$

A thermodynamic equilibrium limitation of about 1% residual hydrogen (Sealock et al. 1988) shifts the methane/carbon dioxide product ratio slightly more toward the carbon dioxide than is suggested in the given stoichiometry.

Early gasification tests in supercritical water showed no evidence of catalytic effects (Modell et al. 1981). Our past catalyst studies for the TEES concept have addressed contacting (mass transfer limitations) and the active form of the nickel catalyst (Butner et al. 1987). Clear evidence was presented on the need for reduction of the nickel catalyst prior to processing (Baker and Sealock 1988). The reduced effectiveness of other Group VIII metals (compared to nickel), because of their oxidation (in high-temperature water) or lack of specific activity, was also reported (Baker and Sealock 1988). Evidence of the instability of conventional catalyst support materials when used at the reaction conditions was initially reported by Elliott et al. (1991). Continuous-flow reactor tests indicated that long-term stability of the nickel catalyst was a critical developmental requirement (Elliott et al. 1989; Baker et al. 1989a; Baker et al. 1989b, Elliott et al. 1991).

Process Development

Process development results can be conveniently separated into catalyst development efforts and continuous reactor test results with biomass feedstocks.

Catalyst Development

The preliminary catalyst tests were performed in a batch reactor. These experiments tested the activity of the catalyst for the gasification and methanation of a model compound, para-cresol, and the long-term stability of the support in the high-pressure water reaction environment. Five groups of tests involving several different catalyst types or support materials are presented. The results of these tests are presented in Table1. The details of these tests are published elsewhere (Elliott et al. 1993a).

Table 1. Summary of Conclusions on TEES Catalysts and Catalyst Supports

Useful Catalytic Metals	Inactive Metals	Metals Oxidized at Conditions
Ru	Pt	Co[2]
Rh	Pd	Fe[2]
Ni[1]	Cu	Cr
		Mo
		W
		Zn
Stable Supports	Unstable Supports	Hydrolyzable Supports
α-Al_2O_3	TiO_2	γ-Al_2O_3
ZrO_2	SiO_2	δ-Al_2O_3
C	Ca/aluminate[3]	η-Al_2O_3
	Kieselguhr[3]	SiO_2/Al_2O_3[3]

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[1] subject to sintering
[2] Baker et al. 1988
[3] Elliott et al. 1991

Base Metal Catalysis of TEES

Various base metals and base metal combinations were tested as catalysts for TEES in the batch reactor system. The test results show that only the copper-zinc oxide catalyst exhibits any significant activity for the conversion of para-cresol or for methane formation. Essentially no activity is seen for all of the other catalysts despite the range of metal loading and physical properties of the catalysts tested. Most of the metals oxidized during the short batch test, as shown by x-ray diffraction (XRD) analysis of the spent catalysts; only copper remained reduced at these reaction conditions.

Innovative Nickel Catalysis of TEES

Several different forms of nickel catalysts were tested in order to evaluate both their activity and their stability in the TEES operating environment. The forms included unsupported metal and solutions of nickel salts, neither of which were likely to be useful but both of which eliminated the need of a stable support. Only the conventional catalyst materials had significant catalyst activity. The nickel nitrate solution, which seems to show some activity, actually was serving as a reactant in that the nitrate oxidized a stoichiomtric amount of organic and then the reaction ceased. Nickel ion in solution appears to have no catalytic activity, as further supported by other tests with acetate (Elliott et al. 1993b). The different nickel metal forms, although highly divided, are just too limited in surface area to be useful as catalysts. The wire mesh had only about 0.0035 m^2/g of surface area, while the nickel metal powder (assuming spherical particles) had only about 0.0045 m^2/g of surface area. For comparison, the Ni-0750 supported catalyst is reported to have 145 m^2/g of surface area.

Sputtered-Ni on zirconia catalysts were nearly inactive. Loading of metal was limited to <20 wt%. Crystal-lite size was reasonable (200-400Å) implying a useful extent of Ni dispersion and surface area, but, apparently, the Ni was not well distributed in the sputtering process and the resulting surface area was low. Addition of the Y did not improve the dispersion as the activity was still nearly nonexistent.

Raney® (Grace-Davison Specialty Chemical Company) nickel is an Al-Ni alloy with the Al leached away by strong caustic to leave a highly porous Ni. The Raney nickel catalysts showed strong activity in the TEES environment both for gasification of organic and for methanation. Nearly all the para-cresol was removed from the water phase as indicated by the reduction of chemical oxygen demand (COD) of greater than 99% in both cases, as it was with the Ni-0750 catalyst. The Ni on alumina catalyst (Ni-0750) showed strong activity. The carbon deposition on the slurried catalyst was only slightly higher than the fresh catalyst.

Conventional Supported-Nickel Catalysts

Numerous conventional supported nickel catalysts have been tested in TEES. The supported nickel catalysts exhibited a wide range of activities in the TEES environment, as shown by the results in Table 2. Table 2 includes data on the percentage of feedstock carbon converted to gas species (methane, carbon dioxide, ethane). The listed time is for minutes at temperature before the reaction was quenched. The Ni-0750 (a hydrogenation catalyst) and the two BASF catalysts, Cat A and Cat B, (methanation catalysts) were the most active for gasification and methanation. The Ni-6220 catalyst (a hydrogenation catalyst) appeared to be nearly inactive. The PK-5 (a methanation catalyst) contains a lesser amount of nickel, 25%, and was not completely reduced in this single batch test, based on hydrogen consumption calculations. Its low activity in the batch test confirms our earlier report of low activity in a continuous reactor test (Elliott et al. 1991). RKNR (a steam reforming catalyst) and C150, G49B, and C11-09-04 (methanation and steam reforming catalysts) have intermediate activities.

The spent catalysts from these tests were analyzed to determine if any significant changes had occurred. In addition, other samples of some of these catalysts were subjected to long-term batch tests in water. These samples were also analyzed to determine changes resulting from exposure to the high-pressure steam/water environment at 350°C. Table 3 lists the components identified in the spent catalysts. XRD analysis of the spent catalysts proved that the nickel metal stayed reduced; however, there were significant changes noted in the composition of some of the support materials.

Table 2. Results of Tests with Various Supported Nickel Catalysts

Catalyst	% Carbon Conversion	Product Gas, Vol%			Time, min	Spent Catalyst Form
		CH_4	CO_2	H_2		
Ni-0750 R-S	88.63	61.9	34.9	2.4	90	Ni, AlOOH (böhmite)
BASF Cat A	73.53	58.2	37.0	3.5	90	Ni,
BASF Cat B	68.62	60.8	34.5	3.7	90	Ni,
C150 R-S	54.21	57.9	36.1	4.1	100	NA
G49B R-S	38.37	55.2	36.4	6.5	100	NA
RKNR R-S	24.30	29.8	29.6	38.8	80	NA
C11-09-04 R-S	5.24	15.2	32.5	50.3	100	Ni, α-alumina
PK-5 (2/3 reduced)	4.44	13.2	39.8	46.0	110	NiO, Ni, α- & η-alumina
Ni-6220 R-S	0.82	3.1	24.2	70.4	75	Ni, amorphous support

NA = not available.

Supported Noble Metal Catalysts

Recently we have begun testing noble metal catalysts for TEES. Particularly interesting are Rh and Ru as these metals have been found by others to be useful methanation catalysts (Vannice 1975). Catalyst formulations with these metals typically contain much lower levels of metal because of their high cost. Ru and Rh catalysts demonstrated significant activity for the conversion of para-cresol to methane and carbon dioxide in the TEES processing system. The COD conversion was >99% for the Ru on γ-alumina catalyzed test. Recent Pt and Pd test results confirm our earlier reports of the lack of activity in TEES of Pd (Elliott et al. 1991).

Catalyst Support Evaluations

Numerous types of catalyst support materials have been tested in the TEES environment. These materials were chosen from commercially available support materials. Extensive reaction with water has been discovered for most of these materials. All forms of alumina, except α-alumina, react to form γ-AlOOH, böhmite. The reaction of γ-alumina to böhmite results in a significant loss in physical integrity, as shown by the crush strength for Ni-0750 in Table 5. The conversion of δ-alumina to böhmite resulted in a dramatic loss in surface area from 147 m^2/g to 15 m^2/g. The stability of the α-alumina may also be tenuous since we are actually operating just outside the α-alumina range (and in the böhmite range) in the phase diagram reported in the literature (Ervin and Osborn 1951). The monoclinic form of zirconia appears to be quite stable at these conditions, and tablets made of this material seem to maintain their integrity. Silica also is unreactive, but the dissolution of some of the material probably explains the destruction of the extruded pellets. Titania also appears to be unreactive at these conditions. One form of tableted titania, similar to the zirconia tablet, lost its physical strength after processing at TEES conditions. A carbon-supported ruthenium catalyst was evaluated for long-term stability in the batch reactor with only water present. Formation of small amounts of carbon dioxide and methane suggests that the ruthenium metal would catalyze the destruction of its support at a slow rate. Extrapolation of the gas production rate for 65 hours suggests a 542-day lifetime for the carbon granule.

Continuous Reactor Tests

Gasification tests were carried out in three scales of fixed-bed catalytic tubular reactor. The bench-scale unit, shown schematically in Figure 1, was described in detail in an earlier report (Elliott et al. 1991). The unit consisted of a 6 ft long X 1 in. I.D. 304SS tube which was fed from a cylindrical feed tank by a reciprocating plunger pump. The reactor was heated by an electrical resistance furnace and essentially served as both the preheater and the reactor. Pressure was controlled in the reactor by a dome-loaded, back-pressure regulator. The pressure regulator was followed by a condenser/separator system in which liquid samples were recovered. Uncondensed product gas was passed through flow meters and vented.

A microtubular version of this reactor system was used for catalyst lifetime studies. All the components shown in Figure 1 for the bench-scale unit were the same for the microtubular reactor system except for the pump and the reactor. A smaller reciprocating plunger pump was used to feed a reactor consisting of 12 in. of 1/2 in. 316SS tubing. In addition to the reactor, there was a preheater section consisting of 7 ft of 1/8 in. tubing. Both the reactor and the preheater were contained in the electrical resistance reactor furnace.

A scaled-up reactor system (SRS) was based on the bench-scale design. It was a transportable system designed at a scale of one-half ton per day of wet feed for obtaining engineering data for further scale-up of TEES. The SRS was mounted on a single 8 ft x 10 ft skid platform that could be transported on a single flat-bed truck. Equipped with three 6 ft X 2 in. I.D. fixed-bed tubular reactors and supporting equipment to achieve conversion, the test system's capacity was a one-half ton per day liquid feed with a design flow rate of 5 gal/hr. Design working conditions for the reactors were 350°C at 238 atm. This system is described in detail by Elliott et al. (1993c).

Evaluation of Catalysts

Several metal catalysts have been evaluated in the TEES continuous reactor systems. Based on catalyst screening in batch reactor tests, the focus of these evaluations was on the use of Ni and Ru as the catalytic metal. Catalyst support effects are also an important consideration, and several different support materials and unsupported Raney nickel catalyst were evaluated.

As shown by the results in Table 3, the long-term operation of Ni-0750 shows a definite loss of activity over time. The long-term loss of activity is apparent even when stable short-term activity has been demonstrated. The loss of activity is evident in the reduced level of COD destruction, lower gas yields, and shift in gas composition away from methane to hydrogen and higher hydrocarbons. The BASF catalyst shows much better long-term stability than the Ni-0750. Note that Table 3 is a combination of bench-scale results for the Ni-0750 catalyst and microscale results for the BASF catalyst, so the gas yield results cannot be compared directly from one catalyst to the other.

Table 3. Extended-Time Experimental Results with Nickel Catalysts

Feedstocks	Ni-0750 p-cresol	Ni-0750 p-cresol & phenol	BASF p-cresol & phenol	BASF p-cresol
Time on Stream, hr	38	72	240	620
Results				
Gasification of Carbon, %	99.1	23.4	101.4	89.2
Reduction of COD, %	99.94	68.2	99.8	97.6
Feed, L/hr	1.6	1.6	0.036	0.017
LHSV, L/L/hr	2.7	2.7	1.2	0.8
Gas Yield, L/hr	41.5	8.9	1.1	0.5
Effluent COD, ppm	30	14900	95	1710
Effluent pH	3.9	4.7	NA	NA
Gas Composition, volume %				
Methane	61	45	59	59
Carbon Dioxide	36	41	39	37
Hydrogen	1.6	6.2	0.4	0.7
Ethane	0.4	1.4	0.5	0.7
Backflush	0.6	5.7	1.0	1.7
Btu/SCF	646	669	634	666

Catalyst bed conditions: 350°C to 369°C and 21 to 22 MPa.
Organic loading of 1.8 wt% in water as feedstock.

Metal agglomeration is a primary concern for catalysts used in TEES. Catalytic metal crystallite size has been correlated with the loss of active surface area and, hence, catalytic activity (Pearce and Patterson 1981). Figure 2 shows that different catalysts exhibit different rates and amounts of agglomeration. For example, the Ni-0750 catalyst shows a nearly straight line growth in crystal size, while the BASF catalyst shows an initial growth of crystal size followed by a stable period which has been demonstrated for up to 4 weeks. The change in the Raney nickel is more nearly like the Ni-0750 than the BASF catalyst. The data in Figure 2 are derived from tests in all three scales of continuous-feed reactor system. There is no significant difference in catalytic metal agglomeration that can be correlated to any of the scales of operation.

A different situation was found with Ru. Ru showed no evidence of crystal growth. As seen in Figure 2, even a slight reduction in crystal size was apparent (although the change is just at the limit of the experimental error of the analysis). There was little evidence of an effect of the support on crystal growth. The Ru did not agglomerate when supported on the δ-alumina (which is also readily converted to böhmite), as is shown in Figure 2. Analyses of the Ru on zirconia showed no sign of change as the Ru crystallite size remained much less than 10 nm for several samples recovered during 6 weeks of operation. Analysis of the zirconia support showed no significant growth of the crystallite size after the first 2 days of operation.

Table 4 provides results of long-term tests for comparison of two Ru catalysts. These tests showed good maintenance of conversion over time for both catalysts. COD destruction remained high with good gas yield. The alumina-supported catalyst showed significant loss of activity after 10 days of operation as evidenced by the lower space velocity required to maintain conversion levels. A shift away from methanation was noticeable toward the end of a 6-week test with the zirconia-supported Ru, while the level of conversion remained high.

Table 4. Extended-Time Experimental Results with Ruthenium Catalysts

	Ru/Al_2O_3	Ru/Al_2O_3	Ru/Al_2O_3	Ru/ZrO_2	Ru/ZrO_2
Feedstocks	p-cresol	p-cresol	p-cresol	phenol	phenol
Time on Stream, hr	80	140	230	432	864
Results					
Gasification of Carbon, %	95.4	90.6	97.6	100.2	83
Reduction of COD, %	98.5	96.6	99.4	99.4	95.6
Feed, L/hr	2.0	1.3	1.2	0.038	0.036
LHSV, L/L/hr	3.7	2.1	1.9	1.5	1.5
Gas Yield, L/hr	46.3	27.7	29.1	1.1	0.85
Effluent COD, ppm	718	1500	279	365	2300
Effluent pH	3.8	3.6	3.9	NA	NA
Gas Composition, volume %					
Methane	60	58	58	58	47
Carbon Dioxide	36	38	38	38	45
Hydrogen	1.6	1.6	1.2	1.6	2.7
Ethane	1.2	1.5	1.2	1.2	1.7
Backflush	1.6	1.9	1.3	1.5	3.4
Btu/SCF	681	671	656	654	615

Catalyst bed conditions: 350°C to 360°C and 21 MPa.
Organic loading of 1.8 to 2.0 wt% in water as feedstock.

Bench-Scale Reactor Tests with Industrial Wastes

Bench-scale reactor tests of TEES were also performed for biomass materials from commercial processes. These materials included olive wash water, delactosed cheese whey, and brewer's spent grain and spent grain liquor. As shown in Table 5, the test with the olive wash water had good results in terms of COD destruction. There was a significant ammonia product in the effluent water from nitrogen in the organic feed. Further treatment for ammonia removal may be required or incorporated into the process. One potential process modification for ammonia removal compatible with TEES is the reaction with stoichiometric amounts of nitric acid (Elliott et al. 1993b). The low gas recovery in these tests was probably as a result of carbonate formation with the ammonia. Alkali in the olive (and cheese whey) feedstock would also form carbonates at these conditions and further sequester carbon dioxide product gas.

In both of the cheese whey tests the result presented was only maintained for a limited time. Loss of catalyst activity occurred over a period of hours, apparently as a result of precipitation of alkali salts in the catalyst bed, coating the pellets and plugging the catalyst pores. Whitlockite, a calcium magnesium hydrogen phosphate ($Ca_{18}Mg_2H_2(PO_4)_{14}$) has been identified by XRD of the deposits. The

Table 5. Experimental Results with Industrial Waste Streams

	Olive Wash Water	Cheese Whey, Delactosed	Cheese Whey, Delactosed
Catalyst	Ni-0750	Ni-0750	5% Ru
Results			
Gasification of Carbon, %	41.9	85.0	76.5
Reduction of COD, %	99.9	97.5	93.4
Feed, L/hr	1.5	1.3	1.8
LHSV, L/L/hr	2.5	2.3	3.4
Gas Yield, L/hr	7.3	80.9	96.1
Effluent COD, ppm	30	3700	8500
Effluent NH_4^+, ppm	350	NA	NA
Effluent pH	6.9	7.0	NA
Gas Composition, volume %			
Methane	62	48	48
Carbon Dioxide	35	48	47
Hydrogen	2.1	1.9	3.8
Ethane	0.5	1.3	1.0
Backflush	0.0	1.3	0.0
Btu/SCF	649	555	515

Catalyst bed conditions: 350°C and 21 MPa.

delactosed cheese whey is a much higher concentration feedstock than tested in TEES in the past (Elliott et al. 1991). The delactosed feed was actually diluted 1:1 with water for these tests but was still about twice as concentrated as in earlier tests. In addition, the delactosed feed would likely be less readily processed than whole cheese whey, as the more easily pyrolyzed components, the sugars, have been removed to a large degree, leaving the fats, proteins, and minerals. Long-chain hydrocarbons, as would be found in fats, have been shown to react more slowly in TEES (Elliott et al. 1993b). Therefore, the results reported in Table 5 are not quite as good as those reported earlier for conventional cheese whey.

Results from two tests with brewer's spent grain are provided in Table 6. The first test was done in the standard tubular reactor configuration. In this test, initial conversion was quite good, but a steady loss of activity was noted. After the test the catalyst bed was removed for analysis. The lower portion of the bed contained catalyst pellets coated with a brown material, which was analyzed by XRD and found to contain, as the principal crystalline phases, hydroxylapatite [$Ca_5(PO_4)_3OH$] and Ni_3S_2. However, the nickel catalyst itself showed no unusual changes. Reuse of this catalyst bed (the 11-hr data set in Table 6) exhibited even poorer activity after handling. Regeneration of the bed was not attempted.

The second test used a reactor configuration incorporating a Carberry, stirred-tank catalytic reactor as a preheater in combination with the tubular, fixed-bed catalytic reactor. Similar results were obtained in this reactor configuration as with the tubular reactor alone. The use of the preheater to bring the feed to temperature more quickly and to increase the amount of the tubular catalyst bed at temperature did not appear to improve the conversion in the combined reactor system. Catalyst overload resulting from mass transfer limitations using the higher concentration feedstock in the combined reactor system may explain the poorer results at 4 hr time on stream. Comparing the two data sets, there is an apparent feed rate effect of lower conversion at faster throughput, although the effect also correlates with time on stream. The higher levels of hydrogen in the product gas are a function of the higher temperature in the catalyst bed (360s vs. 350s in the tubular only test). There did not appear to be as quick a loss of activity in the catalyst bed as in the tubular reactor alone test.

Again, in the combined reactor system, the catalyst bed had a coating, this time after the 12-hr test. In addition, there was a deposit recovered from the bottom of the Carberry reactor. The catalyst coating was similar to that found in the test with the tubular reactor only. The Carberry deposit consisted of the hydroxylapatite and the nickel subsulfide, but other phases were also identified by XRD, including iron phosphate, ammonium iron sulfate, potassium aluminosilicate, calcium carbonate, calcium magnesium sulfate and anorthoclase (an alkali silicoaluminate).

These tests show an improved operability compared with the earlier test results from the tubular reactor (Elliott et al. 1991). In the earlier tests with a less active catalyst, true steady-state conditions were not achieved. The carbon gasification was far lower than the COD conversion, suggesting that carbon was building up in the reactor system as unconverted material. The tests reported here have a good match between carbon gasification and COD conversion with the small difference probably resulting from soluble carbonates formed from the alkali and ammonia byproduct. The higher concentration feedstocks reported in Table 6 have COD loadings more representative of the industrial situation.

Table 6. Experimental Results with Brewer's Spent Grain

	Tubular Only		Tubular/Carberry	
	Filtered 28500 ppm COD	Decanted 41000 ppm COD	Liquor 61500 ppm COD	Liquor 65000 ppm COD
Time on Stream, hr	4	11	4	11
Results				
Gasification of Carbon, %	100.1	67.4	84.7	70.4
Reduction of COD, %	97.7	71.2	96.2	82.2
Feed, L/hr	1.4	1.2	1.2	1.5
LHSV, L/L/hr	2.3	2.0	1.3	1.7
Gas Yield, L/hr	26.1	21.5	49.9	54.0
Effluent COD, ppm	670	12290	2450	12100
Effluent NH_4^+, ppm	220	285	3000	3000
Effluent pH	6.3	NA	7.0	NA
Gas Composition, volume %				
Methane	40	35	50	44
Carbon Dioxide	58	58	45	42
Hydrogen	1.0	2.5	4.5	11
Ethane	0.6	1.4	0.6	0.9
Backflush	0.5	2.6	0.8	1.6
Btu/SCF	434	466	550	548

Catalyst bed conditions: BASF catalyst at 350°C to 360°C and 21 MPa.

Conclusions

The TEES process has now been demonstrated in continuous-feed, fixed-bed catalytic reactor systems on three scales of operation ranging from 0.03 L/hr to 33 L/hr. The systems have been operated with consistency at conditions of 350°C and 205 atm. Aqueous effluents with low residual COD and a product gas of medium-Btu quality have been produced. Catalysts have been demonstrated for up to 6 weeks of operation with reasonable stability. Ruthenium appears to be a more stable catalyst than nickel in this respect. Biomass feedstocks have been processed effectively. Reduced nitrogen in these feedstocks is often converted into ammonia, which is stable at TEES conditions. Inorganic components in these feedstocks have sometimes been deposited in the catalyst bed when compounds were produced at concentrations above their solubility limits.

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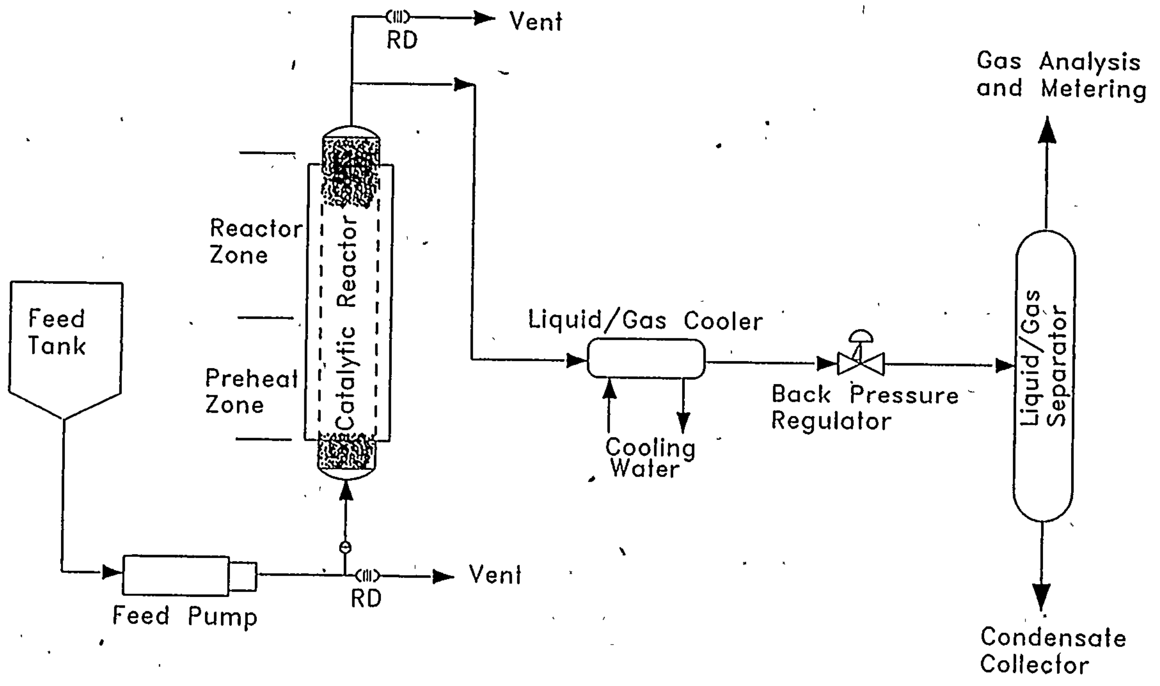

Figure 1. Schematic of Bench-Scale Continuous Reactor System

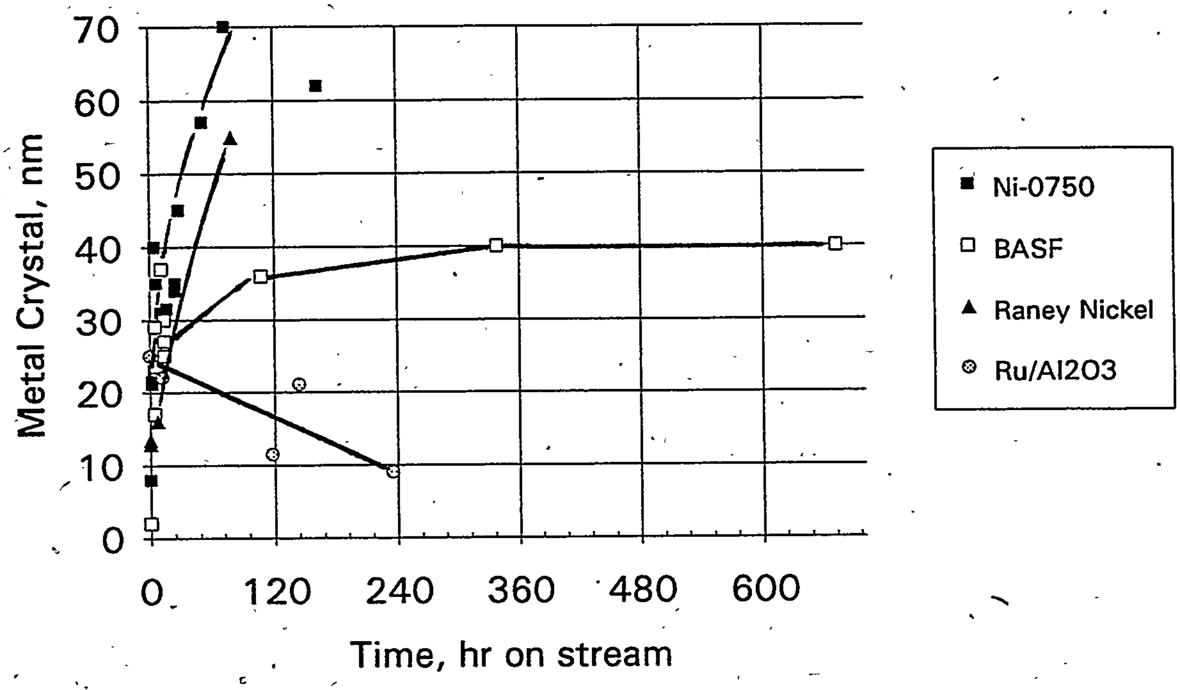

Figure 2. Effect of Operating Time on Catalytic Metal Crystallite Size

BIOMASS GASIFICATION HOT GAS CLEANUP FOR POWER GENERATION

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Abstract

In support of the U.S. Department of Energy's Biomass Power Program, a Westinghouse Electric led team consisting of the Institute of Gas Technology (IGT), Gilbert/Commonwealth (G/C), and the Pacific International Center for High Technology Research (PICHTR), is conducting a 30 month research and development program. The program will provide validation of hot gas cleanup technology with a pressurized fluidized bed, air-blown, biomass gasifier for operation of a gas turbine. This paper discusses the gasification and hot gas cleanup processes, scope of work and approach, and the program's status.

Introduction

Westinghouse Electric has teamed with the Institute of Gas Technology (IGT), Gilbert/Commonwealth (G/C), and the Pacific International Center for High Technology Research (PICHTR) to conduct a 30 month research and development project to validate hot gas cleanup for operation of a gas turbine with a pressurized fluidized bed air blown biomass gasifier. The program is in support of the U.S. Department of Energy's (DOE) Biomass Power Program and is being directed by the Midwest Research Institute through the National Renewable Energy Laboratory (NREL) in Golden, CO. NREL is operated and managed by the Midwest Research Institute for the DOE.

The Biomass Power Program is part of the National Energy Strategy and the continuing effort of the DOE to develop more efficient, environmentally safe power producing technologies, as well as to reduce U.S. dependency on foreign oil. Biomass fuels currently consist of agricultural wastes like bagasse (sugar cane waste), forest residues, wood chips, industrial wood wastes, and urban wood wastes. Long-term the goal is to continue the development of herbaceous energy crops for dedicated fuel supply systems. These energy crops would have significant environmental advantages in that they have little or no sulfur content and produce no net carbon dioxide due to the fact that the carbon dioxide that is produced during combustion is absorbed in the photosynthesis process of crop regrowth.

High efficiency, advanced energy generation systems utilizing biofuels will provide both industrial companies and power producers an attractive option for the use of renewable fuels in lieu of fossil fuels. One of these energy systems will consist of gasifiers with gas cleanup systems providing clean fuel gas for power generation and/or cogeneration applications such as process steam or synthetic fuels production.

System Processes

The Westinghouse Team will perform hot gas cleanup (HGCU) research for an advanced biomass gasification application. HGCU filter system development will be conducted at Westinghouse's Science and Technology Center in Pittsburgh, PA. Actual demonstration of the HGCU system will be performed with IGT's 9.1 metric ton (10 ton) per day RENUGAS® process development unit (PDU) in Chicago, IL, and then at the scaled-up 91 metric ton (100 ton) per day RENUGAS® demonstration plant being constructed in Hawaii (Trenka 1991).

Gasification

The gasification process chosen for scale-up at the demonstration plant being built on the island of Maui in Hawaii was the IGT biomass gasification process called RENUGAS®. This process was developed by IGT under contract to the DOE in the early to mid 1980s (Lau 1993).

A simplified RENUGAS® process flow diagram is shown in Figure 1. Biomass is fed to a single, fluidized bed gasifier vessel that operates at pressure. Inert solids reside in the vessel and form the stable fluidized bed into which the biomass is fed near the bottom. All of the biomass ash is carried overhead with the product gases. Mixing in the fluidized bed of the high heat capacity inert solids with the biomass char distributes the heat energy released from the combustion to the endothermic gasification reactions. By using the inert fluidized bed media, the low bulk density biomass char is retained longer in the gasifier and reduced in size thus exposing more char reaction surface area which contributes to higher carbon conversion. Thus single-screened biomass feedstocks can be fed to the fluidized bed gasifier.

The RENUGAS® process offers different gas product options by simple changes in gasifier operating conditions. The options depend mainly on the pressure selected for gasification and whether air or oxygen is used as the oxidant. If the gasifier is operated under air-blown conditions, then a low calorific gas is produced which can be used as an industrial fuel gas or, if generated a higher pressures, can be used for combined cycle power generation. When the gasifier is operated under oxygen-blown conditions, it produces a medium calorific gas, or synthesis gas, which after upgrading, could be suitable for production of methanol or other chemicals.

Pressurized operation makes the fluidized gas bubbles smaller thus fluidization and mixing are smoother than at near-atmospheric pressures. The pressurized product gases from the gasifier advantageously overcome pressure drops through piping, filters, and possible catalytic beds and thus improves process efficiency for both synthesis gas applications and combined cycle power generation. The addition of steam to the RENUGAS® gasifier accomplishes greater char conversion by the steam-char reaction, lowers oils and tar production, and moderates the temperature in the region about the oxidant gas distributor.

A 9.1 metric ton (10 ton) per day biomass process development unit was built at IGT to operate at pressures up to 3.45 MPa (500 psig) and temperatures up to 982°C (1800°F). Figure 2 shows an isometric view of the PDU equipment extending to a total height of about 15 m (50 feet), with each building deck about 3.7 m (12 feet) apart. The PDU was built to be operationally flexible to investigate various fluidized bed configurations, such as different relative positions of the fluidized bed height to the biomass feed point and the fluidization gas distributors. An angled nozzle was installed for the possible recycle to the fluidized bed of the carryover solids. The bottom closure flange of the gasifier vessel contains nozzles for the introduction of the fluidization gases, the in-bed thermocouples, and an inert bed solids drain.

Different test modules of various gas processing units can be installed at convenient downstream locations for specific studies. The PDU system is operational and is currently being modified to add a hot gas cleanup system to characterize the product gas for gas turbine combustion.

The inside diameter of the PDU fluidized bed gasifier is 29.2 cm (11.5 inches) and is constructed from a rolled sheet of 0.64 cm (0.25 inches) Incoloy 800 H alloy. The 29.2 cm (11.5 inches) I.D. by 3.1 m (10.2 feet) liner is contained within a 0.91 m (3-feet) outside diameter pressure vessel shell. An expanded solids disengaging zone diameter of 45.7 cm (18 inches) extends 3.35 m (11 feet) above the fluidized bed zone. The annular space between the gasifier liner and the pressure shell is well-insulated with packed fiber insulation to minimize heat loss and to approach adiabatic gasification conditions. Process heat is supplied only by the combustion from air or oxygen introduced through the gas distributor. All piping from the gasifier to the pressure let-down valves is refractory-lined carbon steel pipe. Prior to the pressure let down valves, the product gas temperature is reduced to 427°C (800°F) so that unlined carbon steel pipe can be used for the run to the product gas flare.

The PDU equipment is well-instrumented to provide information for energy and material balances for each test. A sampling system prior to the hot gas cyclone collects a large slipstream sample during the steady-state gasification period of the product gas, the condensable species, and the carryover solids for analysis. On-line gas analytical instruments monitor the gasification of the biomass. Fluidized bed thermocouples and differential pressure taps along the height of the fluidized bed report the stable behavior of the fluidized bed.

Other support equipment include a dryer, hammermill, chopper-harvester, boiler and superheater and live-bottom feed metering bin. A simple vertical flare is used for environmental disposal after sampling and measurement of the product gas characteristics.

Hot Gas Cleaning

Gas cleanup systems are necessary to protect combustion turbines and the environment in gasification plants. During the process of fuel conversion (gasification/combustion) emissions, such as particulates, tar, and alkali, are generated that can cause erosion, corrosion and deposition problems within the combustion turbine, which in turn increase maintenance costs and degrade performance. These particulate may also exceed regulated emissions levels.

The HGCU system has advantages over today's commercially available low temperature [<315°C (600°F)] gas cleanup systems for coal gasification plants. Cold gas cleanup systems require large heat exchanger equipment to precede the cleanup function. This additional equipment increases power plant costs and lowers overall plant efficiency. Thus the higher the temperature at which the fuel gas is cleaned, the less energy lost in cooling the gas and the less complex the heat exchanger equipment. There are cost trade-offs though, that have to be considered with the higher temperature component materials needed in the system when the gas is cleaned at temperatures over 649°C (1200°F).

An efficient and reliable hot gas cleaning system is the key technology requirement for the successful integration of a biomass gasifier with a combustion turbine for high-efficiency power generation. Evaluation of hot gas filtration systems being developed for various coal and biomass gasification applications, both in the U.S. and Europe, indicates a rigid ceramic barrier filter concept is the best choice for hot gas particle filtration (Lippert 1992). This technology offers advantages of compactness, effectiveness, versatility, cost, and reliability relative to other approaches. The performance of these devices are basically independent of throughput, show nearly absolute filtration and can be cleaned by simple pulse jet methods.

Several filter element types are at the stage of technical readiness and are being considered for testing in the PDU at IGT:

- Silicon carbide candle. This commercially available item is a long cylinder of porous material, typically 1.5 m (59.1 inches) long and 60 mm (2.4 inches) OD, closed at one end and flanged at the other, and with a surface area of nearly 0.28 m^2 (3 square feet). This is the most-tested filter element, but there may be long-term chemical stability issues when exposed to high-temperature steam/alkali environments.

- Oxide-based candles. Work is being done to develop candles of the same geometry, but that have more chemical inertness, both in oxidizing and reducing environments. Testing has been conducted at Westinghouse facilities, and is advancing to the pilot plant stage. For temperatures above 815°C (1500°F), this technology is preferred.

- Cross flow filter elements. These oxide-based elements offer compact design, [0.74 m^2 (8 square feet) of filtration surface in 9400 cm^3 (0.33 cubic feet) of volume], and have been used in numerous bench and pilot scale programs. Manufacturing improvements are being made that will provide a more monolithic structure, more resistant to thermal stresses, resulting in improved reliability.

Westinghouse is developing commercial designs for hot gas filter systems that would utilize either candles or cross flow filter elements. The candle design is illustrated in Figure 3 and incorporates the following commercial features:

- The mounting and scaling of individual filter elements that allows for accessibility and changeout (Item 1).
- Implementation of a "fail-safe" device that would isolate any failed filter element and preventing any substantial dust leak.
- Arranging of individual filter elements to form assemblies that are connected to a common clean gas discharge pipe and can be cleaned from a single nozzle source (Item 2). Figure 4 is a photograph of a test assembly comprising 18 candle filters.
- Vertical stacking of the assemblies to form basic building modules (called clusters) that allows for efficient packaging of the filter surface area into a pressure vessel (Item 3).
- Supporting the filter clusters from a common high alloy tube sheet structure that is designed to carry the major mechanical and thermal stresses imposed during operation.

The Westinghouse hot gas filter system shown in Figure 3 contains nearly 400 candle elements housed in a 3.0 m (10 feet) diameter, 12.2 m (40 feet) long vessel and has been designed and built for installation on a 10 MWe slipstream from a 70 MW PFBC commercial utility demonstration plant. This single vessel filter system is approximately the same size as would be required for a 50 MW commercial scale biomass gasifier system. Thus, the ability to design and fabricate this system in modular form has already been demonstrated.

The tars/oils produced using biomass feedstocks presents a technical challenge in preventing adverse effects to the filtering system. One of three basic approaches can be taken to deal with the tars/oils: 1) remove the tars/oils before passing them through the filter by either condensing them out at lower temperatures, 2) cracking them in a reactor at high temperature, or 3) keeping the fuel gas at a high enough temperature, > 482°C (900°F), so that the tars/oils remain in the vapor state and don't condense out in the filter system. Condensing out the tars/oils prior to the filter system has the disadvantages of reducing system efficiency and removing the heating value of the tars/oils from the combustion process. This heating value can be as much as 10% of the overall heating value of the fuel. Therefore, retaining the tars/oils in the fuel is advantageous from a system efficiency point of view. Also, a potential problem with operating the HGCU system at > 538°C (1000°F), without a tar cracker, is the possibility of cracking the tars/oils in the HGCU system and creating carbon laydown within the filter.

The use of a tar cracking reactor prior to the HGCU system appears prudent at the IGT PDU. Also the use of the high temperature tar cracking reactor is in concert with running the filter system at the high temperatures for improved power generation costs and efficiency.

Turbine protection also requires removal of alkali vapors from fuel gases. High-temperature, chemical removal is preferred over condensation by cooling the gas for two reasons. First, gas cooling results in reduced plant thermodynamic efficiencies. Second, condensed alkali species will be molten or sticky (as will be concurrently condensed tars) and will impair downstream filter operation.

A process for chemical removal of alkali vapors from hot fuel gases has been developed by Westinghouse (Bachovchin 1986). Gases pass through a fixed bed of pellets of the reactant, emathlite, an inexpensive clay. Alternatively, fine emathlite particles can be injected into the gas, react, and be collected on a filter. Reduction of alkali vapor levels to below estimated turbine tolerance levels of 20 to 50 ppb is practical.

The identities (NaC1, KC1 etc.) and levels of alkali vapors in the produced fuel gas must be known prior to design. In reality, the levels will depend on many factors, as a first approximation the soluble (principally chlorides) and organic alkali species will be vaporized.

For this program, alkali studies will focus on characterizing alkali species and concentrations in the fuel gas, involve feedstock chemical analysis, thermodynamic calculations, and in plant sampling. If measured alkali concentrations for the bagasse are high an alkali getter will be recommended for the demonstration plant in Hawaii prior to installation of the gas turbine.

Work Scope and Approach

The Westinghouse Team will conduct the HGCU research program with the end goal of validating HGCU for operation of a gas turbine with the pressurized fluidized bed air blown biomass gasifier. The approach being taken is to first evaluate the options available for HGCU systems and select the most appropriate system for the application. The filter system chosen will be operated at temperatures in the 760°C (1400°F) to 816°C (1500°F) range. It has also been determined that a tar cracking reactor will be necessary for HGCU filter element protection.

The HGCU filter system and tar cracker will first be operated at the IGT 9.1 metric ton (10 ton) per day RENUGAS® PDU. A series of three to five, 72 hour, steady state tests will be conducted to evaluate performance of the HGCU system. The feedstock for these tests will be bagasse (sugar cane waste). Data from these tests will be used to determine alterations to hardware configurations, changes to the test plans, and design specifications for the scaled-up HGCU to be installed at the Hawaiian demonstration plant.

Once this series of short duration tests are completed the HGCU system and tar cracker will be dismantled and moved to the Hawaiian demonstration plant. There PICHTR will install the equipment in a slipstream on the 91 metric ton (100 ton) per day demonstration plant. A long duration test of 500 hours will then be conducted to demonstrate the durability of HGCU system as well as investigate transient operating conditions.

Again the data from these tests will be used to prepare the design specifications for the full flow HGCU system and the accompanying gas turbine, along with their control systems interface with the gasifier. In addition, a detailed test plan for the gas turbine and full flow HGCU system will be prepared for use during the second phase operation of the demonstration plant.

Program Status

The HGCU system validation program got underway in early April 1993 as seen in Figure 5. Evaluation of the HGCU system options has been made and a HGCU system consisting of ceramic candle filter elements has been chosen as the system for this particular application. The HGCU unit will be operated in the 760°C (1400°F) to 816°C (1500°F) range, at a pressure of 2.2 MPa (325 psia), and a flow of 8534 m^3h (28000 scfh). The PDU HGCU system is in the early stages of design.

A tar cracking reactor has been determined necessary for HGCU filter protection from possible blinding of filter element pores from tar and carbon deposition. This unit is being designed for IGT PDU adaptation.

The PDU at IGT is being modified to accommodate both the HGCU system and tar cracking reactor vessels along with their associated piping and control systems. Provisions for data gathering instrumentation are also being made.

The test plan for the short duration testing periods at IGT has been prepared along with a tentative test plan for the long duration tests to be performed in Hawaii.

Demonstration plant conceptual design and analysis has begun for second phase operation which will include the integration of the 91 metric ton (100 ton) per day gasifier with a full flow HGCU system, a tar cracking reactor, and a 3-5 MWe gas turbine.

Acknowledgments

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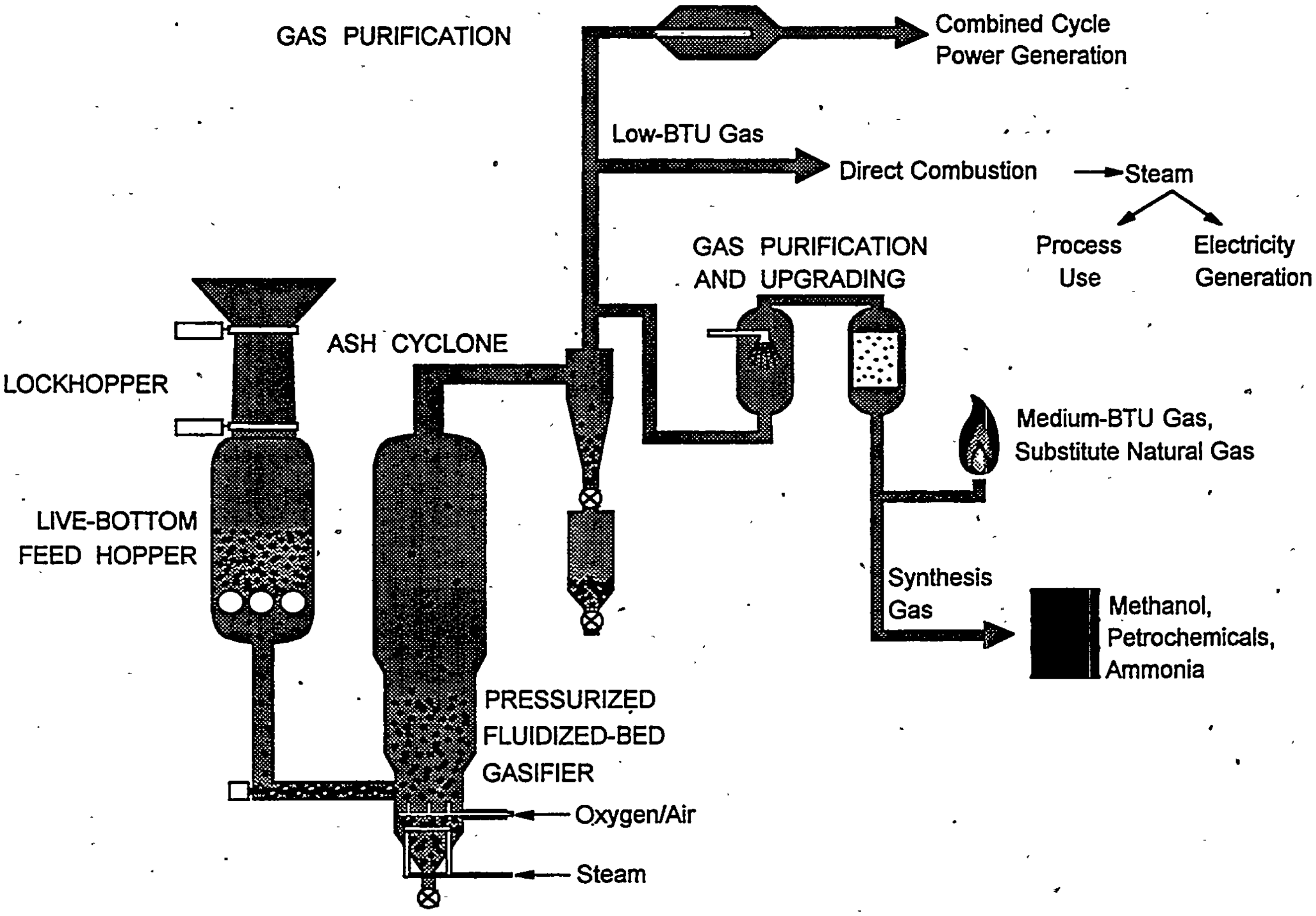

FIGURE 1. RENUGAS® PROCESS OPTIONS

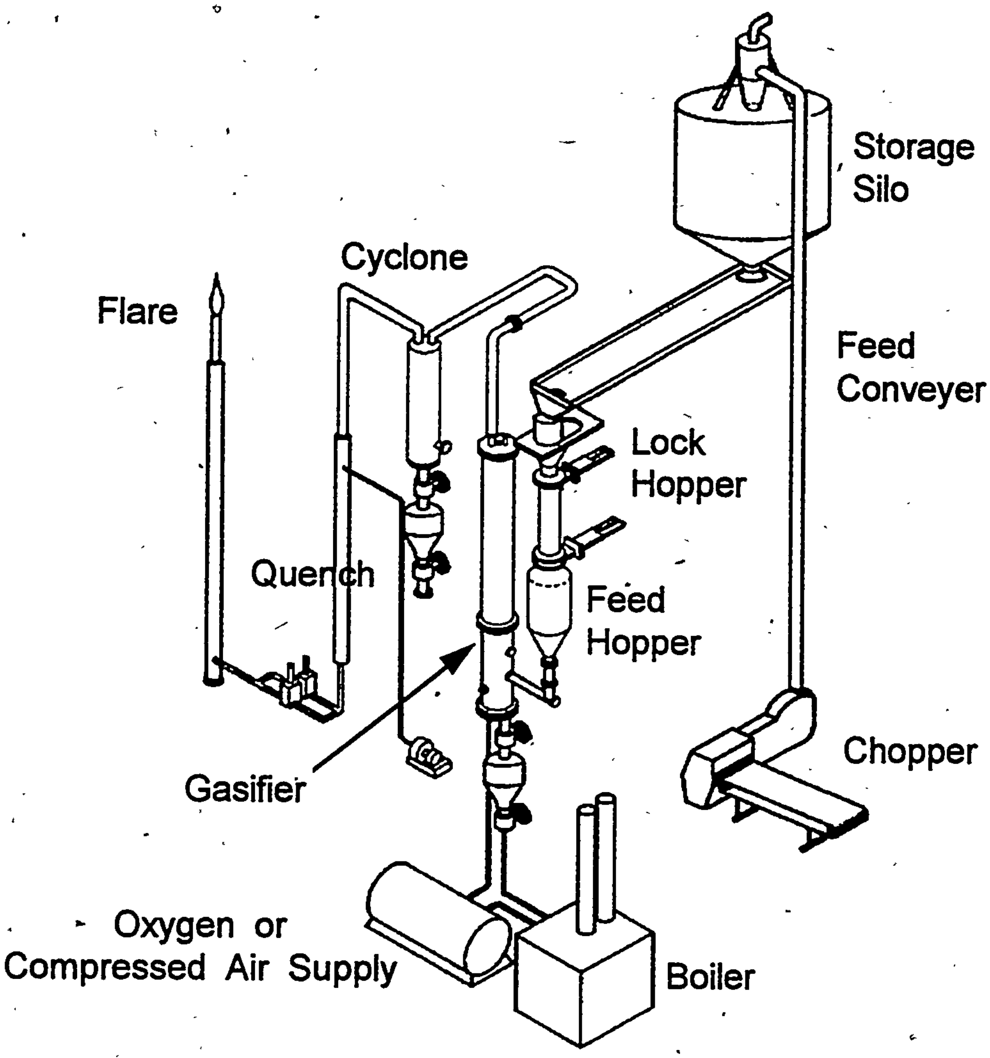

FIGURE 2. RENUGAS® 10-TPD PROCESS DEVELOPMENT UNIT

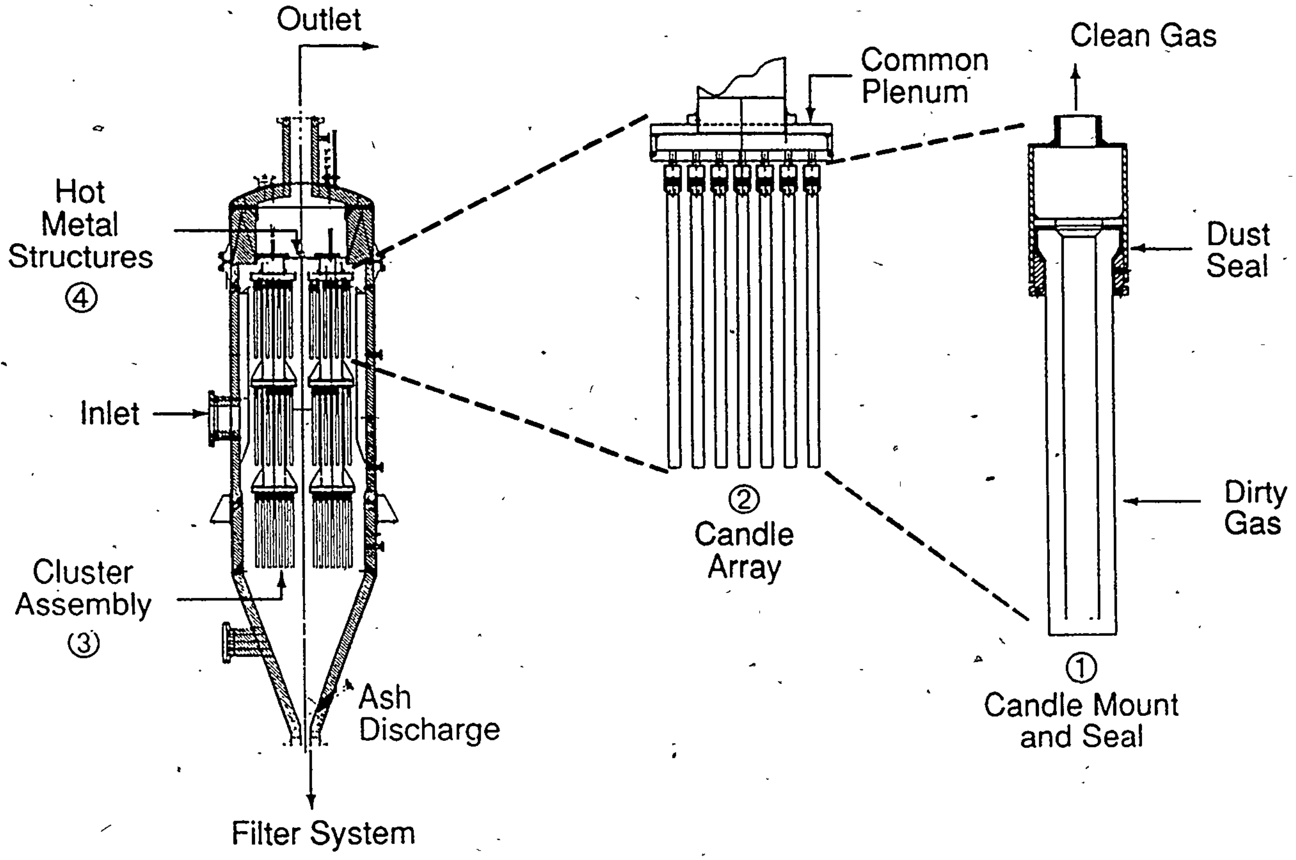

FIGURE 3. CANDLE FILTER SYSTEM

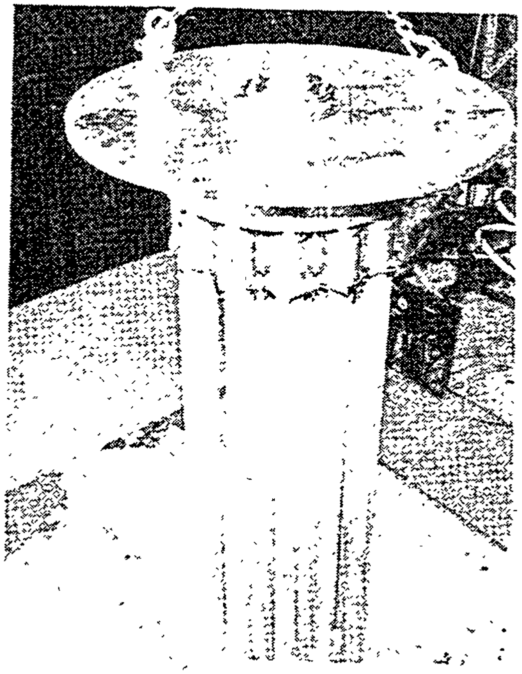

FIGURE 4. CERAMIC CANDLE ARRAY WITH BLOWBACK PLENUM

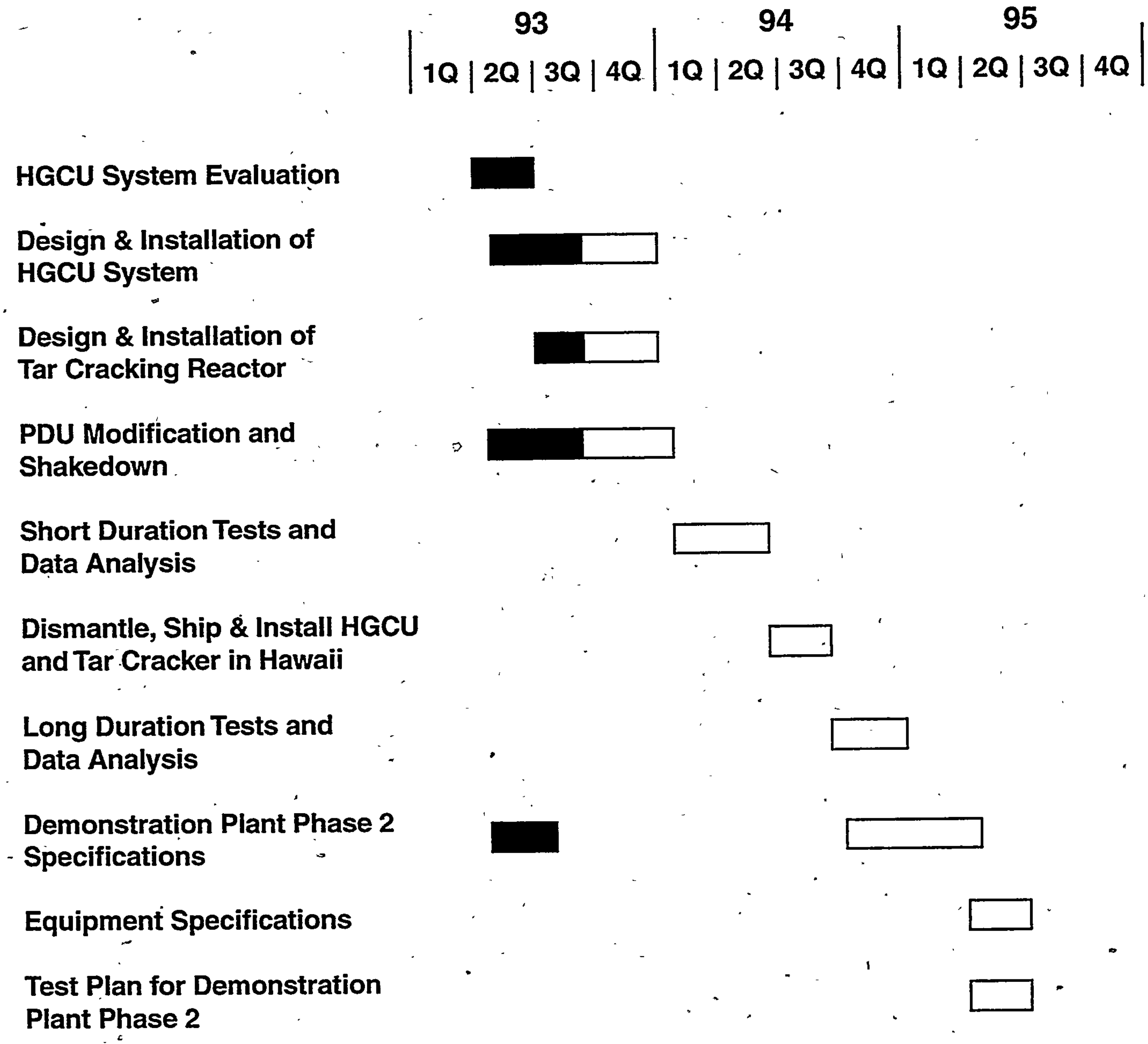

FIGURE 5. PROGRAM SCHEDULE

PROCESS AND DESIGN CONSIDERATIONS FOR THE ANAEROBIC DIGESTION OF MUNICIPAL SOLID WASTE

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Introduction

I. Full scale experience exists and justifies implementing anaerobic digestion for pretreatment of high strength industrial waste water and side streams. Anaerobic treatment of sludge and manure have, in recent years, demonstrated cost effective, environmentally sound treatment of these wastes. Recently attention has focused on the potential for anaerobically treating high solids municipal solid waste to assist in meeting State waste reduction goals, and provide for a new renewable source of energy.

This paper focuses on the fundamental facility design and process protocol considerations necessary for a high solids anaerobic digestion facility. The primary design and equipment consideration are being applied to a 5 to 10 ton per day demonstration anaerobic digestion facility in Bergen, New York, shown in Figure I.

The facility, funded by the Village of Bergen, Comstock Michigan Fruit, and the New York State Energy and Research Development Authority is due to begin operation in the Fall of 1993. It is being designed and will be operationally tested with the assistance of Larsen Engineers.

The results of this demonstration will enable further refinement of the processing requirements as well suggested operational, engineering, and economic parameters for full scale facilities.

II. Previous Research and Demonstration

In 1969 the Bureau of Solid Waste Management of the US Public Health Service funded a project to the University of Illinois to investigate the process condition that would manage conversion of MSW into biogas. Professor John Pfeffer conducted this project utilizing numerous small-scale laboratory studies to show that the thermophilic digestion has substantial potential for MSW.

The University of Maine, in 1984, began the operation of an anaerobic digestion unit to decompose a mixture of cafeteria food waste and cow manure, which today produces enough hot water and electricity to power a 40 kilowatt generator. The cylindrical digester is 28 feet high, 24 feet in diameter and has a capacity of 20,000 gallons. The process operates at 95F, the solids content is around 12% and the digested material has a solids content of 9-10%.

An experimental project called REFCOM (REFuse Converted to Methane) was conducted by Waste Management Inc. in Pompano Beach, Florida in 1985. The facility had front and back end processes and a digester. The front end process contained size reduction, separation of organics, metals, and glass and was similar to a refused derived fuel (RDF) operation. This facility processed only the organic portion of the MSW stream was therefore only a minor processing component in the total MSW Management. Stenstrom, et. al., 1987 summarized the research works performed in the area of anaerobic digestion of MSW both at the bench scale and full scale studies. Golueke (1971) conducted the first of the most recent works studying the anaerobic digestion of MSW. Further works in this area were conducted by Augustine, et. al., 1986.

The United States Department of Energy reported on the economics of anaerobic composting in 1988. Estimates for a single phase 200 ton/day municipal anaerobic composting facility in New York State in 1991 dollars, may result in a tipping fee of about $50-55 per ton.

Since 1992 the State of California Prison Industry Authority has operated a one ton per day anaerobic digester at the Folsom Prison. As a result of the projects success the Authority and the City of Folsom are designing three additional anaerobic reactors to process 100 tons per day of organic waste from the City of Folsom waste stream. Other small pilot projects in the United States include the Disney World System in Orlando, Florida.

Three systems for the anaerobic digestion of MSW which currently exist in Europe are DRANCO (DRy ANaerobic COmposting), a Belgian system and VALORGA, a French developed wet anaerobic system and the BTA process. These systems employ anaerobic digestion as a major component for energy recovery.

The DRANCO digester in Brecht, Belgium, is 808 m^3 in volume and has a capacity to treat 10,500 tons of source separated organics per year. It is a thermophilic process with temperatures around 55 C and total solids concentration at 32%. The retention time is approximately 2-3 weeks.

The process involves size reduction, separation of different fractions of waste stream, fermentation/digestion, dewatering of the residue to 60% solids and further treatment of the residue by aerobic digestion for 10 days. The gas production rate is around 2.2 mm^3 CH_4/m^3 reactor day with a COD reduction of 55%. The DRANCO process itself consumes 30-50% of the electricity provided.

The Valorga process is the first industrial scale anaerobic treatment plant for solid wastes in the world. The process is particularly suited for treating the biodegradable fraction of MSW after source separations it could be used to treat commingles material after front end sorting.

The feed to the digester is 30-35% solids. The digester is operated under mesophilic conditions (37-40C), with an average retention time of 3 weeks. The mixing of the slurry in the digester is achieved by recirculating the biogas under pressure at the bottom of the digester.

The residue coming out is 24-28% solids with good fertilizing qualities.

For the past 3 years the plant has been treating 55,000 tons per year of MSW, with three fermentors of 2,400 cubic meters each. The average biogas production is 146 Nm^3/ton of sorted MSW.

The BTA process was designed and realized for the biologic anaerobic treatment of biogenous solid materials, especially the organic fraction of MSW, in Munich, Germany. It is a two-stage process consisting of four main features as follows:

- Pretreatment of incoming waste by mechanical, thermal and chemical means.
- Separation of dissolved from undissolved biogenous solids.
- Anaerobic hydrolysis of biodegradable solids.
- Mechanization of dissolved biogenous materials.

After slurry passes through the hydropulper, it is treated thermally. A dosage of alkali is given to increase the anaerobic biodegradability. The dissolved and easily digestible materials are then separated from the solids and the separated liquid is fed to the mechanization chamber at mesophilic conditions.

The remaining solids are re-suspended with process water and hydrolyzed in a CSTR (continuous stirred tank reactor) by mesophilic bacteria. This slurry is again dewatered and the liquid is sent to the mechanization chamber. The non-degraded solids have a TS content of 35% which can be used as a compost/soil amendment.

The optimum pH throughout the process is 6-7. The overall retention time is in the range of 9 days. About 70% of VSS input can be degraded within a period of 48-72 hrs.

III. Description of the Anaerobic Digestion Process

Anaerobic digestion is a bioconversion process that can be applied to produce methane, and a stabilized humus from a variety of pure as well as heterogeneous carbonaceous materials with characteristics similar to fertilizers. A mixed population of bacteria convert organic compounds under an oxygen-free environment to a mixture of methane and carbon dioxide along with a few trace gases. Continuous mixing of solid waste is beneficial in the anaerobic process as opposed to the periodic turning associated with aerobic composting. The product gas (also known as biogas) is a medium-Btu gas (heating value of 500-750 Btu per standard cubic foot (SCF) and can be easily upgraded to pipeline quality gas. The permissive pH range is generally 6.5 to 7.5. Among the characteristics the process can effectively mitigate are odor and high biological oxygen demand (BOD).

Thru the biological process organic slurries with solids content up to 10-15 wt% (sometimes higher) are converted to a premium fuel (methane) by a number of coupled biochemical reactions. The ability to reach beyond a 10-15 solids content will be tested in the Village of Bergen of New York, anaerobic digestion facility. The overall feed conversion rate of this biological process is considerably slower than that of the thermal conversion to produce methane, because anaerobic digestion occurs at near ambient temperatures (either mesophilic 35-37 C or thermophilic 55-60 C) and pressures, while thermal conversion occurs at high temperatures and pressures. Because of a higher net energy production than that from a thermal conversion process, anaerobic digestion is a preferred process for gasification of high moisture feeds. This net energy production is heavily dependent on digester design and operating conditions, climatic conditions and other factors.

Generally the feed (substrate) residence time is relatively long for anaerobic digestion, approximately 15-21 days. The long substrate residence time and large quantities of substrate-associated water create the need to provide large reactor (fermenter) volumes to accomplish feed-to-methane conversion at desirable efficiencies. Since slower reaction rates and larger fermenter (digester) volumes could lead to low volumetric methane production rates (volume of methane per unit digester volume per unit time), the design and operational goals of biomass/solid waste-to-methane plants are to maximize the volumetric methane production rate (VMPR) with respect to the digester hydraulic retention time (HRT).

Organic solid waste streams total about 750 million dry tons annually. Production of biogas from these wastes should help minimize the environmental consequences of the waste discharge, and reduce the energy requirements. The heating values of selected components of the MSW waste stream are shown on Table I.

Table I: Heating Values of Selected Municipal Solid Waste Components

Component	Btu/dry lb
Junk Mail	6,378
Newspaper	8,480
Trade Magazine	5,480
Waxed Milk Cartons	11,732
Vegetable Food Wastes	8,270
Cooked Meat Scraps	12,443
Fried Fats	16,466
Shoe Leather	7,826
Evergreen Shrub Cuttings	8,735
Balsam Spruce	9,541
Flower Garden Plants	8,027
Lawn Grass	8,312

Anaerobic digestion of MSW could potentially produce a medium-Btu gas without creating the air pollution concerns associated with incineration. It couples the potential of producing considerable amount of energy (methane) with the simultaneous reduction in the organic waste problems by a less energy intensive process than conventional methods. The application of the biogas and recirculation of the effluent water creates a virtually self sufficient system which does not waste energy or water.

Due to the vertical design of the digester, less space is required, therefore, reducing capital costs for the facility.

IV. Facility Design Process Flow and Operation

Collection of Material

Municipal solid waste may be collected and delivered to the facility as either commingled or source separated material. Source separated material will generally reduce capital and operational costs of the facility. Source separated facilities require less space for preprocessing, less equipment such as air classifiers and screens for sortation and reduced manpower allocated to identify and removing non-organic and residual material.

Additionally, source separated material is less likely to contain toxins, metals, and other residuals which are difficult to dispose of, inhibit the quality of organic humus produced by the digester.

Unloading of Material

Facility design should enhance easy, quick unloading of material in a manner which allows smooth traffic flow, weighing of trucks and rapid conveyance of the material from a live bottom hopper, a pit, or a open tipping floor directly to initial inspection and picking station or conveying line.

This initial conveying line, generally a minimum of 30 feet long and 36" wide allows employees to identify larger contaminants such as glass bottles, paint cans, and HDPE milk jugs.

Metal Detection

Material is transferred from the initial picking station to a metal detector by conveyor moving at approximately 20 to 40 feet per minute. An eddy current separator or air classifier are additional options which may be installed to ensure the removal of lighter non-ferrous materials, plastics, and non-processable paper.

Particle Size Reduction

Organics are then slowly conveyed to a primary shredder or grinder for size reduction.

Particle size reduction is performed either to prepare the waste for direct fuel use or for fabrication into fuel pellets which can then be used in a conversion process. Although the ultimate particle size depends on the conversion processed used, generally material should be reduced to 1" or less in diameter. This may require an additional secondary grinder. Biological processes like anaerobic digestion, are also affected by the size of the particle; the smaller the particle, the higher the reaction rate as more surface area is exposed to the organisms. Many machines such as wet shredders, dry shredders, and hammermills are used to reduce the particle size. The usual particle size in experiments that have been run was around 3 mm, this size can be increased to up to say 3", though in this case we have to keep in mind that this increase in size might increase the HRT as the surface area for the microbes to work on will decrease, resulting in lower gas production rates as was found in a study by Ghosh et al. They reported that gas yields from 10.1 to 5.1 mm median size particles were only 15% and 30% of those obtained with fiber like refuse having a median size of 0.6 mm. Methane content of the digester gases was found to remain unaffected by particle size and in the range of 60-65%. Also, increased particle size might affect the mixing and pumping energy requirements [1].

Mixing

Following the size reduction that results from grinding the material is conveyed to a slurry tank in which the organic municipal solid waste is mixed with water to make slurry of desired solid contents. The Village of Bergen demonstration project will begin producing solids in the 10 to 14% range since traditional anaerobic treatment has been successful in moving and fermenting this low solids content material.

The facility will continue to increase the solids content in the slurry tank (less water, higher concentration of organic MSW) until pumping, mixing, and HRT are retarded due to increasing solids. We hope to reach a solids content in the 20 to 25% range.

The slurry tank is provided with a heating system (hot water boiler) to heat the material to approximately 98°F. A dual fuel hot water boiler may be used, so that after the anaerobic digestion of the organics starts, biogas can be used as a fuel source.

Active Digestion

The mixed solid waste is then pumped into the anaerobic digester.

The Village of Bergen digester volume will be approximately 50,000 gallons. The digester will be provided with gas mixing equipment to mix the organic waste. The temperature of MSW will be maintained to approximately 98°F and 12 to 18 day detention time in the digester will be provided for the anaerobic digestion.

Mixing in the digester is usually done to ensure complete contact of the microorganisms with the substrate (i.e. the feedstock). This increases the efficiency of methane fermentation. It was found by CT Rivard, that gas production from an unmixed system is much less than that from the mixed system. Mixing also helps to reduce the hot and cold spots in the digester, leading to even conditions. There is a misconception that mixing reduces the HRT drastically which is not necessarily true. Mixing helps reducing the HRT to a certain extent only, as was found by Rivard et al. Rivard has also shown that there was no significant difference between the fermentation performance with mixing speeds of 1, 5, 10, and 25 RPM, at a solids concentration of 14% and at mesophilic conditions [2]. There are many methods of digester mixing. Digesters can be mixed by compressing digester head gases by a positive displacement compressor and recirculating the compressed gas through draft tube gas diffusers laid out in peripheral circular patterns. Gas throughput rates and number of draft tube diffusers, depend on the digester size and the selected equipment type. Typical throughput rates used in a study by Ghosh et al [3] were 35-40 CF/min for a digester 16 ft in diameter and 180-240 CF/min for a 148 ft diameter digester. The calculated compressor power requirement ranged from 0.055 HP per 1000 CF for the larger digester to 1 hp per 1000 CF for the smaller digester.

The biogas produced during the digestion process may be used as a fuel source for the hot water boiler. The digested sludge (humus) after post-processing can be used as a soil conditioner. Biogas and humus generation rates will be carefully monitored to compare with the types of organic waste recipes mixed at the preprocessing stage for anaerobic digestion.

Dewatering

The digested solids from the anaerobic digester may be pumped to a heat dryer for further dewatering, producing 25% to 30% solids humus.

The waste water resulting from the dewatering process may be recirculated to the slurry tank to provide the required moisture content for the anaerobic process. This will reduce the quantity of water required to make the slurry as well as will eliminate the disposal of waste water to some extent.

The Village and Larsen Engineers are investigating alternative means of dewatering digested sludge or transporting the sludge directly from the digester to a farm where it may be mixed with wood chips prior to landspreading.

Market Preparation

The pathogen free, organic, high nutrient soil additive will be trucked off site to a farm for aerobic composting or land application. In a full scale facility the aerobic composting may take place on site, immediately following the dewatering process. All digested solids will be submitted to the appropriate laboratories for pathogen and TCCP tests, sieve analysis and other focal and state requirements for beneficial uses of the material.

Loading Rates

The rate of loading depends a lot on the feedstock as well as the gas production expected. highly biodegradable materials can be fed at higher loading rates, though the microbes must not be overworked. In the study by Rivard et al. [4] inhibitory conditions were observed at sludge solids level of 35-36% in a thoroughly mixed system at mesophilic conditions.

Retardation was thought to be due to a large increase in the total volatile acids from the high solids level, causing the pH to decrease below an acceptable level. Since at high rate of loading, the rate at which the methanogens would convert these acids to biogas is reduced, i.e. they are overworked. This is an important observation from the standpoint of the limitation factor on % solids, because from practical point of view it is better to have the feed as dry as possible.

The percentage of methane content to be achieved in the biogas also affects the rate of loading [5].

Pumping Energy

In a study by Ghosh et al [6] it was found that energy supplied for heat exchanger recirculation constituted a major part of the total pumping energy. The total pumping energy was found to decrease as the sludge solids concentration and digester loading rate increased. However, for very low loading rates (e.g. <0.05 lb VS/cubic ft./day), no significant decrease in the pumping energy requirement was seen as the feed sludge solids concentration was increased.

Conclusion

It can be concluded that the operating strategy of a methane generating digestion plant should provide for digester operation at the highest feasible feed solids concentration and largest possible microbial and substrate SRT, as increases in these parameters enhance methane production, reduce optimum HRT and digester volume.

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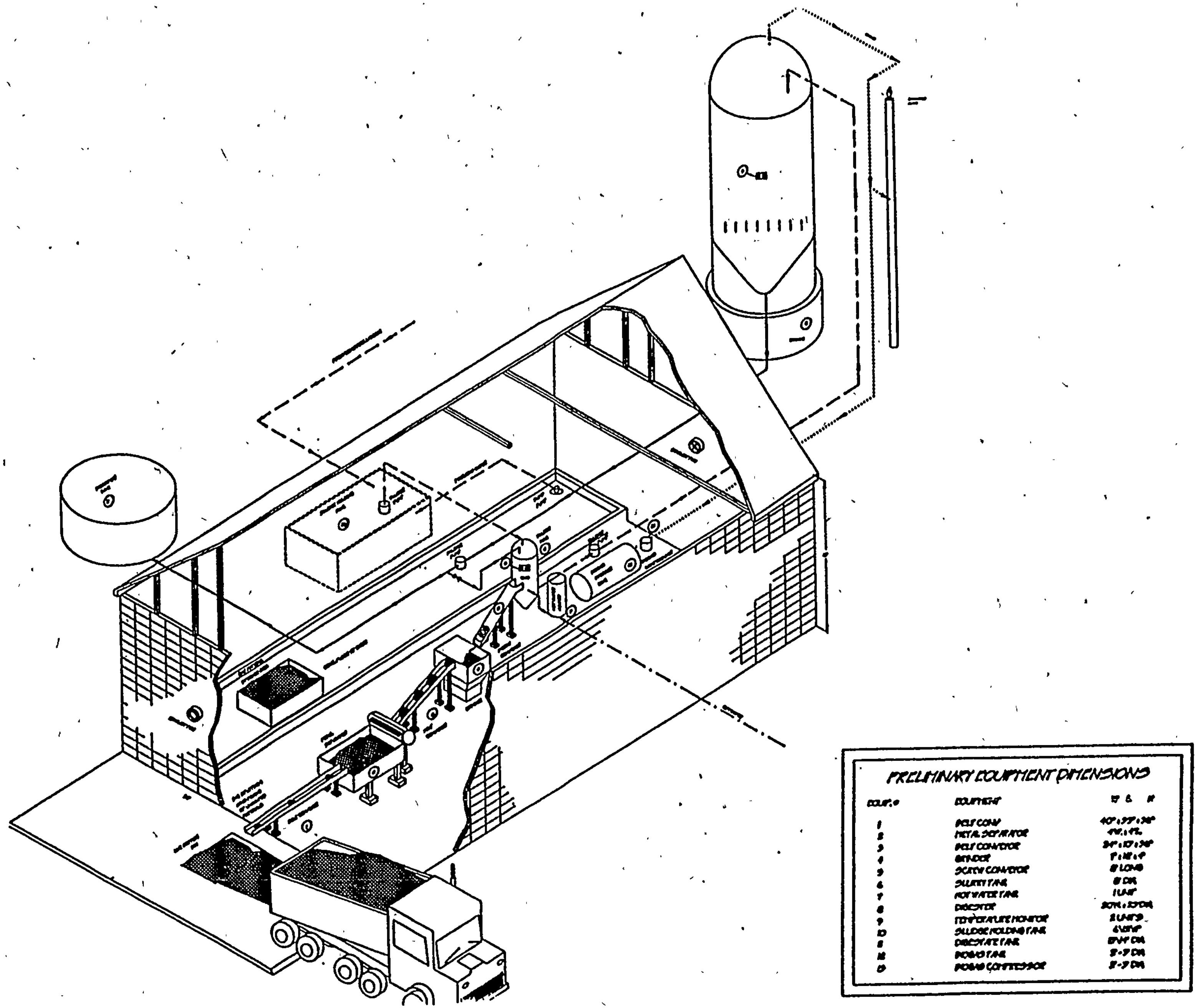

PRELIMINARY EQUIPMENT DIMENSIONS

EQUIP. #	EQUIPMENT	[illegible]
1	BELT CONV	[illegible]
2	METAL SEPARATOR	[illegible]
3	BELT CONVEYOR	[illegible]
4	BLENDER	[illegible]
5	SCREW CONVEYOR	8' LONG
6	SLURRY TANK	8' DIA
7	HOT WATER TANK	1 UNIT
8	DIGESTER	[illegible]
9	TEMPERATURE MONITOR	2 UNITS
10	SLUDGE HOLDING TANK	[illegible]
11	DIGESTATE TANK	[illegible]
12	BIOGAS TANK	[illegible]
13	BIOGAS COMPRESSOR	[illegible]

FIGURE I VILLAGE OF BERGEN, NEW YORK
DEMONSTRATION ANAEROBIC DIGESTION FACILITY

Energy supply of food processing plants and breweries from its specific solid wastes

Behmel, U. ; Leupold, G. ; Meyer-Pittroff, R.
TU-München Weihenstephan

1 Introduction

Disposal of solid wastes (molasses, beer brewer's spent grain, vegetable residues) in industry causes extending problems. Constant utilization in agriculture as animal food is not guaranteed any longer and consequently increasing costs for disposal occur.
The German brewing industry is confronted with the annual disposal of wastes outlined in Table 1:

Table 1 : specific organic brewery wastes [6]

Specification of Waste	kg /hl sales beer	Germany (1991) in 10^3 tons
spent grain	18.86	2, 225
yeast	2.64	311
hot break	1.42	168
cold break	0.22	26
kieselguhr waste	0.62	73
malt dust	0.12	14
labels/paper	0.29	34
packaging	0.04	5

Three chairs of the "TU München-Weihenstephan" have developed a multi-stage process for conversion of wastes from food and beverage industry to biogas [5]. Besides the disposal industry profits of the energy content in waste.
The conversion of brewery wastes outlined in table 1 to biogas with the "Weihenstephaner Verfahren zur Methanisierung organischer Reststoffe" can be regarded as a representative example of future models for solid waste disposal.
For solid retention time in hydrolysis in the bottleneck of methanation of lignocellulosic wastes, research work was focussed on advanced hydrolysis of the heterogenous composed wastes using rumen microorganisms and a combined mechanical and chemical treatment of the lignocellulosic fraction [4][10].

2 Suitability of brewery wastes for methan fermentation

All organic brewery wastes (Table 1) have been investigated for their suitability for methan fermentation. An appropriate method is batch fermentation of spent grain with addition of waste in ratios of accumulation during the weekly production.
After a fermentation time of one week a choice of metabolism products (free fatty acids C_2 - C_7), alcohols, ammonia, phenolic derivates) were analyzed. Total concentration, ratio of free fatty acids $C_2 : C_3 : C4 : >C4$ and reproducibility of a triple batch fermentation were assessed [2].
Well suitable wastes for methanation are waste-paper, hardcover packaging materials, straining cloths and hop spents. These wastes should be grinded to a similar particle size as the spent grain and should be treated in alcaline solution.
The suitability of break and yeast is uncertain. The results have shown non-reproducible fermentations which could cause a diminished process stability. It indicates that the reason is probably the great amount of phenol-protein and phenol-carbohydrate complexes of undefined shape that inhibit microorganisms [2].

3 Technological aspects

Due to the heterogenous composition (Table 2) of the wastes, single or double-stage processes are not feasible for a sufficient performance.

Table 2: Composition of beer brewers spent grain (% of dry matter)

polysaccharides	50 - 55 %
protein	20 - 24 %
fat	10 - 15 %
lignin	8 - 12 %
ash	3 - 5 %

3.1 Hydrolysis

The reason for an insufficient degradation is the high content of easily soluble fat and protein, which are rapidly hydrolized and fermented to short chain fatty acids. The simultaneously occurring drop of pH inhibits a rapid hydrolysis of the lignocellulosic component.
pH-correction by alcaline solutions is no way out because it leads to high concentrations of Na$^+$, K$^+$, Ca^{2+} or Mg^{2+} depending on the applied hydroxyd. Na$^+$ and K$^+$ may inhibit enzyme reaction [1], Ca^{2+} an Mg^{2+} are involved in different reactions of complex formation.
The better choice is a combined chemical-biological hydrolysis where every step put emphasis on a certain substance. Figure 1 demonstrates the individual steps.

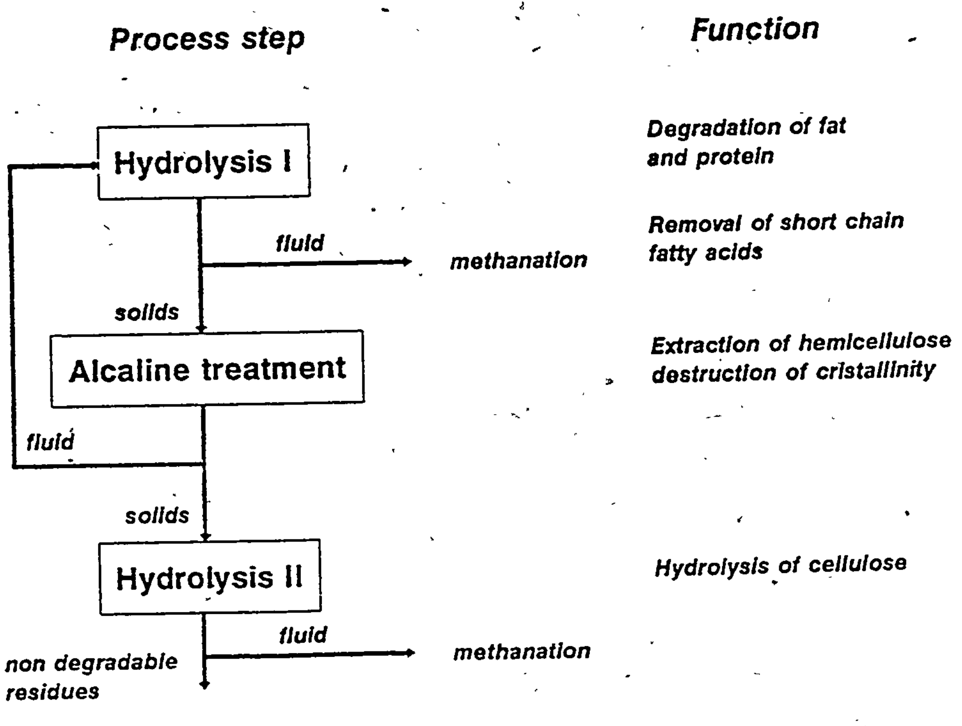

Figure 1: Hydrolysis of beer brewer's spent grain and brewery wastes

Hydrolysis of protein, fat and water soluble sugars (Hydrolysis I) can be performed by microorganisms rapidly within 3 days [10]. The remaining solids consist of hemicellulose, cellulose and lignin. The fluid phase has a high concentration of free, short-chain fatty acids resulting from the fermentation and it is not possible to hydrolyze the cellulosic fraction under these conditions within a satisfying retention time.

It is necessary to remove fatty acids from the process. An appropriate method is a solid-fluid separation by a centrifuge or decanter. Remaining fatty acids in the surface moisture can be washed out with process waste water by the counter current method during transportation to the alkaline treatment. That way an early neutralization of the alkaline solution can be avoided.

3.2 Alkaline treatment of lignocellulose

The structure of lignocellulosics is of complex nature with a high degree of cristallinity of cellulose and cross-linkage of hemicellulose with lignin. It doesnt't lay open any points of attack for enzymes and no points of adsorption for cellulolytic microorganisms. This in fact is the reason for long retention times during hydrolysis of lignocellulosic materials (more than 60 days for spent grain)[7].

Points of attack in the structure can be created by alkaline treatment for most vegetable wastes contain hemicellulose readily soluble in alkaline solutions. During alkaline treatment hemicellulose will be extracted from lignocellulosic materials releasing points of attack for enzymes.

However alkaline treatment doesn't make any sense as long as protein and fat are present. Reactions of neutralization and formation of non degradable by-products from protein occur and perform inhibiting effects on microorganisms.

Effective hydrolysis in alkaline solution requires the following subsequent process steps:

a) Hydrolysis of readily degradable substances like fat, protein and water soluble carbohydrates (Hydrolysis 1).

b) Creation of points of attack in lignocellulose by alkaline treatment.

c) Hydrolysis of the alkaline extract by recirculation to Hydrolysis 1.

Remaining solids can be neutralized with biogas from hydrolysis stages and inoculated again (Hydrolysis 2). Within a retention time of 4 days another 15 - 20 % of solid dry matter can be hydrolyzed.

Improvement of hydrolysis by means of the alcaline treatment can be realized by grinding spent grain with a wet ball mill to particle sizes of $x_{50} = 30$ μm. This degree of grinding is only available with a high energy consumption (Table 7).

3.3 Methanation

Methanation of the fluid phase is not easy to perform due to the high content of amonnia (2.5 - 3 g/l) and propionic acid (4 - 5 g/l). The difficulty is the choice of the optimum pH-level for both substances inhibit methanation in addiction from pH. An alkaline pH of 7.5 to 8 leads to alarming NH_3 concentrations. Lower pH levels increase the concentration of undissociated propionic acid which can penetrate in microorganisms and deactivate it. An appropriate pH level is around 7 to 7.2. Probably application of a double-stage methanation or methanation with a pH-gradient leads to a further reduction of the actual retention time of 4 - 5 days.

Figure 2 illustrates the combination of all process steps.

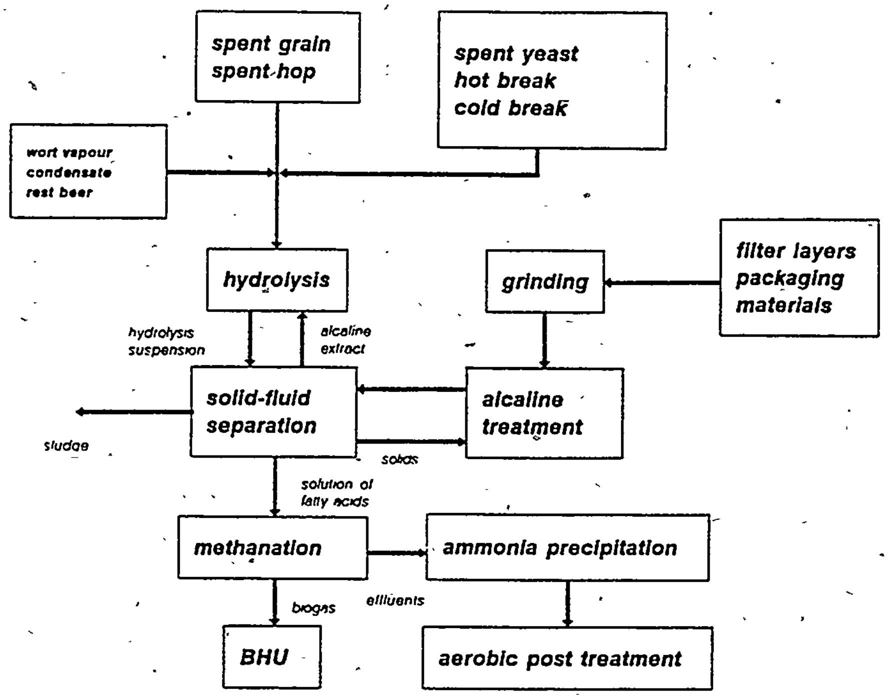

Figure 2: Methan fermentation of brewery wastes

The following data in Table 3 demonstrate the process performance:

Table 3: Process performance of the "Weihenstephaner Verfahren zur Methanisierung von Biertreber"

Dry matter (hydrolysis)	10 - 12 %
Retention time (hydrolysis)	Due to waste composition 4 - 7 days
Solubilization of dry matter	80 - 85 %
Hydrolysis I	37 - 40 %
Alkaline treatment	25 - 32 %
Hydrolysis II	15 - 20 %
Organic loading (methanation stage)	4 - 5 kg COD/(m^3 · day)
Retention time (methanation stage)	4 - 5 days
COD - reduction	85 - 95 %
Biogas composition	CH_4 60 - 67 % CO_2 30 - 35 % H_2S due to protein content 0.1 to 1 % N_2, H_2 traces
Heating value	22 - 24 MJ/Nm^3

Remaining solids were used as fertilizers in agriculture and horticulture. Biogas plant effluents were utilized as liquid fertilizers in agriculture or treated due to the common standards for direct dump in sewers (precipitation of ammonia, aerobic COD - reduction). Biogas is utilized for gaining energy and electric power by a gas-engine driven block heating unit. Waste heat sources of the production process and biogas plant are coupled energetically [8].

4 Technical realization of the biogas plant

4.1 Hydrolyis reactors

Both Hydrolysis stages are stirred tank reactors with a slowly operating winding stirrer guided in an internal tube (Figure 3) following concepts of [9][11].

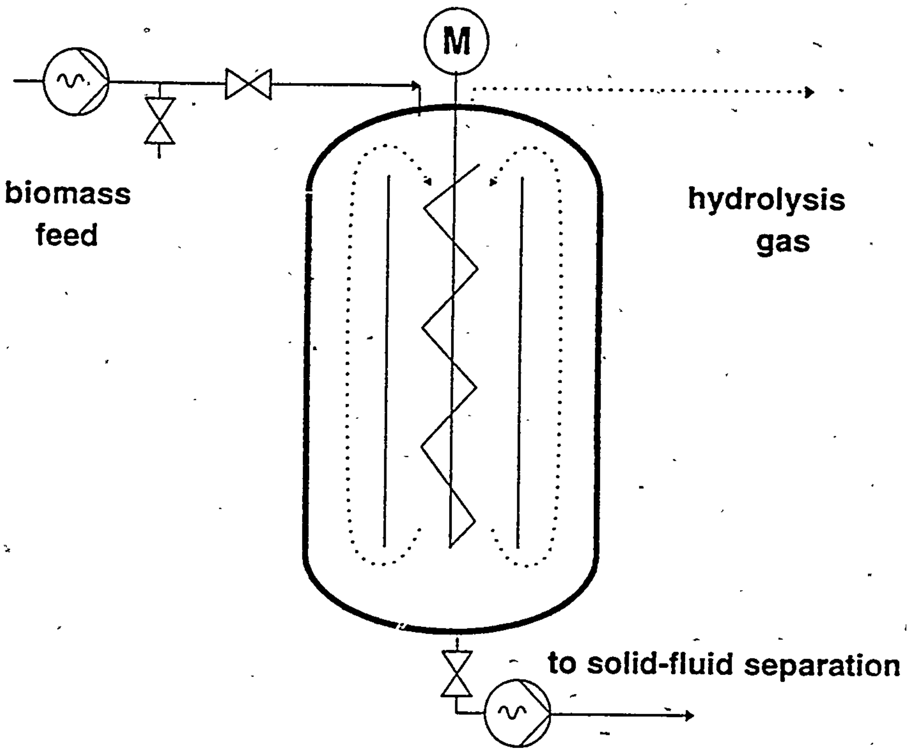

Figure 3: Hydrolysis reactor

During operation, both reactors are totally filled up to avoid foam formation [9]. Given the fact that solid and hydraulic retention time of the substrate are very different the most convenient operating mode is batch operation to guarantee a maximum degradation rate. To meet the supply with microorganisms two methods are suitable. One is recirculation of microorganisms from the hydrolysis stages. The other is co-processing of rumen content, intestine content or liquid manure.

4.2 Alkaline Treatment

For an advanced degradation of lignocellulose and reduction of total retention time a chemical pretreatment in combination with grinding seems to be obligate. Activities in research during the last years concerning pretreatment of lignocellulose have pointed out an increasing degree of solubility with increasing intensity of pretreatment (temperature, concentration of the solvent).
The pretreatment of spent grain of the Weihenstephan process is performed by a continuous driven ball mill in alkaline solution.

Table 4 outlines the process parameters for ball-milling.

Table 4: Process parameters of ball milling [4]

Temperature:	70 °C
Retention time:	6 minutes
Concentration of solvent:	8 g NaOH per 100 g dry matter
Concentration of solids in suspension:	10 % (weight/volume)
Consumption of electrical power:	1,4 - 2,3 MJ/kg dry matter

The remaining alkaline solids can be washed with process effluents in the above described way and neutralized by hydrolysis gas. In a second biological stage a further reduction of dry matter can be performed. 4 days of additional retention time result in a reduction of dry matter of about 15 - 20 %. Economic considerations can lead to a renunciation of the second biological stage.

4.3 Methanation stage

Methanation is performed in a fixed-bed slope reactor with of adapted microorganisms from sewage. The fixed-bed concists in a polypropylene package with a porosity of 95 %. Further process data are outlined in Table 4:

Table 5: Performance data of the methanation stage [4]

COD of the substrate:	22 g/l
organic loading:	4 - 5 g/ld
retention time:	4 - 5 d
gas production:	0,45 m^3/kg dry matter (CH_4 72 - 78 %, CO_2 20 - 24 %, varying amounts of N_2 2-5 % H_2S and H_2 < 0.01 %).

4.4 Biogas storage and utilization

The continuous release of biogas during the process consequently requires a continuous utilization which is not always practible (week ends). Therefore, intermediate storage containers must kept ready. The minimal storage volume should be acquainted with the biogas release on weekend (50 - 55 h).

One practible and cheap method of utilization is storage in low pressure foil storage containers after removal of moisture by condensation in combination with a gas driven block heating unit [8]. Surplus heat can be stored in a hot water storage tank. The produced electric power can provide the consumption of refrigerating plants and subsidiary unit in breweries on weekends as well.

4.5 Effluent treatment

Effluents of our three biogas plants contained some non-degradable organic substances and high concentrations of ammonia (Table 4)

Table 4: Average composition of biogas plant effluents

COD	2 - 6 g/l
acetic acid	20 - 30 mg/l
propionic acid	300 - 350 mg/l
phenylacetic acid	400 - 500 mg/l
phenylpropionic acid	50 - 80 mg/l
benzoic acid	50 - 100 mg/l
phenol	10 - 15 mg/l
biomass	0,5 - 1 g/l
ammonia	2 - 2.5 g/l
cations	10 - 12 g/l (K,Na,Ca,Mg)
heavy metals	Zn, Pb, Cu, Ni, Cd, Hg, Cr due to input material

The most convenient way for effluent utilization is the use as a liquid fertilizer in agriculture. A tightened up environmental legislation restricts this possibility more and more. In Germany the phenolic acids and the ammonium must be removed in case of direct dump into sewers to meet the threshold values for COD (100 - 110 mg/l) and ammonium (5 - 10 mg/l).

An appropriate treatment for ammonia removal is precipitation as $Mg(NH_4)PO_4$ in combination with air-stripping. Precipitation of 75 % of the initial ammonium concentration is performed by addition of MgO and phosphoric acid (Mg : P : N = 1 : 0,8 : 1) [8]. The chemically upgraded water can be utilized as a suspending medium for spent grain. $Mg(NH_4)PO_4$ is a valuable fertilizer in agriculture. Direct dump in sewers requires a further reduction to the threshold limit, only available by air-stripping or biological methods like nitrification/denitrification. A single nitrification is only useful when the maximum permissible load of nitrate in the sewer is harmless.

Recent works in Weihenstephan are focussing on the developement of an aerobic high performance reactor for simultaneous removal of ammonium and COD.

4.6 Rotting of remaining solids

The process releases solids of approximately 70 - 80 kg/t wet spent grain with a moisture content of 35 %. The composition is outlined in Table 5:

Table 5 : Composition and quality of remaining solids (% of dry matter)

Lignin	40 - 50 %
Total Nitrogen (Kjeldahl)	2 - 2,5 %
Cellulose	40 - 45 %
P	0,29
K	0,03
Ca	0,48
Mg	0,07
pH	> 6

Approximately 20 % of spent grain are biologically not convertable to biogas and are released after the process as solid sludge. Odouring substances can be removed by washing with upgraded process water. Compostion is a convenient method for upgrading the solids. For an optimized C/N ratio addition of a well textured waste (f.e. straw) is required [5]. The product can be used as a fertilizer in agriculture as well.

Table 6 shows the quality of the compostion product and the requirement for utilization as a plant substrate:

Table 6: Quality of composts from spent grains and remaining solids from the biogas process

origin	spent grain	released solids	biowastes	
requirements				garden
pH	6.0 - 6.5	6 - 7	6.2 - 8.4	5.5 - 6.5
N	1.75 - 1.77	0.38 - 0.60	0.28 - 0.56	0.06 - 0.12
P_2O_5	3.50 - 3.60	0.33 - 0.65	1.00 - 2.70	0.50 - 1.00
K_2O	1.00 - 1.40	1.05 - 1.10	3.00 - 7.50	0.15 - 0.25
Mg	0.26 - 0.29	0.14 - 0.17	0.25 - 0.45	0.06 - 0.12
total salt	7.10- 7.50	2.60 - 3.50	5.00- 10.00	1.00 - 2.50

Direct compostion yields compost with a hardly tolerable contents of salt. Spreading on agricultural areas on a long term basis can cause an accumulation of salt in the soil. Utilization of composts from solids will be the better choice.

Another application can be the co-firing of a suitable combustion with biomass, for the main component in the solids are carbon, hydrogen and oxygen.

4.7 Measuring and control engineering

Continuous operation of the biogas plant requires the follwing online measurements [4]:

- filling (conductive)
- pH (gel electrode)
- temperature (Pt 100)
- volume and mass (inductive)
- biogas volume (wet gas)

Furthermore, the following parameters should be analyzed in convenient intervals:

- compostion of biogas (gas chromatography)
- free fatty acids (gas chromatography)
- COD (photometric)
- ammonium (ion selective electrodes)

A convenient interval during start-up period up to a stable process (the first 4 - 5 weeks) and process failure is a daily analyze of the mentioned process parameters. During process stability two times a week is sufficient. An appropriate measurement system has been developed by Behmel and Leupold [2]

5 Energetic coupling of a biogas plant and a brewery

According to the presented concept the maximum specific heating supply comes to 2.1 MJ/hl sales beer assuming an isolation of 10 cm layer thickness and an evironment temperature of 0 °C. Recycling of brewery sewages like condensed wort vapour and surplus process sewage can reduce the heating supply drastically to 0.65 MJ/hl sales beer (Table 7). Furthermore it is applicable to utilize surplus heat of economizers or high pressure refrigerator units (Figure 5).

Table 7 : Energy yield and energy consumption of plant units ball mill, centrifuges, stirrers and pumps (MJ/kg dry matter)

energy yield:		10.4 - 11.7
heating supply:		0.65
energy consumption:	with grinding	1.40 - 2.30 (4.7 - 7.7)
	without grinding	0.36 - 0.48 (1.2 - 1.6)

values in brackets:
utilization of primary energy assuming electrical efficieny of 30 % and thermal efficiency 55 % of the block heating unit

boundary conditions:
alcaline pretreatment of spent grain, double stage biological hydrolysis, recirculation of 60 % biogas cffluents, isolated fermenters 0.1 m layer thickness, temperature 0 °C.

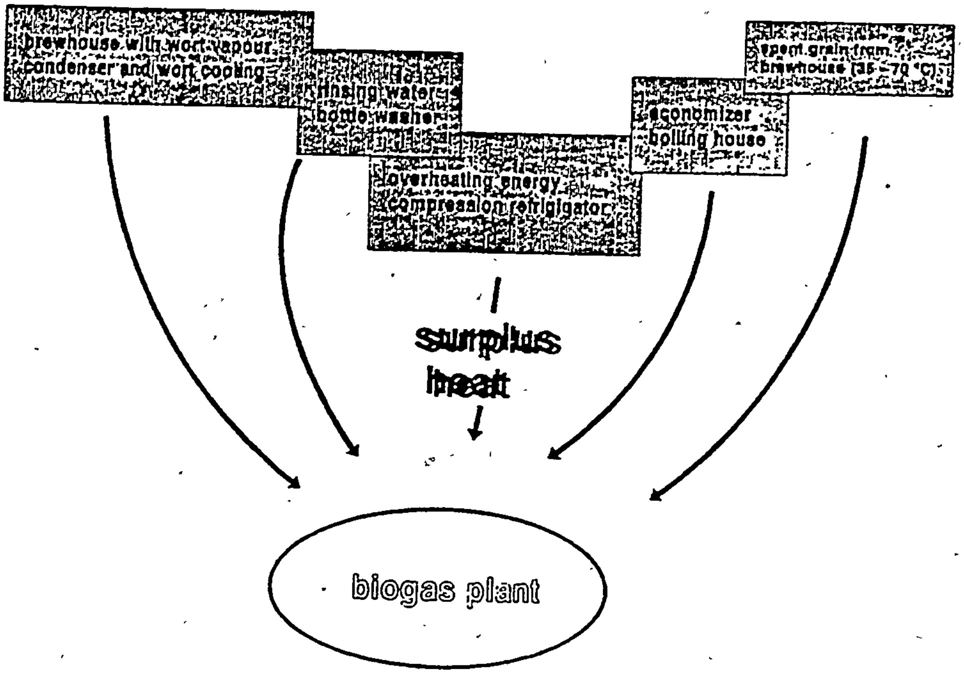

Figure 5: Surplus heat sources in brewery

6 Economic efficiency of a biogas plant

In 1990 investment cost were estimated on about 20 Mio. DM for a biogas plant in a 1 Million hl brewery. According to our own results of research, costs can be reduced on less than 10 Million DM. Costs can be reduced drastically in line with the reduction of fermenter volume and retention time. Figure 6 shows the relation and latest developments in technology.

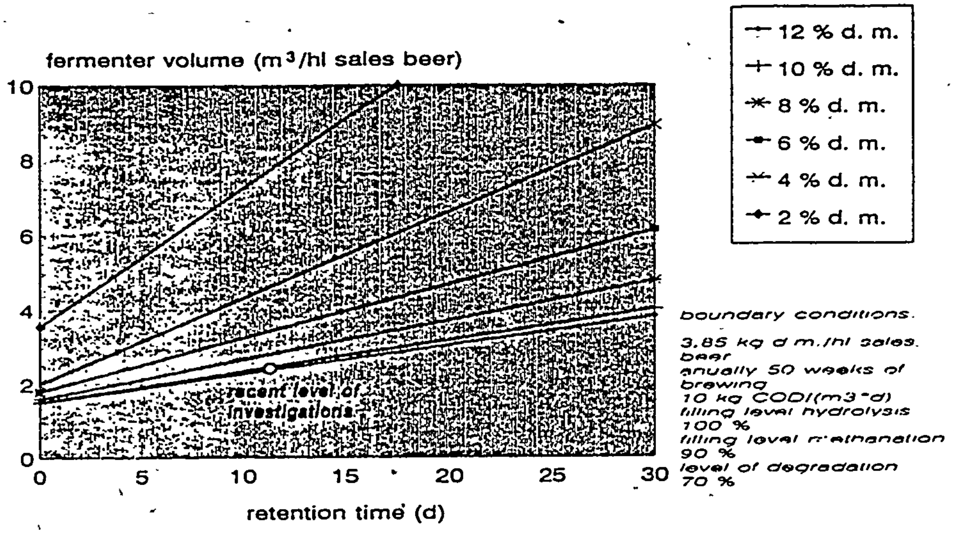

Figure 6: Fermenter volume dependent on retention time [8]

The savings result from a substitution of fossile fuels and savings from costs for electric power. 10.4 - 11.7 MJ of heating energy per kg dry matter of spent grain are available by utilization of biogas (Table 7).

The resulting savings are to be calculated individually for each brewery. It is also dependent on application of grinding. Figure 7 shows the relation between specific cost for disposal and profits assuming realistic annual net profits of 500 000 DM [8].

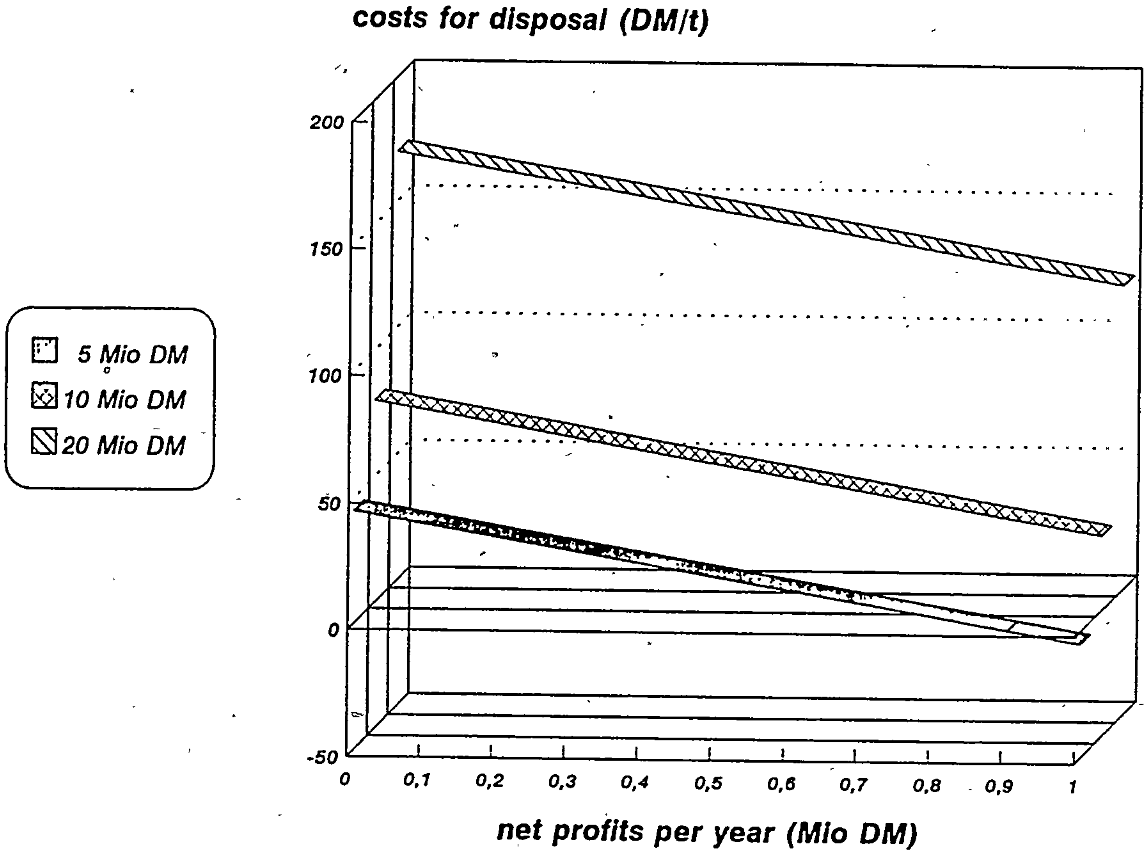

Figure 7 : relation between specific costs for disposal and profits

For supply with regenerative energy and innovative waste disposal, capital investment bonuses by government can be expected. After five years of research work economic efficiency of biogas production from spent grain is possible [5].

7 Conclusions

Biogas production is obviously an alternative for disposal of brewery wastes. Recent investigations resulted in further reductions of retention time for hydrolysis (80 - 85 % of reduction of dry matter within 7 days) and a total retention time in the process of 10 - 11 days. Retention time is directly proportinal to fermenter size and, consequently, this causes a drastic reduction of costs for investment.
Yielded energy can be utilized in the production line so that fossile fuels for production of primary energy can be saved with a positve effect on the worldwide achieved reduction of CO_2 - emissions.
Nevertheless, some problems remain. A good performance of the plant requires sumptous technology. High qualified specialists are required. Related to breweries this concerns reduction of ammonia and cost of technology for a multiple stage biogas plant. Furthermore the high protein of beer brewer's spent grain causes an unnfavourable C/N ratio of approximately 9 - 12. The resulting high concentrations of ammonia cause an inhibited biogas production.
Obviously the high financial risk and the low process stability have prevented a widespread application of methanation of solid biowastes in food processing industry until now.

8 A way out ?

The problems mentioned above indicate the disposal of specific wastes from food processing industries in one biogas plant.
Retention time and probably process stability can be optimized by co-processing other wastes from food industry with a minimum of protein (residues from spice extraction, wastes from vegetable processing industry). Onion peels, ginger and paprika residues have shown a good fermentability.
At locations where such wastes are available, companies are able to dispose wastes in joint action. Figure 8 illustrates a situation near Munich. These companies have lots of difficulties with waste disposal and located in a circle of 25 miles but joint action has not been realized until now.

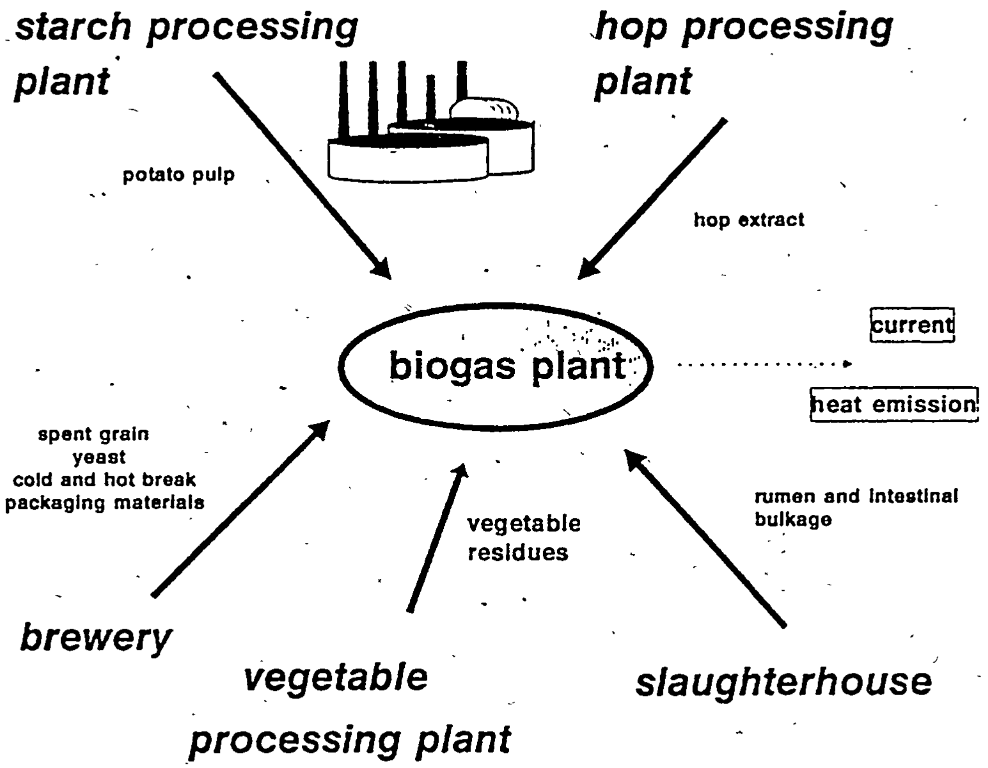

Figure 8 : Waste disposal of food processing industry

Disposal of wastes in joint action in one biogas plant enables a common bearing of costs, financial risk and responsibility. Compared to the case of operating an own biogas plant the risk for each company is minor.
The location for such a biogas plant should be a place where thermal energy and produced current can be utilized completely, possibly not in food-processing industry.
This strategy requires an intensive joint action of concerned companies. A widespread communication is necessary in order to create the infrastructure. This should be a matter of concern for future mamagers.

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BIOGAS PRODUCTION FROM LOW TEMPERATURE LAGOON DIGESTERS TREATING LIVESTOCK MANURE

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Abstract

Laboratory anaerobic digesters were fed dairy and swine manure at the rates of 0.1 and 0.2 kg volatile solids (VS)/m^3-day over the temperature range of 10-23°C. The digesters were operated successfully with little indication of instability. Methane (CH_4) yield, (B,m^3 CH_4/kg VS added) ranged as follows:

Loading Rate (kg VS/m^3-Day)	Manure Type	B m^3 CH_4/kg VS Added
.1	Dairy	.17 - .24
.2	Dairy	.14 - .23
.1	Swine	.25 - .32
.2	Swine	.21 - .27

Introduction

Anaerobic digestion is the process of stabilizing organic matter through the use of bacteria that live in anaerobic (without oxygen) environments. Mesophilic and thermophilic livestock manure anaerobic digesters (mixed tank and plug flow) have demonstrated the potential of producing biogas as an on-site energy source (Fischer et al, 1975; Jewell, 1979; Pos et al, 1985 and Safley et al, 1987). However, this technology has not been widely adopted by livestock producers largely due to

Anaerobic lagoon, another type of anaerobic digester, are widely used in the United States to treat livestock manure. Anaerobic lagoons can produce significant quantities of biogas (Allen and Lowery, 1976; Safley and Westerman, 1988; Safley and Westerman, 1989, Safley and Westerman, 1992b). Chandler et al (1983) and Safley and Westerman (1992a) have demonstrated successful operation of covered anaerobic lagoons. Such lagoons are termed low temperature lagoon digesters (LTLD).

In 1985 North Carolina State University began to evaluate the potential of harvesting biogas from anaerobic lagoons in North Carolina. Safley and Westerman (1988) initially mapped biogas production on several lagoons. The biogas quality and production determined stimulated further investigation. In 1985 a floating cover (50' x 80') was constructed on a poultry lagoon near Princeton, NC (Safley and Westerman, 1989). The lagoon received effluent from a mixed tank digester serving the 70,000 caged layer operation. The additional harvested biogas increased the total biogas production at the site by 5% - 15% depending on the time of year. This floating cover is still in use. The project was partially supported by the Southeast Regional Biomass Energy Program (SERBEP, TVA).

In 1986 a small pilot floating cover (20' x 70') was located on a swine lagoon near Whitakers, NC (Safley and Westerman, 1989). After several months of tests the cover was moved to a dairy lagoon located near Raleigh, NC on the North Carolina State University Unit II Research Farm (Safley and Westerman, 1992b). Results from the evaluation of these two lagoons indicated that biogas is produced throughout the year. However, biogas production rate is much lower during the winter when the lagoon temperatures in shallow lagoons are reduced. The quality of the biogas produced was quite high (60% - 80% methane).

In 1988 an anaerobic lagoon digester system was constructed at the North Carolina State University Randleigh Dairy located near Clayton, NC. This low temperature lagoon digester (LTLD) was designed to serve a 150-cow Jersey herd. The floating cover is approximately 70' x 80'. This project was a joint effort between the North Carolina Agricultural Research Service, the Energy Division of The North Carolina Department of Economic and Community Development and The North Carolina Dairy Foundation. The biogas produced is used to fuel a boiler which supplies all of the hot water needed by the dairy. The design and operation of the Randleigh Dairy LTLD has been described by Safley and Lusk (1990) and Safley and Westerman (1992a).

Safley and Westerman (1990) have suggested that reasonable methane (CH_4) yields are possible for anaerobic digestion at low temperatures if digester loading rates are appropriately reduced. Cullimore et al (1985) indicated that biogas production was initiated between 3°C and 9°C. Stevens and Schulte (1979) have reported that methane yield at lower temperatures (20°C - 25°C) and increased retention times approached that of higher temperatures and shorter retention times. Sutter and Wellinger (1985) indicated that linear gas production increases can occur in the range of 10°C - 20°C.

Safley and Westerman (1990) presented the following equation for use in estimating the appropriate loading rate necessary to give a desired methane yield for a specific temperature based on a known loading rate and temperature for a digester that is performing at the desired methane yield:

$$\frac{LR2}{LR1} = e^{p(T2 - T1)} \qquad \text{-----------------------------------} \quad (1)$$

where: LR1, LR2 = loading rate (kg VS/m^3-day) at T1, T2
T1, T2 = temperature, °C
p = 0.1, rate constant (°C^{-1})
VS = volatile solids

Based on typical loading rates of mesophilic digesters operating at 35°C (1 - 3 kg VS/m^3-day) the predicted loading rates for 10°C would be 0.08 - 0.24 kg VS/m^3-day to achieve similar methane yields. The actual performance of anaerobic digesters operating at lower temperatures must be evaluated in order to be able to determine appropriate loading rates for LTLDs.

Objective

The objective of this research was to evaluate the performance of laboratory-scale anaerobic digesters fed dairy and swine manure at the loading rates of 0.1 and 0.2 kg VS/m^3-day over the temperature range of 10°C to 25°C.

Methods and Procedure

Ten acrylic plastic laboratory digesters (2 liter) were constructed for this project. Biogas production from each digester was measured using liquid displacement (Owens, 1988). Four loading rate/manure source combinations were tested. Two digesters were assigned to each combination as indicated in Table 1.

Table 1
Laboratory Digester Assignments

	Loading Rate	
Manure Source	0.1 kg VS/m^3-day	0.2 kg VS/m^3-day
	Digester Numbers	
Dairy	1 & 2	3 & 4
Swine	6 & 8	7 & 10

The dairy manure for the experiment was collected fresh (feces only) from the concrete surface of one of the feeding/lounging lanes at the NCSU Randleigh Dairy on a monthly basis. This lane housed only mature milking cattle. The swine manure used during the experiment was collected fresh monthly from one of the finishing barns (feces only) at Carroll's Foods, Inc. Farm No. 37. Both the swine and dairy manure were stored in a cooler (~ 5°C) on the same day as collected. Representative subsamples were initially evaluated for total solids (TS). Using the TS information the respective manures were diluted to approximately 2% TS, thoroughly mixed, placed in a 1-liter polypropylene containers and refrigerated (2°C). A subsample was collected prior to freezing and analyzed for TS, volatile solids (VS), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH3-N), alkalinity, pH, volatile fatty acids (VFA) and chemical oxygen demand (COD).

The digesters were fed on a daily basis. At the time of feeding the biogas production was noted. Once a week a biogas sample was taken to determine CH_4 concentration. The CH_4 concentration in the biogas was determined using a Shimadzu model GC-15A gas chromatograph.

The dairy digesters were initially filled with effluent from a low temperature lagoon digester operating at Randleigh Dairy, a university research farm, (Safley and Westerman, 1992a). The swine digesters were filled with liquid taken from the anaerobic lagoon at Carroll's Foods, Inc. Farm No. 37, a company-owned farm. This site is located near Warsaw, N.C. Therefore, the material that was used to start the digesters was taken from mature anaerobic treatment units. The dairy digesters received approximately 50 mL of effluent from the Randleigh Dairy digester weekly to assist in maintaining a vigorous bacteria population. A similar quantity of swine lagoon liquid was added to the swine digesters each week.

The experiment was initiated in April 1991. The temperature of the incubators was set at 25℃. The temperature in the dairy digesters was maintained at 25℃ for approximately three months to allow the digesters to stabilize and acclimate to the feed material. The swine manure digesters required approximately five months to stabilize. The incubator temperature was then gradually dropped in 1℃ increments.

Results and Discussion

Influent and effluent characteristics for the dairy and swine digesters are presented in Tables 2 and 3, respectively. The dairy digester influent and effluent characteristics indicate several items of interest.

Methane yield (B, m^3 CH_4/kg VSA) was computed weekly throughout the experiment for each digester. B was determined using the loading rate of the digester, the biogas production and the concentration of methane in the biogas. After reviewing the data it was apparent that the performance of all digesters during the early stages (incubator temperatures of 24℃ and 25℃) of the experiment ws erratic. This indicated that full stability was not initially realized. Therefore, the data collected for the incubator temperatures of 24℃ and 25℃ were removed from the data base to be evaluated..

B was regressed against digester temperature using the general linear models procedure developed by SAS (1982). The linear models were of the form illustrated in Equation 1. The models developed are presented in Table 4.

$$B = A + CT \text{..................................} (1)$$

B = methane yield, m^3 CH_4/Kg VS added
A = intercept
C = temperature coefficient
T = temperature, ℃.

The data points used in the regression models for the different digesters and the combined models for a given loading rate and manure feed type are presented in Figures 1-4. For each loading rate/manure type combination the duplicate test digesters gave similar performance.

Table 2
Dairy Manure Digester Influent and Effluent Characteristics

		Effluent			
		Digester Number			
Parameter	Influent	1	2	3	4
TKN, mg/1	841	420	407	445	443
S.D.	337	54	58	59	74
NH_3-N, mg /1	49	266	263	243	250
S.D.	41	44	46	47	49
Alkalinity mg/1 as $CaCO_3$	1337	2223	2202	2202	2233
S.D.	732	119	124	180	197
TS, %	2.17	0.39	0.37	.54	0.52
S.D.	.70	0.06	.04	.24	0.23
VS, % TS	84.6	59.7	60.1	63.2	63.9
S.D.	2.8	4.9	4.5	6.3	5.5
pH	6.3	7.8	7.8	7.5	7.6
S.D.	0.4	0.2	0.3	0.3	0.3
VFA (as acetic acid), mg/1	1067	65	61	78.4	90.4
S.D.	406	154	142	132	218
COD, mg/1	24610	3226	2998	4681	4783
S.D.	12245	846	699	2314	2322

Notes:

1. S.D. - Standard Deviation
2. Digesters 1 & 2 fed at 0.1 kg VS/m^3-day
3. Digesters 3 & 4 fed at 0.2 kg VS/m^3-day
4. Number of samples - 77
5. Weekly samples for 18 months

Table 3
Swine Manure Digester Influent and Effluent Characteristics

Parameter	Influent	Effluent Digester Number 6	 8	 7	 10
TKN, mg/1	1056	542	550	566	564
S.D.	362	143	140	141	147
NH_3-N,mg/1	240	463	463	472	464
S.D.	329	121	126	130	136
Alkalinity mg/1 as $CaCO_3$	1759	2537	2541	2626	2626
S.D.	637	404	556	525	550
TS, %	2.47	0.28	0.29	0.30	.31
S.D.	1.25	0.03	0.05	0.05	.06
VS, % TS	78.2	50.9	51.4	51.3	52.7
S.D.	7.9	6.2	6.3	5.8	5.6
pH	6.6	8.0	7.9	7.8	7.8
S.D.	0.3	0.3	0.3	0.4	0.3
VFA as acetic acid, mg/1	1407	52	65	80	51
S.D.	518	121	184	176	129
COD, mg/1	22856	1549	1633	1809	1922
S.D.	14653	357	369	507	474

Notes:

1. S.D. - Standard Deviation
2. Digesters 6 & 8 fed at 0.1 kg VS/m^3-day
3. Digesters 7 & 10 fed at 0.2 kg VS/m^3-day
4. Number of samples - 77
5. Weekly samples for

Table 4
Coefficients for Methane Yield Models

Manure Type	Loading Rate (kg VS/m^3-day)	Data	Intercept Estimate (m^3 CH_4 / kg VSA-°C) (A)	Standard Error of Intercept Estimate	Slope Estimate (m^3 CH_4 / kg VSA-°C) (C)	Standard Error of Slope Estimate	No. of Observations
Dairy	0.1	Digesters 1 & 2 combined	0.1153	0.0083	0.0053	0.0006	119
	0.2	Digesters 3 & 4 combined	0.0820	0.0083	0.0063	0.0006	123
Swine	0.1	Digesters 6 & 8 combined	0.2011	0.0185	0.0053	0.0013	100
	0.2	Digesters 7 & 10 combined	0.3177	0.0132	-0.0044	0.0009	104

NOTES: Model B = A + CT
VSA - Volatile Solids Added

The low loading rate (0.1 kg VS/m^3-day) swine digesters performed similarly to the dairy digesters in that B gradually decreased with decreasing temperature (21% reduction from 23°C to 10°C). However, the high loading rate (0.2 kg VS/m^3-day) swine digesters indicated an increased B for decreasing temperature (26% increase from 23°C to 10°C). This would probably indicate that these digesters were not fully stabilized when the experiment began and that the bacteria actually strengthened during the test. This could also imply that there was little actual change in B over the temperature range tested.

Conclusions

Based on the findings of this research the following can be concluded:

1. Anaerobic digestion of dairy and swine manure can be successfully accomplished over the temperature range of 10°C to 23°C for loading rates in the range of 0.1 - 0.2 kg VS/m^3-day.

2. Methane yield, B (m^3 CH_4/kg VSA), increases linearly over the temperature range of 10°C to 23°C for dairy and swine manure.

3. B for the temperature and loading rates evaluated is similar to that achieved at higher temperatures and loading rates.

The information presented in this paper can be directly used to design anaerobic digesters that are intended to operate at low temperatures. This data helps to support the concept of LTLD digester systems for on-farm energy production.

Acknowledgements

Special appreciation is extended to Ms. R.S. Huie who managed the digesters during the experiment and helped to analyze the samples. Appreciation is also extended to Ms. D.A. deBruyne, Ms. C.H. Hayes, Mr. D.A. Williams and Mr. S.L. Crawford for assisting with the management of the digesters and to Dr. F.G. Giesbrecht who advised the authors on the statistical analysis of the data. This project was supported by the Southern Regional Biomass Energy Program (Contract TV 84062-V), and the North Carolina Agricultural Research Service.

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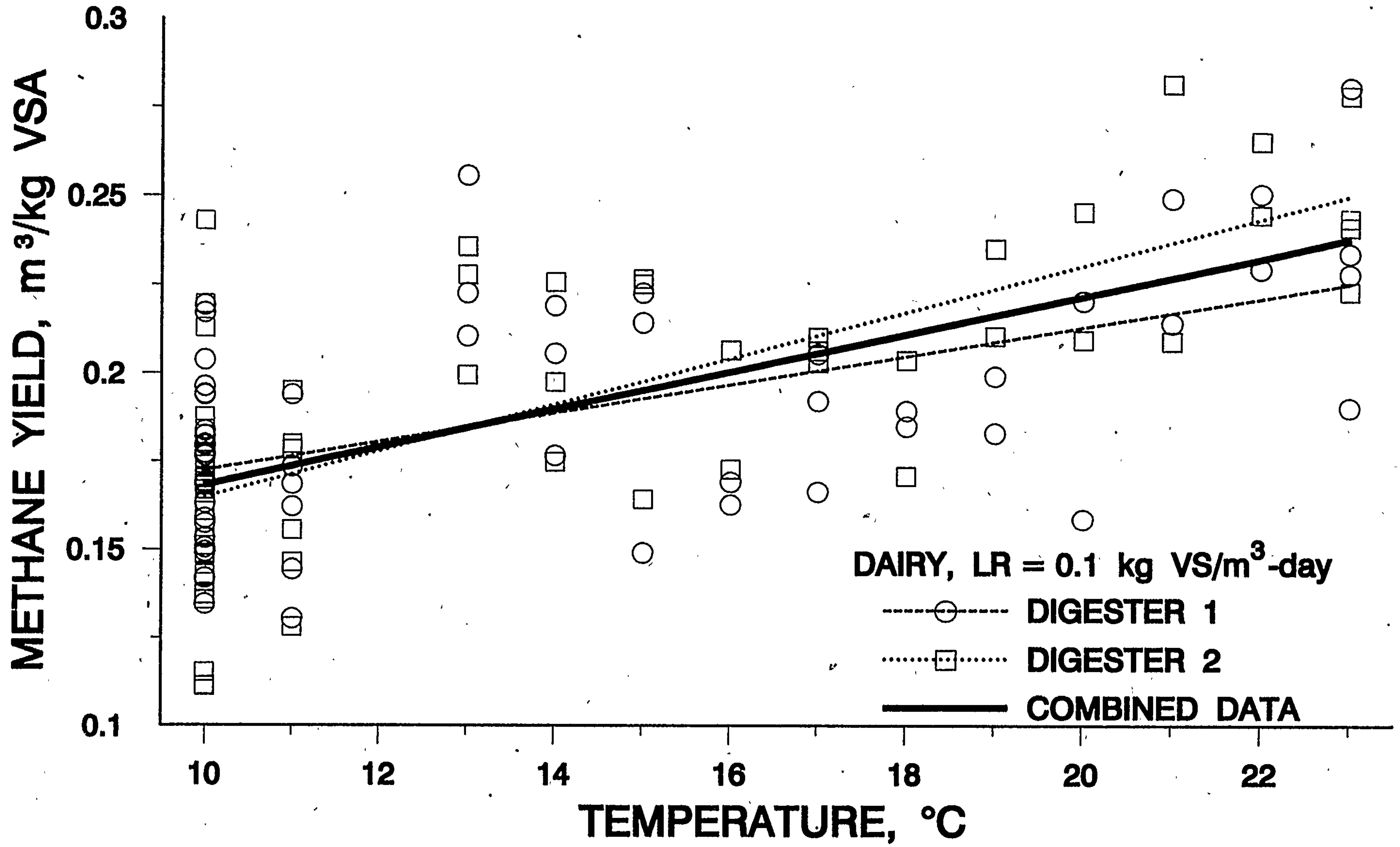

Figure 1. Methane yield for digester for dairy manure at the loading rate of 0.1 kg VS/m^3-day.

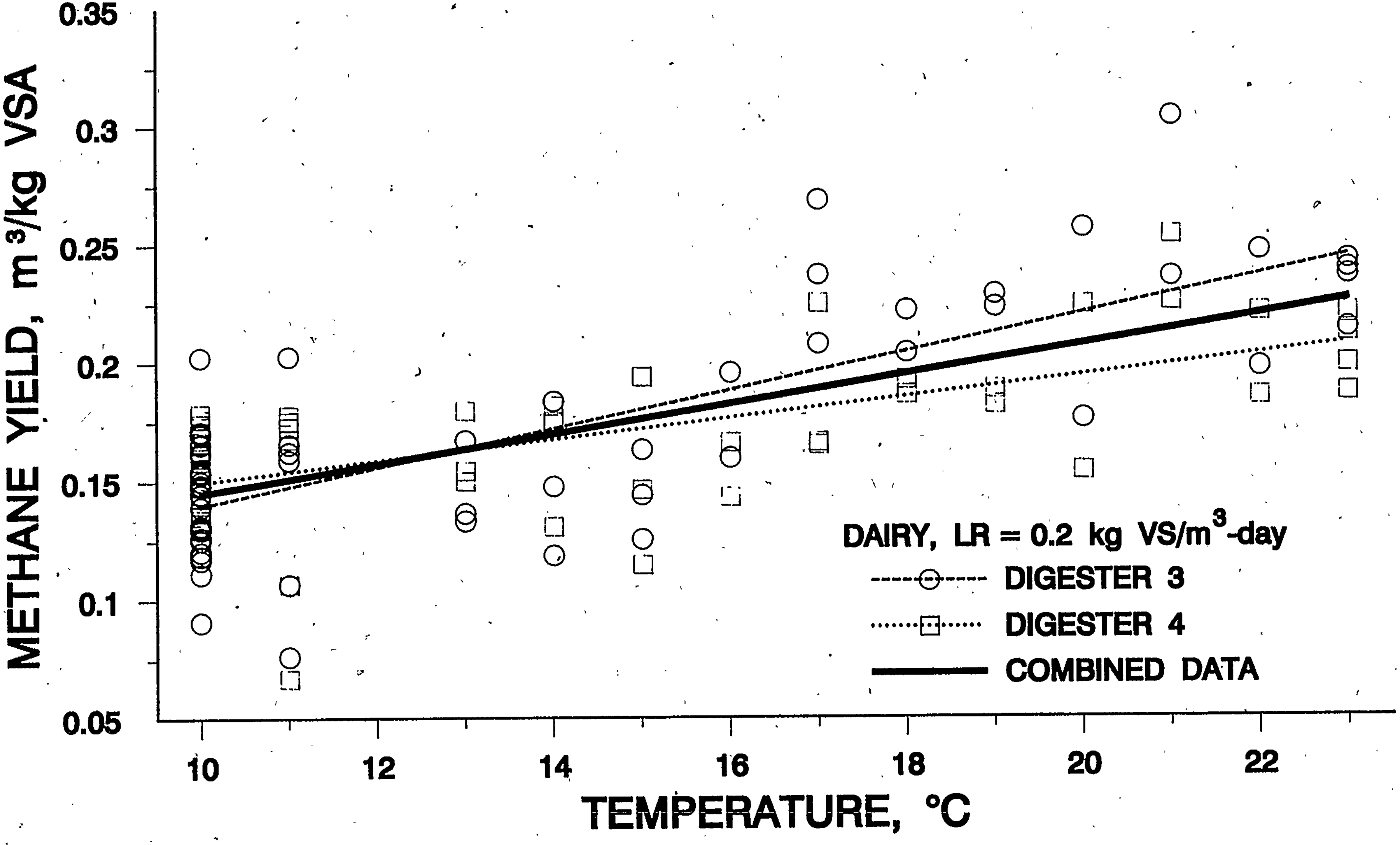

Figure 2. Methane yield for digester fed dairy manure at the loading rate of 0.2 kg VS/m^3-day.

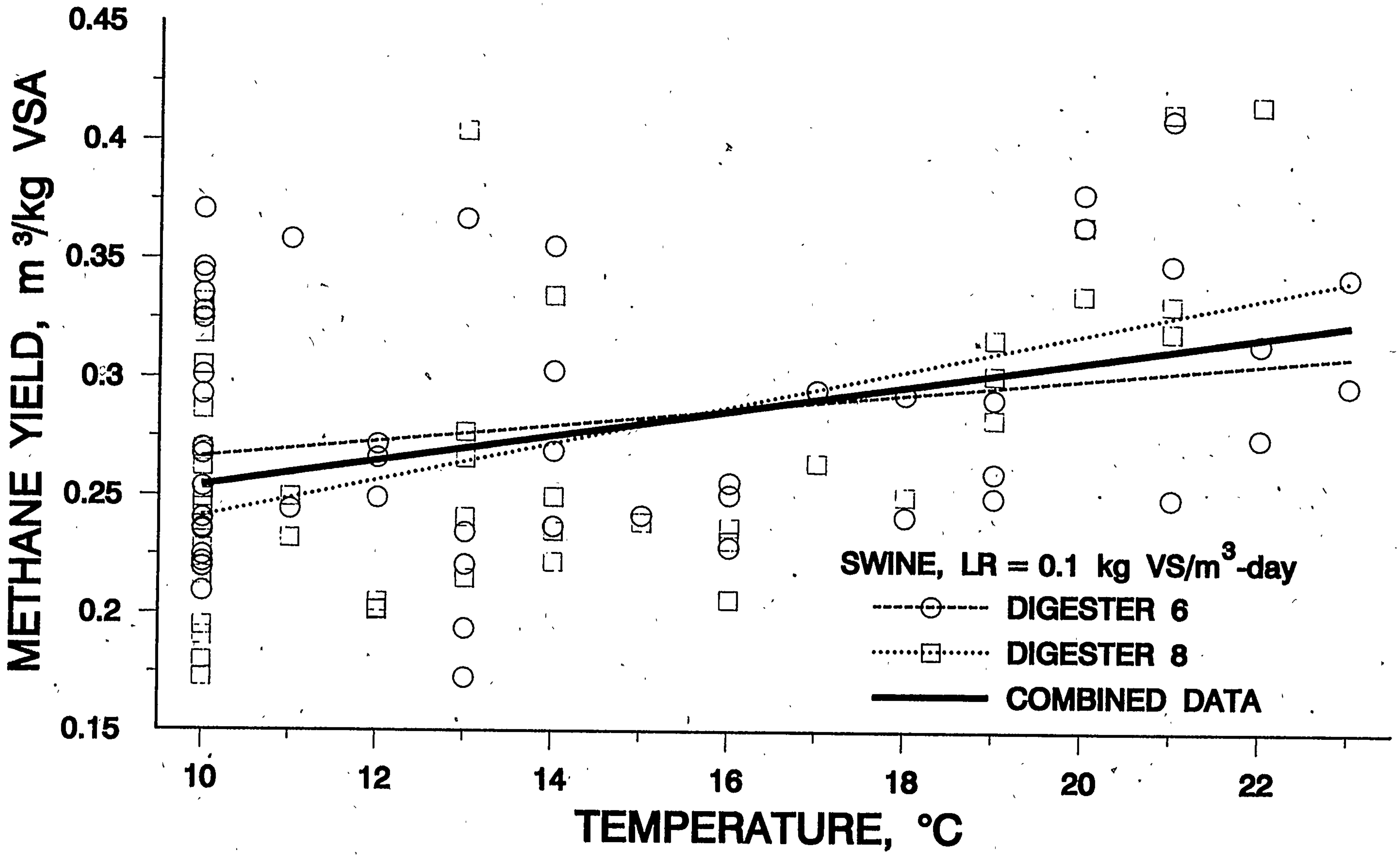

Figure 3 Methane yield for digester for swine manure at the loading rate of 0.1 kg VS/m^3-day.

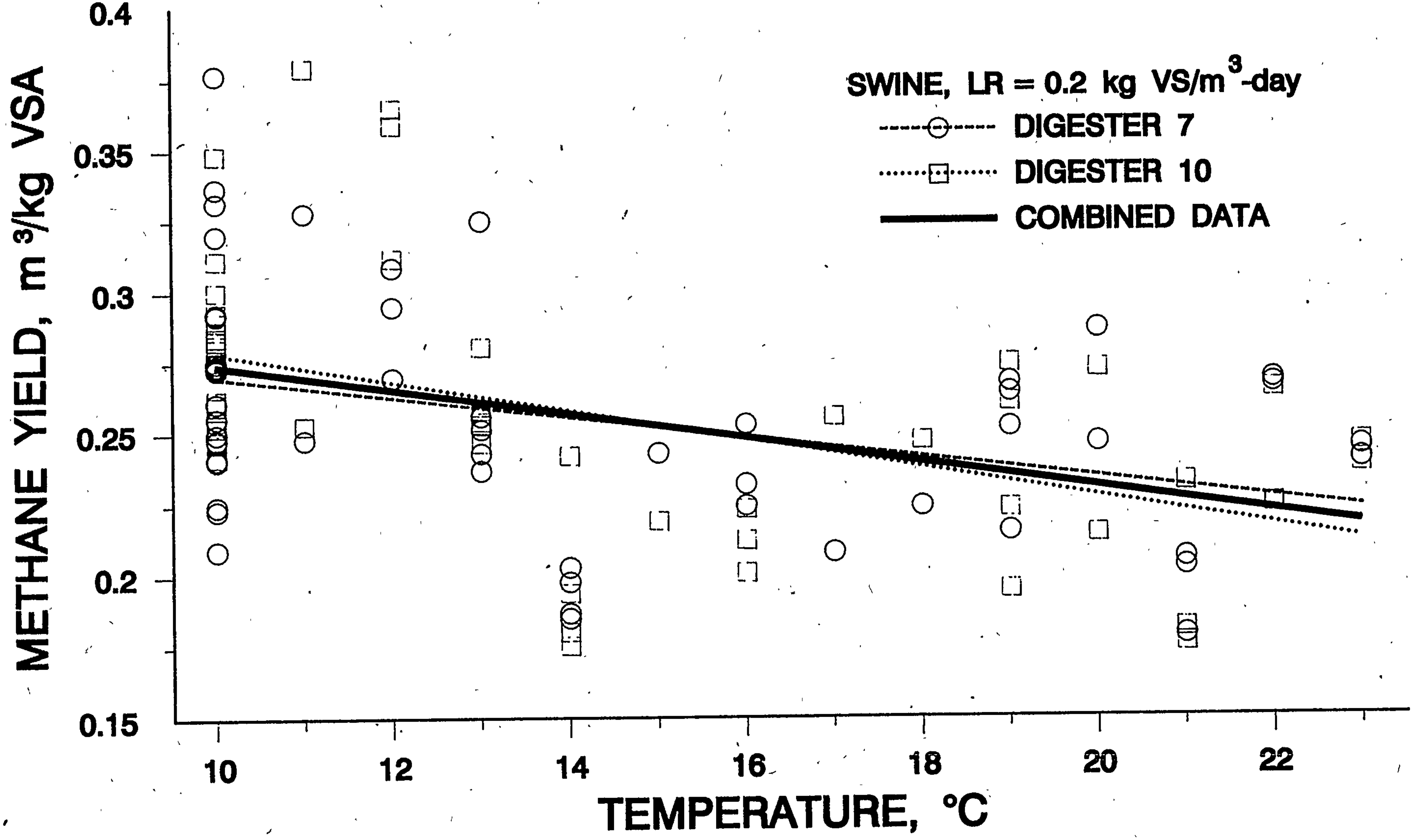

Figure 4. Methane yield for digester fed swine manure at the loading rate of 0.2 kg VS/,^{3}-day.

THE R.D.F. GASIFIER OF FLORENTINE AREA

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ABSTRACT

L.E.G. (Low Energy Gas) from large biomass gasification plants, to be used as a fuel for electricity production, is a suitable mean for adding value - from an energetic point of view - to the R.D.F. (Refuse Derived Fuel) and to the agricultural and forestry residues. R.D.F. can be converted to a clean gas turbine fuel by gasification that consists in a partial combustion with oxigen or air and steam. In that sense it seems worthwhile to analyse the capacity of a gasifier such as the Greve in Chianti's recirculating fluidized bed gasifier.

The world's first full-scale R.D.F. gasification plant has been designed in Florence; it is now realised in Greve in Chianti and, at the moment, is starting the industrial management.

The plant is designed to gasifie 200 t/d of pelletized R.D.F. producing about 17.000/19.000 Nmc/h of low energy gas (LEG) with a net calorific value (NCV) of about 5 MJ/Nmc and a total energy content (at the outlet of the gasifiers) of about 7.5 MJ/Nmc.

The produced LEG will be partly burned on site for power production while partly will be cooled, dedusted and transported to the kiln of the adjacent cement factory.

The design idea of R.D.F. gasification starts from field of waste treatment and recycling and develops new, advanced technical and economical sinergy with the field of industrial production and elecytric power generation.

The gasification of fuels derived from selected wastes (and/or industrial refuse) and the exploitation of the lean gas produced is the most advanced point in the development of heat conversion processes.

The world's first full-scale R.D.F. gasification plant has been designed and realised in Greve in Chianti. (Florence)

The plant includes the following main sub-systems:

- R.D.F. receiving, storage and feeding systems;
- Two circulating fluidized bed gasifiers (CFBG);
- One process gas combustion and heat recovery system;
- One rotary kiln combustion system (as spare and emergency line);
- Thermal cycle with steam turbine for electric energy production (dimensioned for two process gas combustion lines); capacity 6.7 MWe;
- Heat recovery from cooling of LEG;
- Flue gas treatment systems for the process gas and the rotary kiln combustion lines;
- Automatic monitoring and control system.

In the near future the plant will be completed with a second process gas combustion and heat recovery line.

In the month of March the tecnical commissioning of the plant has been completed.

The plant is designed to gasifie a maximum load of 200 t/d of pelletized R.D.F. with average N.C.V. of about 16.7 MJ/Kg producing about 17.000/19.000 Nmc/h of low energy gas (LEG) with a net calorific value (NCV) of about 5÷6 MJ/Nmc and a total energy content (at the outlet of the gasifiers) of about 7.5÷8 MJ/Nmc.

Table 1) shows running values recordered during the total 3000 h worked by the plant from the start up, especially refering to the test period (Jenuary-March 1993) and to the maximum charge loaded using R.D.F. with NCV 12 MJ/Kg.

TABLE 1)

EXPERIMENTAL VARIANS OF RUNNING INSTALLATION (there' s only one boiler set up)				Average experimental varians during the running period: 1993 January/March
Varians	Unit of measure	TEST TO PEAK LOAD		
RDF mass to "CFBG"	(kg/h)	**3500**	**3450**	**2500-2600**
Lean gas produced	(Nmc/h)	7219	7265	**5170 - 5380**
Electric power produced	(MW)	3,645	3,460	**2.450 - 2.520**
Rg	—	**93,06%**	**91,71%**	**89,88%**
Re	—	**19,51%**	**19,38%**	**18,79%**
Rte	—	**18,52%**	**18,10%**	**16,58%**
RT	—	**17,24%**	**16,60%**	**15,24%**
Calorific value of (RDF) = 5000kcal/kg = 20.93 MJ/kg				
Calorific value of lean gas: 2000 - 2200kcal/Nmc = 8.37 - 9.2 MJ/Nmc				

RUNNING WITH PEAK LOAD				
CONFIGURATION	RDF mass to "CFBG"	Lean gas produced	Electric power produced	Gas to cement factory
"CFBG" PLANT GASSIFICATION G1 and/or G2	6.1 ton/h	13000 Nmc/h	3.5 MWh	6300 Nmc/h = 55400 MJ/h

Rg = GASSIFICATION EFFICIENCY OUTPUT:

$$Rg = \frac{\text{(total enthalpy of lean gas put in the combustion chamber)}}{\text{(total enthalpy of RDF put in the "CFBG")}}$$

Re = ELECTRIC EFFICIENCY:

$$Re = \frac{\text{(electric power produced on alternator terminal)}}{\text{(total enthalpy of vapour product in boiler)}}$$

Rte = THERMO-ELECTRICAL EFFICIENCY:

$$Rte = \frac{\text{(electric power produced on alternator terminal)}}{\text{(total enthalpy of lean gas put in the combustion chamber)}}$$

RT = RUNNING TOTAL EFFICIENCY: [Rg*Rte]

$$RT = \frac{\text{(electric power produced on alternator terminal)}}{\text{(total enthalpy of RDF put in the "CFBG")}}$$

The produced LEG will be partly burned on site for power production while partly will be cooled, dedusted and transported to the kiln of the adjacent cement factory.

The design idea of R.D.F. gasification starts from field of waste treatment and recycling and develops new, advanced technical and economical sinergy with the field of industrial production and elecytric power generation.

The gasification of fuels derived from selected wastes (and/or industrial refuse) and the exploitation of the lean gas produced is the most advanced point in the development of heat conversion processes.

Gasification, especially when done with "fluidized bed" type reactors, meets three requirememts of primary importance today:

- Completere-utilization and exploitation of selected material;
- High energy output;
- Almost total elimination of pollutants in the emissions.

We speak of a fluidized bed when the gaseous phase used as combustion agent or gasification reactant (usually in preheated areas) moves upwards through granular material, the "bed" (such as sand or ashes), at such a speed that the entrainment force exerted on the particles compensates for the force of gravity; in this way the particles of fuel move and are in close contact with the gas.

In traditional (not recirculated) fluidized beds, the speed of the flow is so low that the particles are not transported by the flow. The movement of the particles and the type of flow is irregular and turbulent, like that of boiling water.

The gasification reaction occurs in the fluidized bed when the fuel is let into the hot bed and the air is used as a means of fluidization in quantities which are sub-stoichiometric compared to the combustion. The fuel is mixed and reacts immediately in the bed.

A fundamental characteristic of fluidized bed systems is a widely optimized heat and mass balance, due to the perfect heat exchange obtained between the solid and gaseous phases (combustible/air, gas).

Special attention is paid to recirculated fluidized bed systems (internal or external circulation), especially when applied to heterogeneous matter like "R.D.F.", because they ensure a perfect mixture of the matter with the bed, much higher efficiency and exhaust the gasification reaction thanks to the increase in duration which can be obtained by recirculation.

Such systems also make very accurate regulation possible which is especially important for gasification phases where oxygen is scarce. The fuel introduced into the reactor moves with the material of the bed and is thus first dried and then gasified. The reaction temperature in the bed is kept even by the partial development of exothermal reactions.

The quality and the quantity of a residual product derived from the process started can be determined, starting with a controlled composition R.D.F. combustible, by regulating the principal reaction parameters.

It is worth noting the importance of the gasification process (of the various types of reactor development) in the control of environmental impact problems.

In fact the advantages with regard to this aspect can be summed up as follows:

1) The use in the gasifier of a controlled fuel with constant quality, composition and physical state;
2) Only the stoichiometric oxigen strictly necessary for the thermo-chemical gasification reaction is sent into the reducing ambient;
3) Limited volumes of gas are produced which, unlike pure combustion fumes, are a valuable product for energy purposes;
4) Less clinkers produced as compared to thermal destruction and, as explained in point 1), they are of a better quality;
5) Absence in the fuel intake (as it originates from selected currents of refuse) of conditions that might set off any reaction which could form dangerous micropollutants, also thanks to the operating conditions described in point 2);
6) No discharge into the atmosphere during the gasification process;
7) Use of the gas produced by combustion in the gaseous phase at an extremely high flame-temperature and with the reaction air stoichiometrically necessary;
8) Possibility of implementing the process directly at users' premises, separating the operation of disposal of solid refuse (which ends at the production of good quality R.D.F.) from that of using the combustible produced for energy purposes;
9) There is no need for any additional system for reducing the smokes produced by the combustion mentioned in point 7) in case of combination with special industrial uses (cement works, revolving calcination ovens, furnaces) or ones already equipped with systems for controlling atmospheric pollution by traditional combustibles.

TABLE 2) MAIN CARACTERISTICS OF THE R.D.F.

TYPE A	pellets - briquette			
FORME	small cilinders or others			
			FROM	**TO**
DIMENSION (average)	diameter	mm.	10	15
	lenght		50	150
BULK DENSITY		Kg/m^3	500	700
COMPOSITION	H_2O	% by weight	5	10
	Ash		9	16
	S		0,05	0,3
	Cl		0,4	0,8
NET CALORIFIC VALUE		MJ/Kg	16	21
		Kcal/Kg	3900	5500
ASH MELTING POINT	higher than	°C	1150	
HEAVY METALS **(approximative values)**	Pb	mg/Kg	50	150
	Cr		50	200
	Cu		50	100
	Zn		200	300
	Ni		25	20
	Cd		1	2
	Hg		0,1	1

Table 2) shows the characteristics of the R.D.F. with which we want to feed our plant. In the plant is possible to receive various types of fuel but the one shown is to be considered the ideal one, the first choice, the quality we need to optimize the process.

Other types of R.D.F. can however also be used. The characteristics illustrated are those of the palletized, low-humidity type (important factor for eliminating storage problems) with marked capacity for feeding recirculated fluidized gasification reactors. The specification capacity, 3 tons/h allows us to deal (with 144 tons a day) with all the R.D.F. produced in the Area Fiorentina area, the plant being responsible for transforming into energy the best quality R.D.F. coming from the Sesto Fiorentino selection plant.

Table 3)-4) shows the type of gasifiers we are building in Greve.

There are two reactors, with a unit capacity of 20 thermic MW, with a marked vertical development, in order to improve the complete recirculation of the bed, and with a special system for separating clinkers and flue dust.

TABLE 3)

MAIN CHARACTERISTICS OF THE CIRCULATING FLUIDIZED GASIFIERS

NUMBER OF UNITS	2		
TYPE	cyrculating fluidized bed		
THERMAL CAPACITY (each)		MW	20
OPERATION TEMPERATURE		°C	875
RDF GASIFICATION CAPACITY (each)	design max. min.	Kg/h	3000 4200 1800
LOW ENERGY GAS PRODUCTION (each)	design max. min.	Nm^3/h	6500 10000 3500

TABLE 4)

TYPE OF GASIFIER

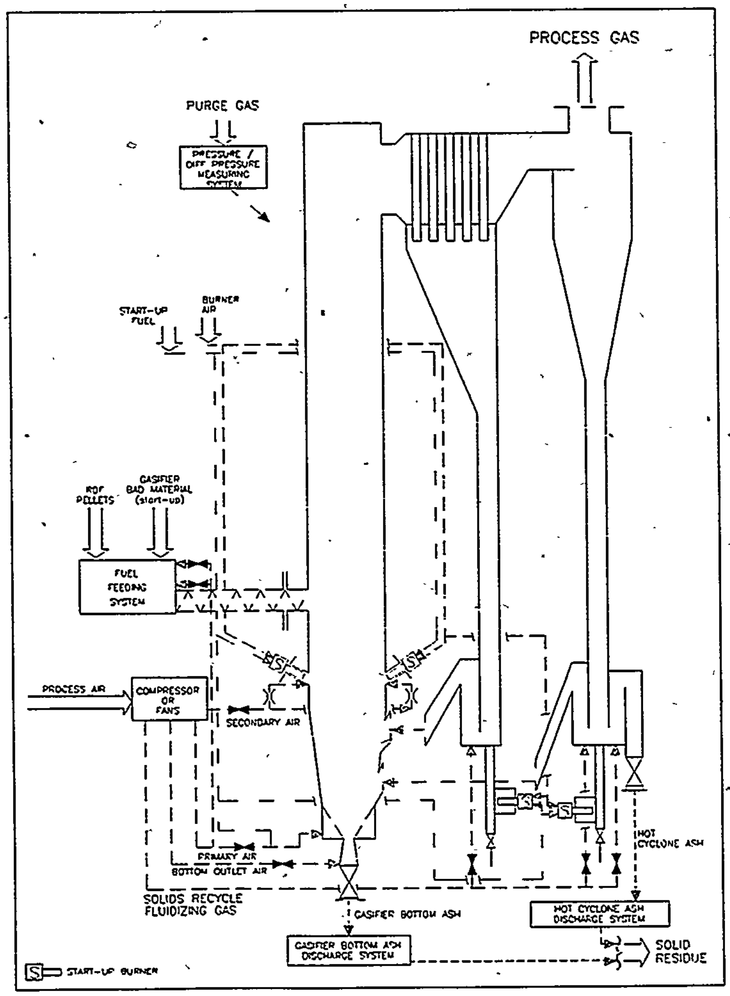


TABLE 5)

MAIN CHARACTERISTICS OF THE PROCESS GAS

			FROM	TO
TEMPERATURE		°C	800	900
PRESSURE		KPa	3	5
COMPOSITION	H_2	%	7	9
	CO	by volume	9	13
	Cx Hy		6	9
	CO_2		12	14
	N_2		47	52
	H_2O		10	14
	Others		0,5	1
NET CALORIFIC VALUE		MJ/Nm^3	4,5	5,5
		$Kcal/Nm^3$	1100	1300
TOTAL ENERGY CONTENENT AT THE OUTLET OF THE GASIFIER		MJ/Nm^3	7	9,2
		$Kcal/Nm^3$	1700	2200
MINOR COMPONENTS	Particulates	g/Nm^3	30	70
	TAR (incl. BTX)		25	40
	HCl		0,5	1,5
	H_2S		0,3	1
	NH_3		1,5	3

Table 5) shows the average characteristics of the lean gas that can be obtained by heat treatment of the R.D.F. The gas obtained has good heating power (about 9 MJ/Nm^3) which, although it cannot be compared to methane or to natural gas, is useful in cement production, both from the energy and environmental points of view, subject to some slight alterations to the pre-calcination of the CLINKER section.

If the gas is used for cement production, the few pollutants present in it are completely retained and incorporated inside the oven; when used for electric power production there is a very thorough for treatment and depuration (see Tables 8 and 9).

Table 6) shows depurated values at the emissions (flue gas) experimentally fixed in starting and texting period.

TABLE 6)

RESUMPTIVE FLUE GAS ANALYSIS

'92 JUNE - '93 MARCH

Parameters	Average value of period	Limitation D.P.R. 203/89
TEMPERATURE (°C)	120 - 145	130
DRY SMOKE (Nmc/h)	30000 - 50000	52000
Macropollutants:		
* TOTAL DUSTS (mg/Nmc)	3 - 7	10
* Pb (Lead, mg/Nmc)	max 0.005	3
* Cd (Cadmium, mg/Nmc)	inferior to 0.0004	0,1
* Hg (Mercury, mg/Nmc)	0.008 - 0.05	0,1
* HCl (mg/Nmc)	3 - 20	30
* HF+HBr (mg/Nmc)	inferior to 0.1	2
* SO2 (Sulphur dioxide, mg/Nmc)	5 - 15	100
* NOx (Nitrogen oxides, mg/Nmc)	200 - 300	300
* HCT (Loose carbon, mg/Nmc)	0.5 - 2	10
* CO (Carbon monoxide, mg/Nmc)	2.5 - 5	50
Micropollutants:		
§ PCDD and PCDF (Total, mg/Nmc)	13,1E- 6	4,0E-3
Isomeric classes observed: 4F, 4D, 5F, 5D, 6F, 6D, 7F, 7D, 8F, 8D (whose classes: 4D, 5D, and 6D aren't detectable)		
# PCB (Total, mg/Nmc)	163,0E-6	0,1
# IPA (Total, mg/Nmc)	14,0E- 6	0,05

* Concentration of Oxygen that is in 11% of smokes

§ Minimum amounts took with instruments: 0.005 ng/Nm.

Minimum amounts took with instruments: 0.2 ng/Nmc

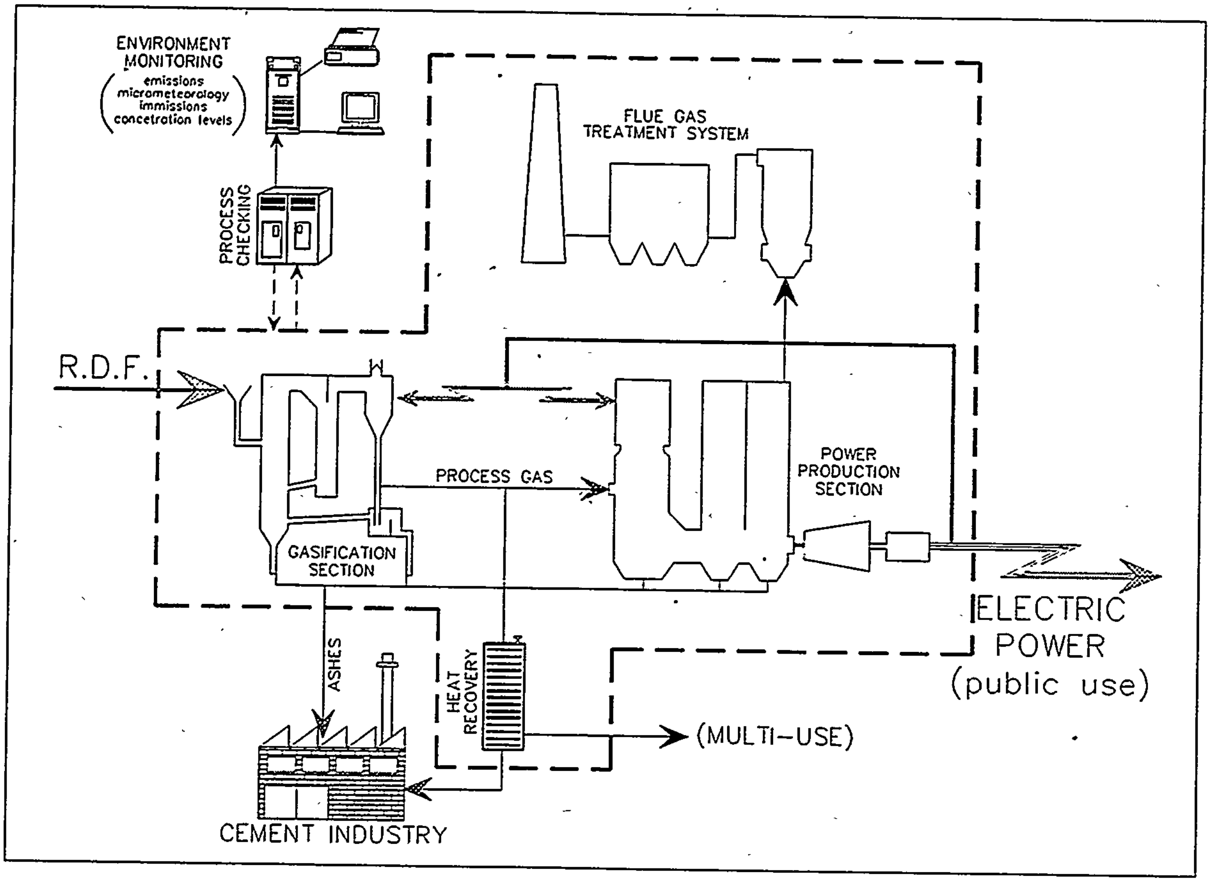
We intend to develop industrial type synergies with this kind of process and to optimize the transformation of R.D.F. into energy. This is particularly relevant because our Region's Regional plan, foresees a fairly high production of R.D.F. even in the present situation, that is, before the processes of "prior reclamation" and of preselection of industrial refuse in order to produce R.D.F. come into operation. The plan foresees over 1000 tons a day of R.D.F. derived from R.S.U. selection and processing plants; this quantity can certainlybe increased if the concept previously referred to is applied to the earlier operation, thus contributing to the further development of the market for alternative fuels.

Attention is drawn to the Greve plant's notable operational elasticity characteristis. There is the possibility of feeding lean gas to the nearby cement works, the possibility of producing electric power by direct combustion of the lean gas itself in a boiler or of producing part lean gas and part electric power.

This is an operational elasticity which is increased by the versatility of the plant and the operational range of the reactors which provide very wide margins.

The basic objective of the Greve gasifier is also to keep the cycle within the combination of the two plants (gasifier and cement works÷see Table 7).

TABLE 7)



From an overall evaluation of the two sections we note that by using R.D.F. we obtain:

- Enough electric power to meet the internal needs of the gasifier;
- An output of electric power for public use;
- Sending of partially cooled gas to the cement works;
- Internal recycling of the gasification asches which are easy to re-use as additives in cement production.

The only other output of the system to the outside is the depurated flue gas for which we have worked out a very advanced programme of enviromental monitoring, including continuous monitoring of the principal parameters of the emissions and intakes (Table-10).

TABLE 8)

FLUE GAS TREATMENT SYSTEM DOWNSTREAM THE PROCESS GAS COMBUSTION LINE

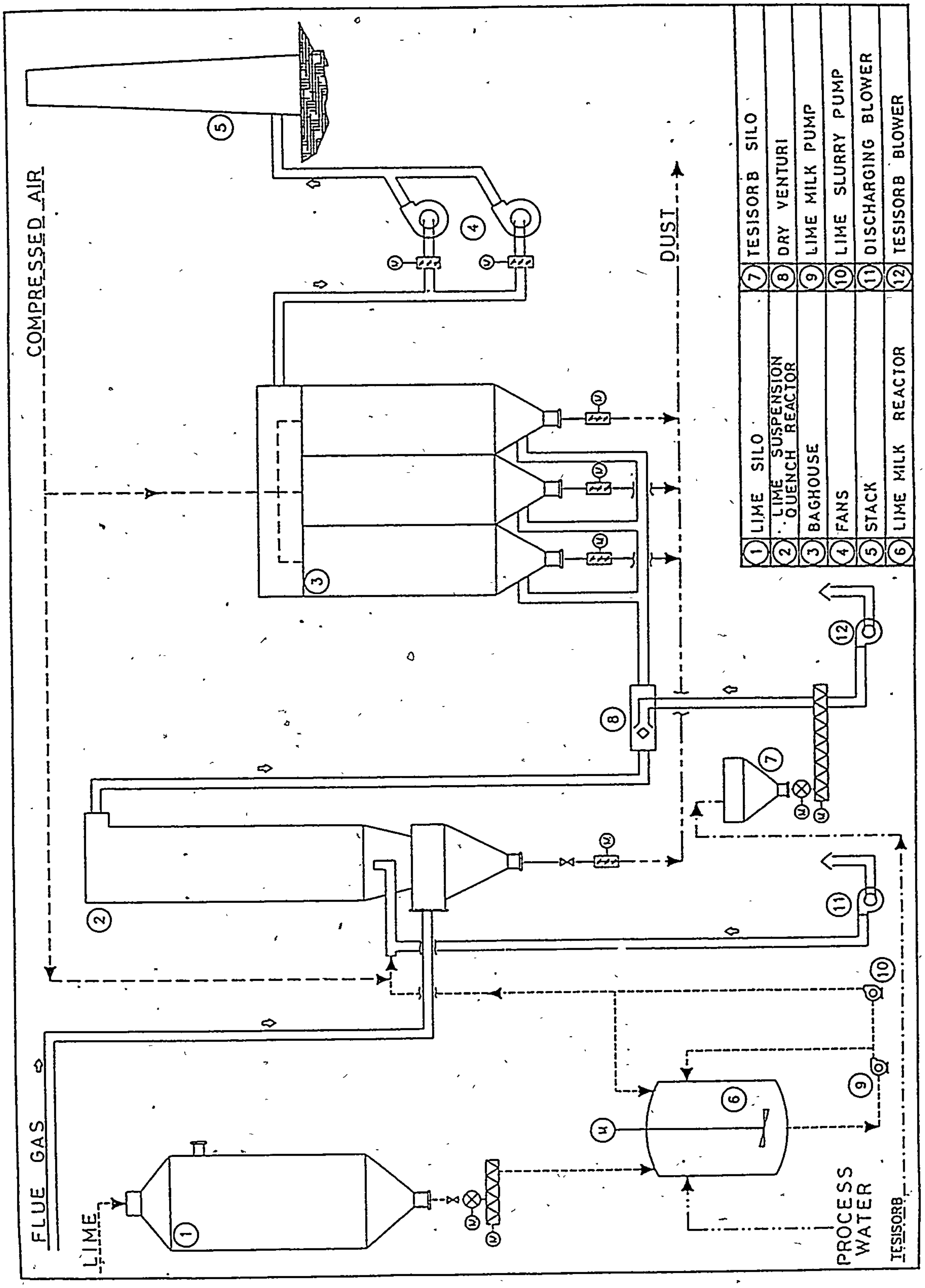


TABLE 9)

MAIN CHARACTERISTICS OF THE FLUE GAS TREATMENT SYSTEM DOWNSTREAM THE PROCESS GAS COMBUSTION LINE

INLET				
FLUE GAS FLOW		Nm^3/h	25000	
			FROM	TO
FLUE GAS TEMPERATURE		°C	160	180
FLUE GAS COMPOSITION	H_2O	% by volume	9	12
	CO_2		10	11,5
	N_2		71	73
	O_2		6	9
POLLUTANTS CONTENT (dry gas-design)	HCl	mg/Nm^3	1100	
	HF + HBr		20	
	SO_2		800	
	Dust		11000	
	Heavy metals		20	

OUTLET			
FLUE GAS FLOW		Nm^3/h	28000
FLUE GAS TEMPERATURE		°C	130
			LOWER THAN
POLLUTANTS CONTENT dry gas referred to 10% of O_2	HCl	mg/Nm^3	30
	HF + HBr		2
	SO_2		100
	Dust		5÷10
	Heavy metals		3
	(totals) of wich:		
	Pb		2
	Cd		0,1
	Hg		0,1

TABLE 10)

ENVIRONMENTAL MONITORING OF INTAKE			
Station n° 1 - in VICCHIOMAGGIO			
Parameter	**Numbers of analytical calculation**	**92/93 March' s average calculation**	**Law Limitation**
DUSTS	*about 4000*	*42.66 µg/mc*	*150 µg/mc*
SO2	*about 4000*	*13.94 µg/mc*	*150 µg/mc*
NO2	*about 4000*	*28.43 µg/mc*	** 135 µg/mc*
Station n° 2 - in S. ANGELO			
Parameter	**Numbers of analytical calculation**	**92/93 March' s average calculation**	**Law Limitation**
DUSTS	*about 6500*	*50.56 µg/mc*	*150 µg/mc*
SO2	*about 6500*	*6.79 µg/mc*	*150 µg/mc*
NO2	*about 6500*	*23.33 µg/mc*	** 135 µg/mc*
** 98° percentile of 1 hour average concentration took throughout the year.*			

The fact that the cycle is closed: the uese of the ashes in cement production, the creation of an intermediate energy carrier, the re-utilization of abandoned areas in the production ambient, the limitation of the impacts of the emissions; all these elements have contributed to creating an "Overall impact of the work with a positive value".

There is great scope, both in our region and internationally, for exporting this model and this concept of the utilization by industrial type plants of fuels derived from refuse.

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Analysis of Tars Produced in Biomass Gasification

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Abstract

Parametric tests on tar formation, varying temperature, equivalence ratio, and residence time, are performed on a bench-scale, indirectly-heated fluidized bed gasifier. Prepared tar samples are analyzed in a gas chromatograph (GC) with a flame ionization detector, using a capillary column. Standards containing dominant tar species have been prepared for GC calibration. The identified peaks include single-ring hydrocarbons, such as benzene, to five-ring hydrocarbons, such as perylene; depending on the gasification conditions, the identified species represent about 70 to 90% (mass basis) of the tar constituents.

Under all conditions tested, benzene and naphthalene were the most dominant species. Temperature and equivalence ratio have significant effect on tar yield and tar composition. Tar yield decreases with increasing temperature or equivalence ratio. The test results suggest that lower temperature favors the formation of more aromatic tar species with diversified substituent groups, while higher temperature favors the formation of fewer aromatic tar species without substituent groups. Higher temperature or equivalence ratio favors the formation of polyaromatic compounds. Oxygen-containing compounds exist in significant quantities only at temperatures below 800°C and decrease with increasing temperature, equivalence ratio, or residence time.

Introduction

Biomass gasification yields essentially three different products: gases, condensable tars, and solids (char and ash). Tars are loosely defined as organic condensable compounds (at room temperature) formed in thermochemical reactions; the major tar species derived from biomass gasification range from single-ring to five-ring aromatic hydrocarbons. Very few past studies on biomass gasification include the analysis of tars, partly because gases are the predominant product of gasification, but also because tars are far more difficult to sample and to analyze than gases. Most information presently available on biomass-derived tars was obtained in pyrolysis studies, usually involving relatively low reaction temperatures; however, the amount and make-up of tar species that evolve in pyrolysis of biomass at temperatures below 600°C may bear little resemblance to tars that evolve in gasification of biomass/oxidant at temperatures above 700°C. Understanding tar formation in biomass gasification is fundamental to the sound engineering and operation of biomass gasification systems and controlling emissions — the research described here seeks to broaden the understanding of tar formation under various gasification conditions.

Procedure

Parametric tests on tar formation, varying temperature, equivalence ratio, and residence time, were performed on a bench-scale, indirectly-heated fluidized bed gasifier. The gasifier has an inside diameter of 89 mm and an overall height of 2500 mm and feeds biomass continuously at rates up to 3.4 kg/h. Details of the gasifier system are reported elsewhere [1]. Sawdust, with 8.2% moisture content (dry basis), was the feedstock in all tests.

A tar and gas sampling system (Fig. 1) was developed and installed at the outlet of the gasifier. A sintered metal filter removes particulates carried over with the product gas. The filter housing is maintained at 450°C by an electric heater to prevent condensation of tars in the filter. A twin-chamber, dry-ice condenser-trap quenches the filtered gas and condenses most of the tars. The light fraction of the tars exiting the dry-ice condenser-trap is removed downstream by two solvent scrubbers connected in series. Methanol is the solvent in these two scrubbers. The sampling volumetric flowrate is monitored with a rotameter and is maintained at a constant level by a metering valve. An acetone rinse is applied after each sampling period to flush tars condensed on the sampling line into the dry-ice condenser-trap. The sample solution then is filtered to remove insoluble solids that pass through the sintered metal filter.

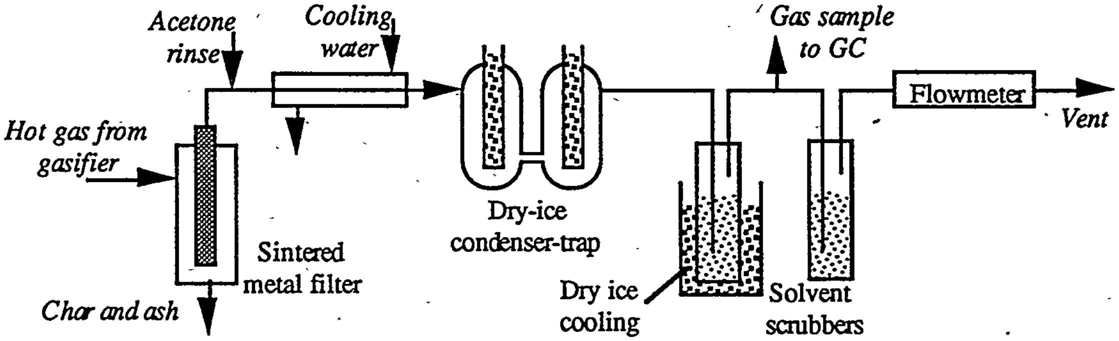


Fig. 1. Tar and gas sampling system.

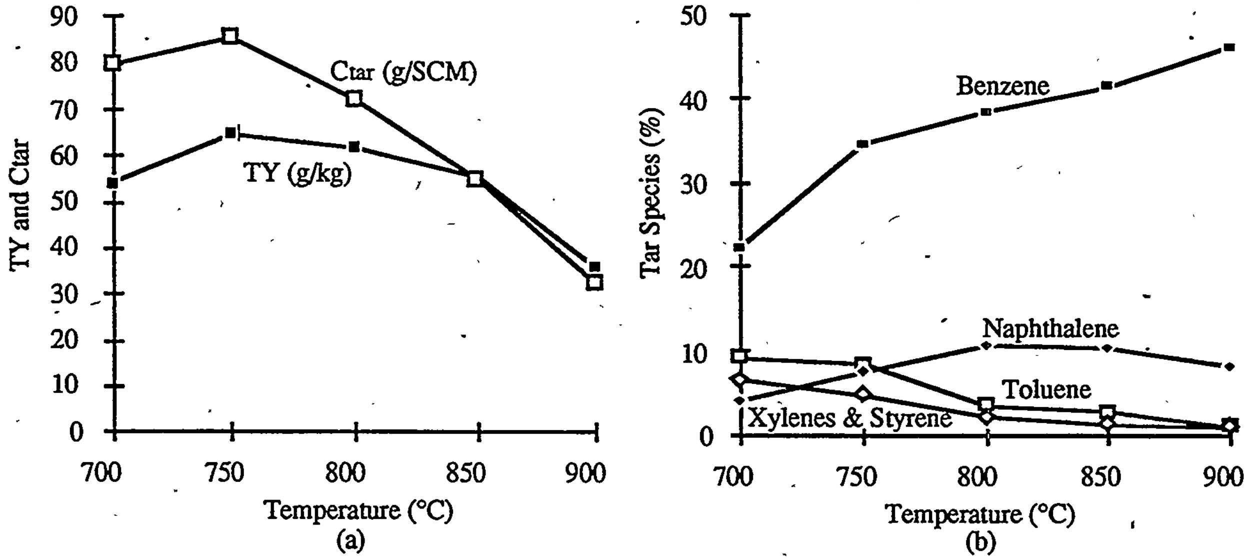
Prepared tar samples are analyzed in a Perkin Elmer AutoSystem gas chromatograph (GC) with a flame ionization detector. An Rtx-5 capillary column is used for tar analysis. Although tars may consist of over one hundred different chemical compounds, in most cases, only about 20 species are present in significant quantities [2-4]. An external standard, containing the dominant tar species, has been prepared for GC calibration. The identified peaks include single-ring hydrocarbons, such as benzene, to five-ring hydrocarbons, such as perylene; these represent about 70 to 90% of the tar constituents (mass basis), depending on the gasification conditions.

Test Results and Discussion

Parametric tests were performed to investigate the influence of gasification parameters on tar yield and tar composition. Gasification parameters in this study include: temperature (T), equivalence ratio (ER), and residence time (t). Oxygen was the oxidant and nitrogen was used as a trace gas or as a diluent to adjust the residence time. No steam was injected in any of the tests and the biomass feedrate was controlled at 3.4 kg/h in all tests. Under most conditions tested, the following tar species were present in significant (> 5%) concentrations: benzene, naphthalene, toluene, xylene and styrene (combined), and phenol. The other identified tar species existed in concentration of less than 5%, individually, and are classified as oxygen-containing, single-ring, two-ring, three-ring, and four-ring aromatic compounds. The five-ring compound, perylene, existed only in trace amounts. Test data, such as gas composition, gas yield, and carbon conversions, were generally consistent with those reported in an earlier study [1], and therefore are not included in the following discussion.

Temperature

Tests varying temperature were performed at fixed equivalence ratio (ER=0.22) and residence time (t=8.9 s). Tar yield increases slightly as temperature increases from 700 to 750°C and then decreases with further increase in temperature as shown in Fig. 2a. Tar concentration (inert-free basis) follows the same trend as tar yield.



(a)

(b)

Fig. 2. (a) Tar yield and tar concentration; (b) tar species versus T.

Benzene increases significantly, while toluene, and xylene and styrene decrease steadily as temperature increases (Fig. 2b). Naphthalene increases as temperature increases from 700 to 800°C, and then decreases slightly at higher temperatures. Oxygen-containing compounds such as phenol, cresol, and benzofuran, exist in significant quantities only at T < 800°C; among these compounds, phenol is the most abundant species (Fig. 3a). Single-ring and two-ring compounds (excluding benzene and naphthalene) decrease, and three-ring and four-ring compounds increase, with increasing temperature (Fig. 3b).

The test results suggest that, in general, lower temperatures favor the formation of more aromatic tar species with substituent groups, while higher temperatures favor the formation of fewer aromatic tar species without substituent groups (because these aromatic hydrocarbons without substituent groups are relatively stable). Degradation of such aromatic hydrocarbons occurs at T > 850°C where a sharper decrease in tar yield is observed in Fig. 2a. Higher temperatures also favor the formation of polyaromatic compounds that have two or more fused benzenoid rings.

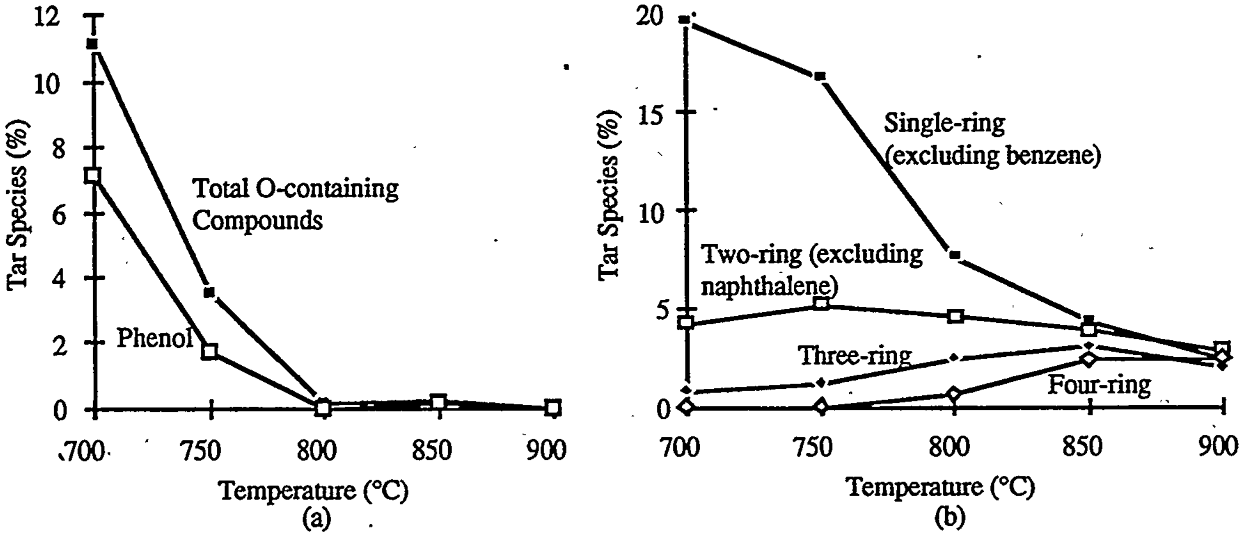


Fig. 3. (a) Oxygen-containing species; (b) tar species by number of rings versus T.

Equivalence Ratio

Tests varying ER from 0.22 to 0.32 were performed at three different temperatures, 700, 800, and 900°C. All test results yielded similar trends. Test results for only 700°C are presented because oxygen-containing and some of the other single-ring compounds exist in insignificant quantities at T > 800°C. Tar yield and tar concentration decrease with increasing ER (Fig. 4a).

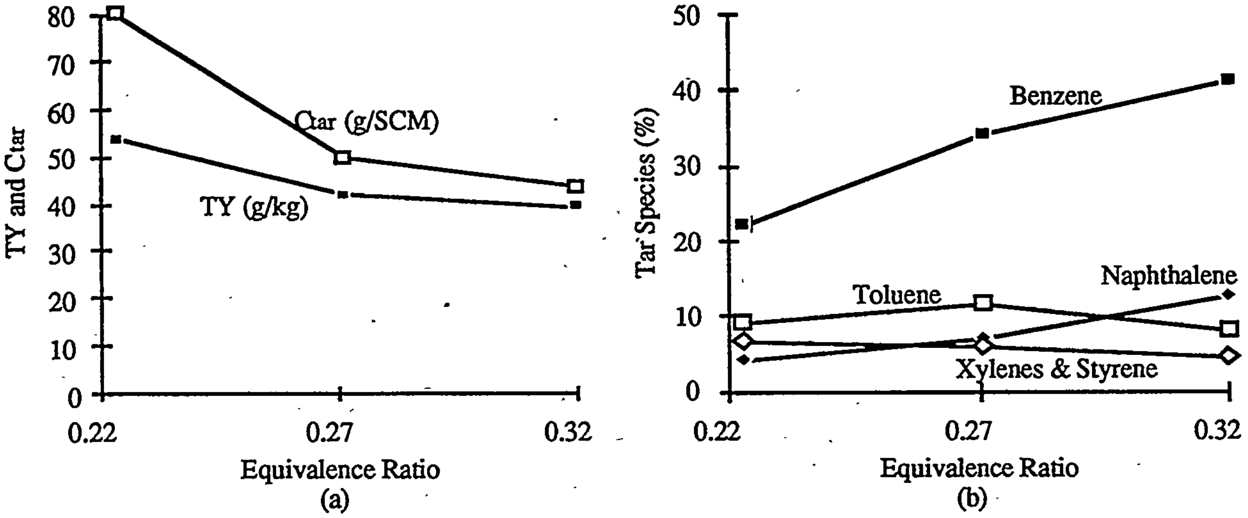
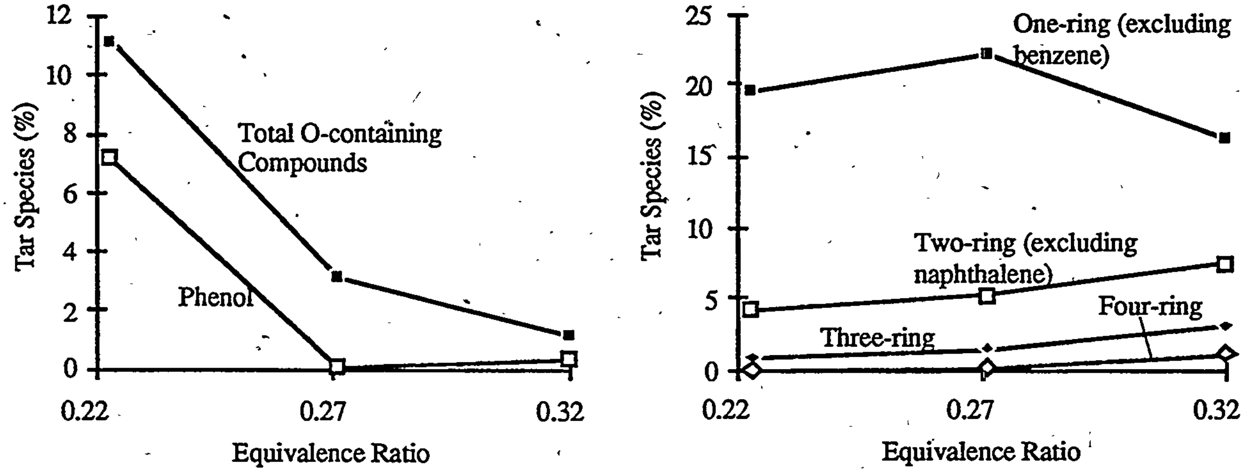


Fig. 4. (a) Tar yield and tar concentration; (b) tar species versus ER.

Benzene and naphthalene increase significantly as ER increases (Fig. 4b). Toluene increases slightly with ER in the range ER=0.22 to ER=0.27, but decreases at higher ER. Xylene and styrene decrease approximately linearly with increasing ER. Oxygen-containing compounds decrease dramatically as ER increases, as shown in Fig. 5a. Phenol represents about 7% of total tars at ER=0.22, but at higher ER, less than 0.4% of tars. Single-ring compounds (excluding benzene) increase slightly from ER=0.22 to ER=0.27, but decrease at higher ER, as shown in Fig. 5b. Two-ring (excluding naphthalene), three-ring, and four-ring compounds all increase with increasing ER. This suggests that increasing ER also stimulates the formation of polyaromatic compounds.



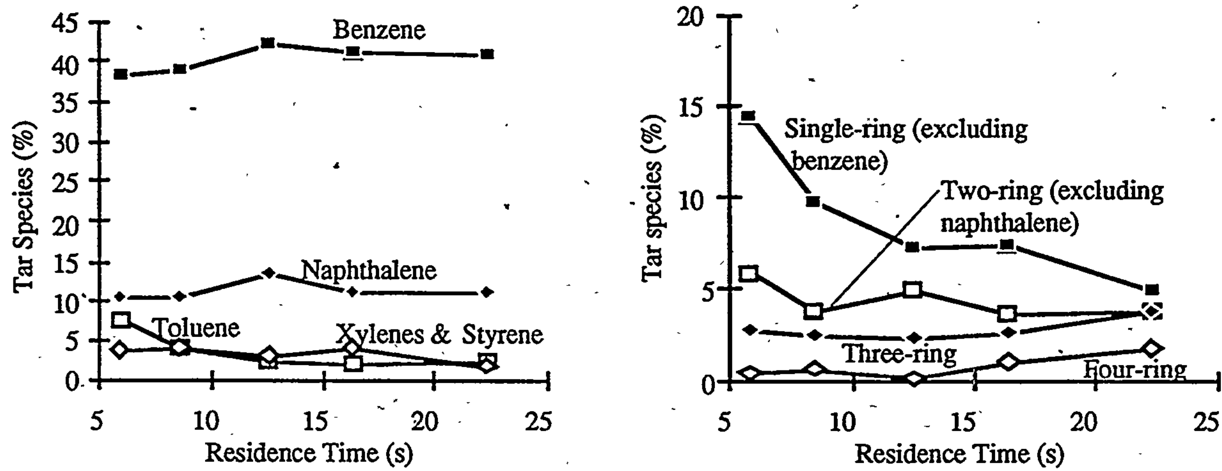
(a)

(b)

Fig. 5. (a) Oxygen-containing species; (b) tar species by number of rings versus ER.

Residence Time

Residence time was adjusted by varying nitrogen flowrate with all other operating parameters fixed. The tests were performed at T=800°C and ER=0.22. Tar yield and tar concentration in the product gas are not highly dependent on residence time in the range tested;



(a)

(b)

Fig. 6. (a) Tar species; (b) tar species by number of rings versus t.

however, residence time affects tar composition. Benzene increases slightly as residence time increases (Fig. 6a). Naphthalene remains about the same regardless of residence time. Toluene decreases, while xylene and styrene generally decline with increasing residence time. Single-ring and two-ring compounds (excluding benzene and naphthalene) decrease, while three-ring and four ring compounds increase, as residence time increases (Fig. 6b).

Summary and Conclusions

Parametric tests, varying temperature, equivalence ratio, and residence time, were performed to investigate tar formation under different gasification conditions. The following conclusions are based on the test results:

1. Temperature and equivalence ratio have significant effects on tar yield and tar composition. Although residence time in the range tested showed little influence on tar yield, it affects tar composition. Tar yield decreases with increasing temperature or equivalence ratio.

2. Lower temperatures favor the formation of more aromatic tar species with diversified substituent groups, while higher temperatures favor the formation of fewer aromatic tar species without substituent groups.

3. Higher temperature or equivalence ratio stimulates the formation of polyaromatic compounds.

4. Oxygen-containing compounds exist in significant quantities only at temperatures below 800°C; among these compounds, phenol is the most abundant species. Oxygen-containing compounds decrease with increasing temperature, equivalence ratio, or residence time.

Acknowledgments

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TEMPERATURE AND PRESSURE DISTRIBUTIONS IN A 400 kW_t FLUIDIZED BED STRAW GASIFIER

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Abstract

The temperature and pressure distribution characteristics of a 400 kW (thermal) dual-distributor type fluidized bed straw gasifier were investigated. The effects of the bed height, equivalence ratio (actual air-fuel ratio:stoichiometric air-fuel ratio) and fluidization velocity on the temperature and pressure variations in the gasifier were studied. Generally, the bed temperature reached the steady state condition within 15-20 minutes. The average temperature of the dense bed ranged from 649°C to 875°C depending on the levels of operating parameters used. The bed temperature increased linearly with increases in the equivalence ratio, higher bed temperatures were observed with lower bed height and no clear trend for the bed temperature with respect to variations in fluidization velocity was observed. The bed height, equivalence ratio and fluidization velocity affected the pressure drop in the fluidized bed gasifier. Increasing the fluidization velocity and/or decreasing the equivalence ratio resulted in higher pressure drops in the dense bed and the freeboard regions whereas increasing the bed height increased the pressure drop only in the dense bed.

Introduction

Several attempts towards the utilization of straws as an energy source in conventional thermochemical conversion units have failed mainly because of their low density, high volatile content and low ash fusion temperature (Salour et al., 1993; Ravn-Jensen, 1988; Wilen et al., 1986; Kraus, 1985; and Whiteway et al., 1985). This resulted in an increased interest in using fluidized bed technology for combustion and gasification of crop residues. Uniformity of temperature and its control have always played an important role in the success of a such technology. The high heat transfer rates, which are possible because of the large amount of transfer surface per unit volume of the fluidized bed, combined with the high heat capacity and continuous agitation of the bed material results in isothermal conditions throughout the bed both in lateral and vertical directions (Botterill, 1986; Zenz and Othmer, 1960). These characteristics allow precise control of temperature in fluidized bed systems which is important in obtaining the maximum yields of desired products while avoiding possible agglomeration problems during the operation. Pressure drop across the bed is another important parameter to consider during the design and operation of a fluidized bed reactor. It determines the pressure drop across the distributor plate, the quality of fluidization and the size and the rating of blowers to be used to supply air to the fluidized bed system (Grace, 1986). There are number of distinct regimes (bubbling, slugging, turbulent and fast fluidization) that exist in gas solid fluidized beds and pressure drop measurement have always been the most common method in determining the regime that the fluidized bed is operating at (Lancia et al., 1988; Vukovic et al., 1984; and Yerushalmi and Cankurt, 1979).

Objectives

The main objective of this study was to investigate the effects of the equivalence ratio, fluidization velocity and bed height on the temperature and pressure distributions in a dual distributor type fluidized bed straw gasifier.

Material and Methods

Fluidized Bed Gasifier

The fluidized bed gasification system used in this study is shown in Figure 1. It was made of 8 mm thick, 310 stainless steel cylinder of 22.5 cm diameter and 2.7 m total height. A cyclone was connected to the exit of the disengagement section to capture the solid particles (dust, bed material and ash/char) escaping from the bed. A propane fired start-up system was used to raise the temperature of the bed material up to 600°C before starting to feed straw to the reactor. The fluidizing column and the cyclone were insulated using flexible Inswool-HP blanket to reduce the heat losses from the system.

The dual distributor type feeding mechanism that was developed to feed the low density fuel material (cereal straw) into the fluidized bed gasifier consisted of a main distributor plate, a secondary column, a secondary distributor plate and a feeding tube. Two identical air supply units (primary and secondary) were used to provide air to the fluidized bed gasifier. The primary air supply (from blower-1) was used to fluidize the bed material within the main fluidizing column,

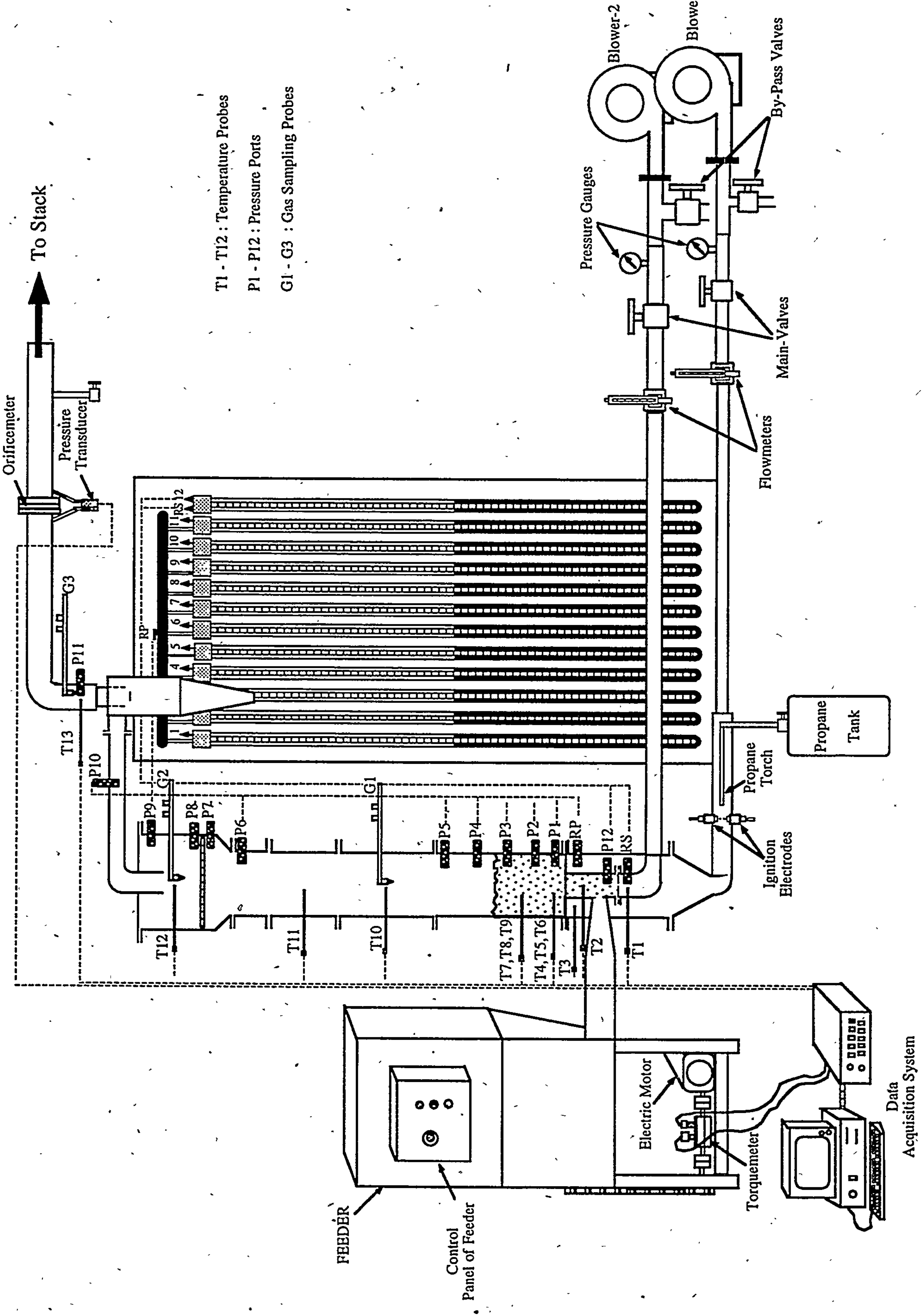


Figure 1. Experimental Apparatus.

whereas the secondary air supply (from blower-2) was creating a jet of air within the secondary column which carried the bed material and the fuel (the chopped straw that is fed into this secondary column) to the main fluidizing column above the main distributor plate. Detailed descriptions of fluidized bed gasifier can be found elsewhere (Ergüdenler and Ghaly, 1992).

Temperature Measurement System

Special purpose thermocouple probes (Cole Parmer Type-K, Catalog No. N-08516-70) were used to measure the temperature variations within the gasifier. Temperature probes (T1) and (T3) were used to measure the temperature of the fluidizing gases before entering into the secondary and main columns, respectively. The temperature within the secondary column, where the feed material was first delivered, was measured by the temperature probe (T2). In order to monitor the temperature distribution in the dense bed, temperatures at two axial positions, each with three radial positions (T4, T5 and T6; and T7, T8 and T9, respectively) were measured. In addition, temperatures at two different locations in the freeboard region (T10 and T11) and one location at the exit of the cyclone (T12) were recorded. All the thermocouple probes were connected to a micro-computer based data acquisition and control system.

Pressure Drop Measurement System

Dwyer slack-tube manometers (Model No. 1211-200) were used to measure the pressure drop at different locations in the fluidized bed gasifier. The first measurement point (P1) was 50 mm above the main distributor plate. Four other pressure taps (P2, P3, P4 and P5) were positioned above the first one equidistant from each other (120 mm apart). One pressure tap (P6) was located in the free board, just before the enlarged section. Three pressure taps (P7, P8 and P9) were used in the enlarged section. The last measurement point was located on the outlet duct connecting the bed exit to the cyclone inlet. Each of these pressure taps were connected to a separate U-tube manometer using flexible tygon tubing and the other ends of the manometers were connected to the reference point (RP), which was located 50 mm below the main distributor plate (inside the wind box), through a manifold. The pressure drop across the secondary distributor plate was measured independent from the others using the reference point (RS) and a tab above the plate (P12).

Experimental Procedure

The alumina sand was placed into the reactor to a bed height of 25.5 cm. The primary air supply was turned on to fluidize the sand particles in the main fluidizing column and the air flow rate was adjusted to 0.56 m^3/min (0.67 kg/min). The computer based data acquisition system was activated to monitor and record both the temperature, the pressure drop and the feed rate values. The temperature of the bed material was raised to 600°C by combusting the propane-air mixture. The start-up system was, then, shut down while keeping the primary air supply on to cool the bottom section (wind-box) of the gasifier before starting to feed the straw. When the temperature in the secondary column reached 500°C, the secondary air supply was turned on and adjusted to the minimum rate (0.56 kg/min) required to carry the sand particles from the secondary column into the main column. The feeder was turned on and the fuel feed rate was adjusted to allow excess air in order to achieve complete combustion of straw. The bed temperature was, thus, increased rapidly (to 750°C) by the energy released from the combustion of straw. The fuel feed rate and air flow rates were adjusted to the desired respective levels and the system was operated under this condition for half an hour to insure that the steady state condition was reached in the fluidized bed. When data recording was completed, the feeder, secondary air supply and primary air supply were shut down. The same procedure was followed with all equivalence ratio-fluidization velocity combinations. The whole procedure was, then, repeated for the bed height of 12.5 cm.

Results and Discussion

Temperature

The average values of temperatures recorded at the inlet below the secondary distributor plate (T1), in the secondary column (T2), in the wind-box below the main distributor plate, in the dense bed (T4-T9), in the freeboard (T10 and T11) and at the exit of the cyclone (T12) are given in Table 3. The lowest temperature readings were recorded below the secondary distributor plate (T1) and ranged between 147°C and 271°C. The temperatures recorded in the secondary column (T2) were lower than those measured in the dense bed and ranged between 498°C and 653°C. The temperature readings within the wind-box below the main distributor plate (T3) varied between 323°C and 534°C. The average temperature of the dense bed ranged from 649°C to 875°C depending on the operating conditions. Operating the gasifier at the equivalence ratio of 0.35, fluidization velocity of 0.28 m/s and bed height of 12.5 cm, where average bed temperature of 941°C was recorded, was an exception to this. The temperature readings obtained from the 6 probes in the dense bed showed that the temperature distribution within the bed was quite uniform. A standard deviation of 2.45-5.52°C from the mean bed temperatures (648-875°C) was observed. The temperature readings at the wall region of the dense bed were 3-5°C lower than the mean bed temperature because of the low solid circulation in this region and the heat loss through the wall. The temperature probe located at the bottom center (T4) was exposed to the jet created by the secondary air supply and, thus, gave 3-10°C lower temperature readings compared to those obtained from the temperature probe located 10 cm above bottom (T7). Temperature readings in the freeboard region, close to the bed surface, (T10) were very close to the mean bed temperatures. However, the temperatures recorded in the freeboard region close to the exit (T11) and at the exit of the cyclone (T12) were much lower (200°C) than the mean bed temperatures due to the heat losses through the gasifier walls. The bed temperatures observed in this study (661-875°C) are within the range (650-865°C) reported by Corella et al. (1989), Hartiniati et al. (1989) and Maniatis et al. (1988).

The equivalence ratio significantly affected the gasifier temperatures. A significant decrease (214°C) in the bed temperature was observed when the equivalence ratio was reduced. The reduced amount of air (or oxygen) per unit weight of fuel supplied caused a reduction in the amount of heat released to sustain high temperature reactions. Unstable temperature patterns (with time) were observed at the equivalence ratios of 0.17 and 0.35 whereas at equivalence ratios of 0.25 and 0.20, the bed temperature usually reached the steady state condition within 15-20 minutes. The unstable bed temperatures observed at the equivalence ratio of 0.17 were due to the difficulty in sustaining the reaction temperatures at such low equivalence ratio. Maniatis et al. (1989) reported on the difficulty of operating the gasifier at equivalence ratios below 0.20. The temperature profiles obtained in this study have a similar pattern to those reported by Maniatis et al. (1988) and Xu et al. (1986) when gasifying chopped wood and rice hulls in a fluidized bed gasifier, respectively.

When the gasifier was operated at the lower bed height (12.5 cm) an increase (40-80°C) in the mean bed temperature was observed because of the reduced heat capacity of the gasifier owing to the reduction in the amount of bed material. The increase in the bed temperature resulted in the failure of the tests conducted at the equivalence ratio of 0.35 at higher fluidization velocities (0.33 and 0.37 m/s) due to the agglomeration of the bed material. The rapid fluctuations in the bed

Table 1. Average Reactor Temperature* (°C).

Bed Height (cm)	Fluidization Velocity (m/s)	Equivalence Ratio	Inlet			Dense Bed								Freeboard		Exit
			T1	T2	T3	T4	T5	T6	T7	T8	T9	Mean	STD	T10	T11	T12
25.0	0.37	0.35	244	639	464	869	878	872	879	877	874	875	3.81	866	772	740
		0.25	195	591	413	798	808	803	811	806	803	805	4.41	800	764	740
		0.20	168	549	367	729	734	729	740	732	729	732	4.31	726	708	693
		0.17	147	503	323	670	681	676	681	679	677	677	3.91	669	651	640
	0.33	0.35	242	619	452	846	853	843	851	851	846	848	3.67	841	721	685
		0.25	199	606	438	812	825	818	823	823	819	820	4.59	819	765	735
		0.20	176	539	372	690	697	691	695	695	692	693	2.88	689	675	662
		0.17	157	498	335	646	652	646	651	651	648	649	2.55	647	633	621
	0.28	0.35	261	653	534	873	877	870	879	877	873	875	3.34	859	729	682
		0.25	226	610	500	781	783	778	788	782	779	782	3.37	776	739	709
		0.20	194	546	419	687	685	682	689	685	684	685	2.45	681	666	650
		0.17	174	517	386	664	662	657	665	661	659	661	2.86	657	638	622
12.5	0.37	0.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		0.25	246	606	439	832	838	831	843	839	831	836	5.10	818	722	695
		0.20	193	575	393	801	800	793	805	799	793	799	4.59	782	743	725
		0.17	167	542	354	748	748	743	752	747	743	747	3.44	731	710	699
	0.33	0.35	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		0.25	255	598	443	799	805	800	809	807	801	803	4.20	783	678	649
		0.20	204	578	407	771	773	768	779	774	768	772	4.20	760	716	696
		0.17	171	525	352	701	697	694	706	697	695	699	4.52	688	670	659
	0.28	0.35	271	623	480	950	905	890	977	964	958	941	35.0	873	789	737
		0.25	220	605	473	814	823	818	830	825	819	822	5.52	798	762	729
		0.20	209	573	434	755	755	749	763	757	751	755	4.97	740	706	681
		0.17	191	546	383	715	714	710	722	715	711	715	4.13	696	676	660

* Average of 10 readings
STD = Standard Deviation

temperature readings (standard deviation of 35°C) from the mean bed temperature (941°C) was a clear indication of agglomeration under these operating conditions.

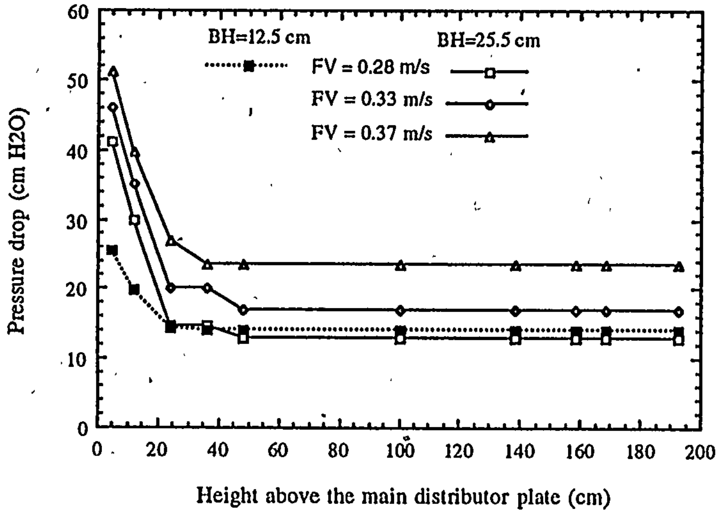
Pressure Drop

The variation of the pressure drop with bed height and fluidization velocity, at different equivalence ratios are shown in Figure 2. Increasing the equivalence ratio resulted in lower pressure drops both in the dense bed and the freeboard regions at all fluidization velocities and bed heights. This was attributed to the increases in the straw feed rate which increased the amount of solids considerably both in the dense bed and in the freeboard region. For instance, while operating the gasifier at the 25.5 cm bed height (which gave a bed material mass of 26 kg) and a fluidization velocity of 0.37 m/s, increasing the straw feed rate from 0.75 kg/min to 1.55 kg/min (reducing the equivalence ratio from 0.35 to 0.17) resulted in a net increase in the total mass of the bed material. The increase in the straw feed rate due to increased fluidization velocity and/or decreased equivalence ratio resulted in considerably higher solid concentrations (especially char) in the freeboard since the char was entrained in the form of fly-ash. The increase in the density of the gas due to the reduced bed temperatures at the lower equivalence ratios, was considered to be another factor contributing to the rise in the pressure drop.

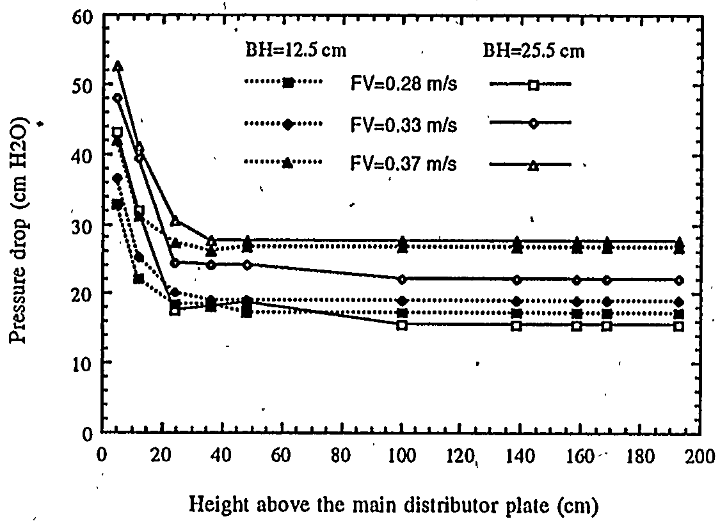
Increasing the fluidization velocity increased the pressure drop in the fluidized bed, both in the dense bed and the freeboard regions. Hydrodynamic studies showed that the bed pressure drop increases linearly when the gas velocity is increased until the incipient fluidization condition is reached (Clift, 1986; Geldart, 1986; Cheremisinoff and Cheremisinoff, 1984; and Grace and Clift, 1974) . At the incipient fluidization condition, the pressure drop across a fluidized bed equals the weight of the solids in bed per unit area and further increases in the gas velocity do not increase the pressure drop. However, this applies to systems with constant weight of solids. In this study, the fluidization velocity was raised by increasing both the air supply and the straw feed rates in order to keep the equivalence ratio constant. Therefore, the increase in the fluidization velocity resulted in the a net increase in the total mass of solids both in the dense bed and the freeboard regions of the fluidized bed gasifier. Increasing the bed height, however, increased the pressure drop in the dense bed but did not have any effect on the pressure drop in the freeboard region.

Conclusions

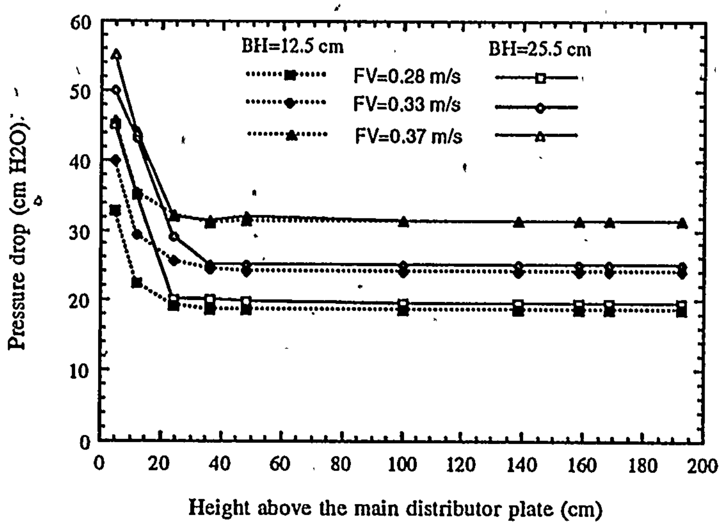
A dual-distributor type fluidized bed gasifier was used to investigate the effects of equivalence ratio, fluidization velocity and bed height on the temperature and pressure distributions of the gasifier when operating on wheat straw. The equivalence ratio, fluidization velocity and bed height affected the reactor temperature. The bed temperature increased linearly with the increase in the equivalence ratio. Generally, the bed temperature reached the steady state condition within 15-20 minutes. However, increased temperature patterns were observed at the equivalence ratio of 0.35 whereas unstable bed temperatures were observed at the equivalence ratio of 0.17. Decreasing the bed height resulted in higher bed temperatures. No distinct temperature trend for the bed temperature with respect to the fluidization velocity was observed. The minimum and the maximum bed temperatures observed in this study were 648°C and 941°C, respectively. The equivalence ratio, fluidization velocity and bed height affected the pressure drop in the fluidized bed. Increasing the fluidization velocity and/or decreasing the equivalence ratio resulted in higher pressure drops in the dense bed and the freeboard regions whereas increasing the bed height increased the pressure drop only in the dense bed. Both the temperature and pressure drop distribution measurements were related to the agglomeration of the bed material and the quality of fluidization.



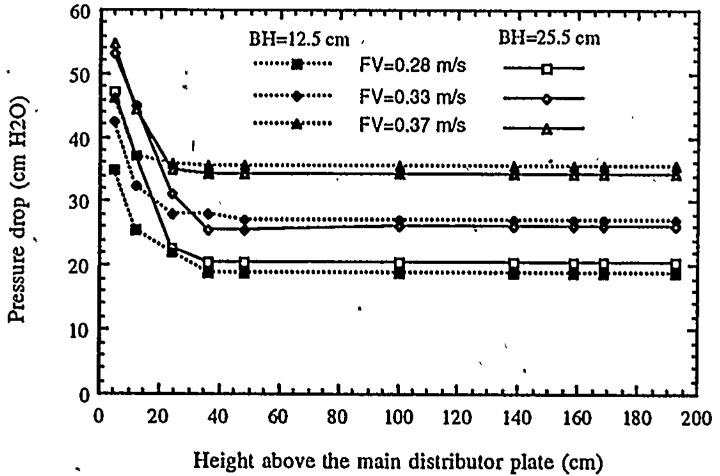
(a) Equivalence Ratio = 0.35



(b) Equivalence Ratio = 0.25



(c) Equivalence Ratio = 0.20



(d) Equivalence Ratio = 0.17

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MANUFACTURING COMBUSTIBLE BRIQUETTES FROM FORESTRY AND TIMBER INDUSTRIES' WASTES IN ORDER TO REDUCE THE OVEREXPLOITATION OF FUELWOOD IN CENTRAL AMERICAN FORESTS

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Abstract

A serious degradation of central american forest is currently taking place because of uncontrolled fuelwood overexploitation. As an example, it is estimated that in Guatemala over 40% of forest destruction is caused by this reason (Source: Gremial Forestal de Guatemala 1992).

In the meanwhile, waste biomass from the sawmills representing between 30 and 50% of total wood volume processed, due to low technological level of the facilities, and having an energetic potential equivalent to their thermal and electric needs (Source: P.E.I.C.C.E., 1992) is destroyed through uncontrolled burning, thus causing important environmental and landscape impact, since the byproducts are incinerated outdoors on the spot the constant smoke together with the noise level produced by the diesel power generators makes working conditions painful for the large laborforce usually operating these sawmills because of low wages in these countries.

To help solve this increasing problem, it would be possible to use the waste biomass for the production of electric power, through cogeneration, for sawmill selfuse or selling to the public electric lines, or even manufacturing of fuel briquettes which would have an potential market in countries such as República Dominicana, Honduras Guatemala, etc. as a substitute for charcoal and fuelwood, thus permitting a considerable reduction of the environmental degradation and predation suffered by forest areas in these countries.

For these reasons, we consider it of interest to study briquetting technics and their intrinsic problems in depth. For such purpose, we have carried out a series of real scale briquetting

experiences with different types of lignocelulosic wastes and mixtures of them under different conditions, aiming to optimize procedure methodology and reduce production expenses, thus making offer increase easier.

Manufacturing procedure and analytics developed to carry out the experiences are described in the present document. Main results obtained are summarized, and mathematical, energetic, analytical and economic aspects are discussed aswell.

Introduction

In order to quantify the energetic potential represented by lignocelulosic products, following Annex 1 indicates heating values of some of the main autochthonous and exotic species present or furnishable in Central America (Solano, R. 1992).

Likewise, Table 1 shows current biomass utilization data in the different Central American countries (Hall, D. 1991).

Table 1

Use of biomass in Central America

COUNTRY	BIOMASS USE (per capita)		BIOMASS USE (10^6)		COMMERCIAL USE (10^6 toe)	BIOMASS AS % OF TOTAL ENERGY
	twe	toe	twe	toe		
COSTA RICA	0.79	0.28	2.01	0.74	0.97	43
DOMINIC R.	0.32	0.11	2	0.72	1.97	27
GUATEMAL	0.87	0.31	7.01	2.5	0.97	72
HAITI	0.66	0.23	3.43	1.22	0.21	85
HONDURAS	0.85	0.3	3.65	1.3	0.61	68
JAMAICA	0.26	0.09	0.63	0.22	1.76	11
NICARAGUA	0.93	0.34	3.13	1.11	0.71	61
PANAMA	0.54	0.19	1.15	0.41	0.92	31

twe - Tonne wood equivalent (15 GJ air dry).
toe - Tonne oil equivalent (42 GJ).

As of the situation of briquetting of woodwastes in Central America, it is remarkable that several briquetting facilities currently face repairs or even plain cease, due to problems related to the processes of physical transformation of extremely heterogene waste materials, all of which decisively limits the generalized implantation of this kind of clean and renewable energetic technologies. For this reason, the best conditions to manufacture combustible briquettes from woodwastes are studied.

Materials & Methods

A total of 20 types of briquettes have been manufactured and analyzed from an energetic, chemical and physical point of view, in order to define the best handling and densification conditions of the different types of forest waste biomass, as well as deepening in each specific problem and evaluating production costs in each situation. Analytical technics have been developed for the determination of the properties of the briquettes as a fuel, and the final results allow a briquette quality classification.

The forest waste materials used here are chips from the following species: Eucalyptus globulus (eucalyptus), Pinus pinaster (pine), Pinus sylvestris (bark used), Populus nigra (poplar) and Quercus pyrenaica (Turkey oak).

The sawmill wastes used were savings and sawdusts from tropical hardwoods such as Sapely, Samba and Guatambú as well as Oak.

These materials were obtained in the forests during the cleaning labors as chips generated by using portable forest chippers. The chips' moisture varied between 40 and 60% W.B., and a few months of natural drying reduced these values to between 10 and 15%, a level considered suitable for densification, according to previously completed experiences (max 17%, min. 8%). Table 2 shows the relation between moisture content and heating value. (Solano, R. 1992).

Table 2

Energy content of wood in relation with moisture content.

MOISTURE (% W.B.)	H.H.V. (kJ/Kg wet wood)	L.H.V. (kJ/Kg wet wood)
15	15.810	14.319
30	13.020	11.360
45	10.230	8.401
60	7.440	5.442
75	4.650	2.483

H.H.V - High Heating Value, L.H.V. - Low Heating Value.

A granulometric classifying and milling Pilot Plant of 250 - 500 kg/h was used to carry out the waste conditioning previous to compactation. Once the chips were milled, the next step was densification through the impact system, using a 18 Kw power Swedish briquetting equipment (BOGMA ENERGY A.B., model V-40) equipped with a doser silo and a 5 m long cooling channel for that purpose. The briquetting machine generates briquette pieces about 40 mm in diameter with a frequency of 200-350 kg/h.

Afterwards, the combustibility analyses of the different briquettes were carried out, recording the loss of weight that takes place during the combustion in an open furnace, as well as studies on impact endurance (friability). To such purpose 5 kg of briquettes are introduced into a trommel 60 cm in diameter and 60 cm long that spins at 20 rpm, which produces the knocking of briquettes and their disintegration. Periodically, at intervals of 15, 30 and 120 minutes the whole content from the trommel is drawn out, then one proceeds to quantify the different granulometric fractions. From these data we obtain the so-called "Friability Rate (If) " (Carre, J. 1989), and the" Resistance Rate (R)" (Ortiz, L. 1991).

$$If_{(ti)\%} = \frac{If_{[t(i-1)]} * [(P_{i-1}+P_{ti}) \;/\; 2] * t_{i-1}}{ti}$$

$$R = 100 - \delta$$

P(ti)...... Percentage of non disintegrated briquettes at the (ti) moment
δ.......... Horizontal angle of the line that links $\mathbf{If}_{(120)}$ with the origin (100%)

(*) <u>SCALE</u> : R ≈ 100 = Maximum potential resistance
R ≈ 50 = Minumun resistance (total desegregation)

As hitting time increases, the "Friability Index" tends to diminish following a rate related to the nature of the specific briquette.

A subjective "Quality Index (Q)" (Ortiz, L. 1992) is calculated below, based upon the data of real density (d) and resistance (R) parameters, with the purpose of unifying both these parameters in one single value. The formula used to calculate this " Quality Index " is:

$$Q = \frac{d + (10 * R)}{2}$$

It is thus possible to compare the different types of briquettes and establish optimal working conditions in each simulated situation.

On the other hand, the main energetic parameters, such as moisture content, percentage of volatile components, ash percentiles and L.H.V. have been determined for all briquettes manufactured. A catalogue and a differential qualitative classification between the different types of briquettes have been established based upon these values.

Results

To properly densify the waste biomass without using adhesive substances it is required to conditionate it up to moisture levels between 8% and 15% with particle size shorter than 10 mm.

In the cases here studied, during the densification process, a slight dehydration in the raw material takes place as a consequence of both the high pressures generated (30 t/cm2) (Source: BOGMA A.B.-Sweden) and the temperature rise in the compactation chamber (150 - 200°C) (Lequeux, J. 1989) that causes a small part of the water to evaporate when passing to atmospheric environmental conditions. This moisture reduction is usually between 4% and 8%, which raises the added value of the densified owing to the fact the lesser net heating value rises up to 2% with regard to the raw material, while the normal increase is of about 1%. The main characteristics of the briquettes obtained are shown in Table 3.

Table 3

Characteristics of the briquettes

BRIQUETTE	M	D	V	A	LHV	R	Q
TROPICAL WOODS							
Samba	8.0	1.119	78	1.7	17.025	97	10
Sapeli	8.5	1.119	78	0.7	17.050	63	8.5
Guatambu	9.0	1.135	81	1.2	16.669		
FAST GROUND SPECIES							
Poplar (3 mm)	9.0	1.048	75	5.3	16.130	88	9.6
Poplar (8 mm)	9.0	1.048	75	5.3	16.130	93	10
Eucalypts (3 mm)	9.5	985	80	1.2	16.962	71	8.4
Eucalypts (8 mm)	9.5	1.013	80	1.2	16.962	75	8.8
OAKS							
Turkey Oak (5 mm)	11.0	1.031	80	2.3	15.499	90	9.7
CONIFEROUS							
Pine Bark (3 y 8 mm)	14	1.031	65	7.7	15.056	62	8.2
Pine (3 mm)	9.5	1.194	78	1.0	17.372	80	9.9
Pine (8 mm)	9.5	923	78	1.0	17.372	62	7.7

M ..... Moisture content on wet basis (%).
D ......Real Density (kg/m3).
V ..... Volatile material on dry basis (%).
A ..... Ash content on dry basis (%).
NHV...Low Heating Value at moisture level (kJ/kg)
R.......Impact resistance (max 100, min 50).
Q.......Relative quality ratio (0 to 10).
( )......Maximum particle size.

In general, the briquettes obtained are of good quality, by and large, and in the combustion proves in household heating and chimneys eventually carried out their behaviour as a fuel was very good. The external look of the briquette pieces varies depending on the raw material used in each case. Thus, differences in coloration graining, cracking degree, behaviour of water and density may be observed (Ortiz, L. 1992).

The least cohesive briquettes as well as the most obviously faulty out of the ones produced turned out to be the corresponding to the Pinus gendre (milling at 8 mm): bark, pruning wastes from Pine with or without remains of Turkey Oak thinning. For this reason, different mixtures were made (at 1/1 rate) from these materials with industrial wastes of fine granulometry like the coniferous bark (P. sylvestris) and sawdust Oak (Quercus robur). Mixing the shaving of Pine with bark, it was achieved to increase the briquettes density in a 10% in relation to those of Pine. In the case of briquettes from Oak sawdust and Pine a remarkable improvement was achieved in external look, as well as a rise in density of about 12% with regard to those of milled Pine at 8 mm. Turkey Oak briquettes mixed with bark are barely denser than those of pure bark (Δ3%) and, qualitatively, a remarkable improvement in the external characteristics is obtained; such as a lesser cracking, bigger length of pieces, curve reduction etc. When mixing Turkey Oak with Oak sawdust, a decrease in density of 2% with regard to Turkey Oak briquette takes place as well as an increase of 1% in relation to pure Bark. Finally, the briquettes from mixing Poplar and Oak sawdust are 4% denser than those of Poplar and 6% denser than those of pure Oak.

The briquettes of hardwood tropical woods have oil substances that cover the surface with a very nice coloration.

Combustion

The combustion of the briquettes is quite good (very intense for the first 30 minutes and slower after that). Comparatively, pine bark briquettes have a lesser combustibity speed as well as a higher percentage of unburnt material, regardless of the raw material granulometry due to a higher content in ashes of the bark and the sand attached during the handling and dragging of forestry wastes. For this reason, the unburnt, present at the end of this experience of bark briquettes self-combustion is of about 7% of the initial weight, whereas the average in wastes of Poplar and Turkey Oak, is about 5%. Briquettes producing a lesser volume of unburnt are those of Pine and Eucalyptus with values in the order of 2%.

The larger the milling size used, the more heterogenous the particle structure is. Because of that when wastes are milled at 8 mm, a greater variability in the density of the different briquettes may be observed (up to 2%) that when finely milled waste is used (3 mm).

Energetic consumption

Milling

Turkey oak forest chips shorter than 5 cm were used in order to evaluate the electric consumption during the granulometric reduction and densification periods within the hygrometric and granulometric boundaries pre-established according to the previous experiences.

Energetic consumptions and matter flows vary considerably in terms of the largest desired particle size. The higher consumption values appear for the damper samples and, obviously, for the most finely milled. Table 4 shows the main values obtained.

Table.4

Milling consumption and maximal flow in terms of moisture content

MOISTURE (% W.B.)	PARTICLE SIZE (mm)	FLOW (kg/h)	CONSUMPTION (Kwh/t)
15.0	8	129	50
	5	160	77
	2	102	190
11.5	8	134	43
	5	172	48
	2	82	140.
10.0	8	294	37
	5	140	40
	2	132	100

Briquetting.

The results obtained show that when the same material is used with a moisture content at the limit of adequate briquetting conditions (15 %); it is advisable to finely mill the product (2 mm or 5 mm). Nevertheless, when the material appears with a moisture content close to the lower limit defined (10% W.B., for example) it turns more interesting to use the waste milled with wide hole meshes (8 mm).

Table 5 condenses all values obtained.

Table 5

Electrical consumption & mass flow during the briquetting process in terms of particle size and sampling moisture.

MOISTURE (% W.B.)	PARTICLE SIZE (mm)	FLOW (kg/h)	CONSUMPTION (Kwh/t)
15.0	8	200	69
	5	244	68
	2	320	
11.5	8	240	65
	5	248	64
	2	348	55
10.0	8	276	65
	5	270	59
	2	36	46

The total energetic cost of physical transformation is shown in Table 6.

Table 6

Partial & total electric consumption on milling and briquetting of Turkey Oak

MOISTURE (% W.B.)	PARTICLE SIZE (mm)	MILLING (Kwh/t)	BRIQUETT (Kwh/t)	TOTAL (Kwh/t)
15.0	8	50	69	119
	5	77	68	145
	2	190		
11.5	8	43	65	108
	5	48	64	112
	2	140	55	195
10.0	8	37	65	102
	5	40	59	99
	2	100	46	14

The best briquettes are obtained when an intermediate working moisture content is used (11.5%). In this case, the ones manufactured with coarsely milled waste (8mm.) are slightly better, eventhough the differences with finely milled product briquettes (3 and 5 mm) are minimal. Table 7 shows the main properties of Turkey oak briquettes obtained under the different conditions studied.

Table 7

Physical properties of Turkey Oak Briquettes

MOISTUR (%W.B.)	PARTICLE SIZE (mm)	DENSITY (kg/m^3)	FRIABILIT RATE	RESIST. RETE (%)	QUALITY RATE (5-10)
15.0	8	897 ±60	56	80	8.5
	5	1046 ±12	77	90	9.7
	2	1061 ± 5	70	88	9.7
11.5	8	1074 ±10	74	88	9.7
	5	1059 ± 5	71	86.	9.6
	2	1081 ± 9	68	85	9.6
10.0	8	1060	76	89	9.7
	5	1074 ± 3	59	81	9.4
	2	1042 ±25	25	68	8.6

Mathematical Aspects.

The fitting of the electric consumption curves in milling and briquetting allows to extrapolate data obtained through general procedure. Four types of equations have been tested:

1) $y = a + bx$

2) $y = e^{(a + bx)}$

3) $\frac{1}{y} = a + bx$

4) $y = a * x^{(b)}$

The best fitting with the obtained data is given by the exponential type curve: $\mathbf{C} = \mathbf{K} * \mathbf{S}^{(k)}$ where **C** represents electric consumption in Kwh/t and **S** is the minimum particle size in mm.

In the case of milling & milling consumption, the curves obtained have correlation factors under 0.9 .

Conclusions

Moisture content appears to be the main conditioning parameter for the compactation process and the quality of the briquettes generated, whereas maximum particle size and granulometric distribution play a secondary role which, nevertheless, allows for a reduction in final quality handicaps, when the working moisture content of the products stands close to the practical tolerance limits (8 to 17% w.b.).

In order to densify materials like Poplar and Eucalyptus it is advisable to make a granulometric reduction using mills equipped with large-bored holes (8 mm) since, this way, the obtained briquettes are of better quality than if finely milled waste (3 mm) is used. Besides, energetic transformation costs are remarkably reduced.

Wastes from Pine pruning and residues of Turkey Oak thinning are advisable to mill very finely (3 mm) to obtain quality briquettes and thereby it is essential to assume higher costs in the milling phase.

In relation to Pine bark, it is recommended to mill them using meshes of big diameter holes (10-20 mm) and mixing them with bad quality fibrous wastes, because if are mixed with good quality wastes the qualitative improvement obtained in the mixed briquette with regard to pure bark briquettes is achieved at the expense of losing some materials that, independently briquetted, would generate better quality fuels of a higher added value and price.

Sawdust briquettes, even those showing high density, split and crack during combustion,with great initial weightlosses, since very strong flames are generated. On the other hand, when speaking of briquettes manufactured with wastes of irregular and somewhat fibrous granulometry, fragmentation is shown down, since the fibres present produce a certain linkage causing a slower progress of flames, and thus a lesser initial weightloss,which will increase during the following phases of combustion, opposite to what happens with granular sawdusts.

It may be then deduced that each type of briquette has a set of characteristics that make it more adequate for use in specific processes, with qualitatively different energetic requirements.

Follows Table shows the relative classification of the different types of briquettes obtained:

Table 8

Relative classification of briquettes quality.

RAW MATERIAL 1 (%)	SIZE (mm)	RAW MATERIAL 2 (%)	SIZE (mm)	Q
GOOD QUALITY				
POPLAR (100%)	8			10
SAMBA (100%)	5			10
PINE (100%)	3			9.9
POPLAR (50%)	8	OAK (50%)	5	9.9
TURKEY OAK & PINE	8	OAK (50%)	5	9.8
OAK (100%)	5			9.7
TURKEY OAK & PINE(100%)	3			9.6
PINE (50%)	8	0AK (50%)	5	9.6
TURKEY OAK & PINE(100%)	8			9
MEDIUM QUALITY				
EUCALYPTUS (100%)	8			8.8
TURKEY OAK & PINE(50%)	8	POPLAR (50%)	8	8.6
SAPELY (100%)	5			8.5
BAD QUALITY				
EUCALYPTUS (100%)	3			8.4
PINE (50%)	8	BARK (50%)	8	8.3
BARK (100%)	3			8.2
BARK (100%)	8			8.2
PINE (100%)	8			7.7

Economical aspects.

The increase in energetic costs generated by milling the waste down from 8 to 5 mm is almost totally compensated for by the consumption decrease registered during the briquetting phase (especially the dryer the product is). Nevertheless, the remarkable increase in electric consumption produced when milling goes on from 5 to 2 mm is never compensated for by the consumption decrease registered during densification, so that trespassing the lower 5 mm particle size limit does not seem advisable.

On the other hand, the quality of briquettes does not improve significantly when products milled below 5mm are used, so that this granulometric limit is considered the smallest advisable in qualitative and energetic terms. Nevertheless, if large productions are intended for briquetting machinery redemption, commercial policy, opportunity or seasonal interests, it could be interesting to assume higher milling expenses, in order to obtain very fine granulometries (2mm), since production increase can reach more than 50% compared to that of coarsely milled product.

Per unit grossproduction costs of fuel briquettes are evaluated as follows (Table 10), considering the results obtained and assuming a set of hypothesis (Table 9):

Table 9

Calculate Hypothesis

RAW MATERIAL	h = 10% w.b. & S < 5mm
PRICE OF RAW MATTER	0 $/t
INFRASTRUCTURE	Pre-existing
EQUIPMENT PRICE	60.000 $
WORKING HOURS	5.000 h/y
YEARLY PRODUCTION	1.250 t
REDEMPTION PERIOD	10 y
PRICE OF ELECTRIC ENERGY	0.1 $/kwh
COST OF LABOR FORCE(Automatic system)	2.5 $/h

Table 10

Briquettes gross production cost

EQUIPMENT REDEMPTION	5 $/t
MAINTENANCE AND SPARE PARTS	1 $/t
LABOR FORCE	10 $/t
ELECTRIC ENERGY	6 $/t

Which represents a total cost of about 22 $/t, that could be remarkably reduced if a one man operated multiple machine group is installed, or if larger production capacity plants are installed (i.e. 1000 Kg/h ... 10 - 12 $/t).

In the case that it would be necessary to physically bring the raw matter to the ideally established conditions, an additional cost of between 1 and 25 $/t would be generated.
Packing costs may vary between 5 $/t for retractile plastic packaging and 20 $/t for cardboard box packaging.

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Annex I

Heating value of some autochthonous & exotic Central American species

SCIENTIFIC NAME	COMMON NAME	HHV (kJ/kg)
Acacia farnesiana	Aromo	19.218
Albizzia molucana	Gavilancillo	19.525
Alnus nepalensis	Nepalese alder	20.749
Andira inermis	Carne asada	19.904
Araucaria sp.	Araucaria	20.093
Artdcarpus integrifolia	Jackfruit	21.565
Aspidosperma megalocaspum	Amargo	19.716
Bombax malabaricum	Bombacho	19.722
Bombax sp.	Bombax	19.506
Capara guianensia	Cedro macho, Caobilla	19.569
Cassia fistula	Caña fístula	18.363
Cassia siamea	Cassia	19.381
Casuarina cunninghamiana	Casuarina	19.981
Casuarina quisetifolia	Casuarina	19.580
Cocos nucifera	Coco	21.052
Cryptomeria japonica	Japonese pir	22.672
Dilenia indica	Dilenia	21.700
Eucaliptus camaldulensis	Eucalipto	19.737
Eucaliptus deglupta	Eucalipto	21.107
Eucaliptus globulus	Eucalipto	20.719
Ficus retusa	Higuerón	19.314
Gliricidia sepium	Madero negro	20.566
Gmelia arborea	Melina	22.200
Grevilla rdbusta	Gravilea	20.367
Hymenolobium sp	Cola de pavo	20.197
Lagerstroemia speciosa	Reina de las flores	19.306

SCIENTIFIC NAME	COMMON NAME	HHV (kj/kg)
Mangifera indica	Mango	18.692
Melia azederach	Paraiso, Almez	21.092
Ormosia sp.	Ormosia	20.155
Parinari excelsa	Parinaria	20.068
Pinus caribea	Pino	20.298
Pouteria sp.	Nispero	20.200
porouma aspera	Lija	19.611
Protium	Copales	21.000
Podocarpus milankianus	Ciprecillo	22.723
Populus sp.	Alamo	20.096
Psidium guajaba	Guajaba	18.556
Pterocarpus officinalis	Sangrillo	19.500
Quercus sp.	Roble	19.900
Rhizophora mangle	Mangle colorado	18.962
Sacoglotis sp	Chiricano	20.993
Sapium sp.	Yos	19.570
Simarouba amara	Aceituno	20.344
Sterculia urens	Sterculia	21.460
Swietenia macrophylla	Caoba	19.779
Symphonia globulifera	Cerillo	19.799
Symploccos sp.	Corral	20.400
Tabebuia serratifolia	Guayacán	20.135
Tamarindus indica	Tamarindo	20.100
Talisia oliviformis	Dantisca	23.723
Tectona grandis	Teca	22.892
Tetragrastris panamensis	Canfín	10.339
Toona ciliata	Cedro australiano	21.200
Vatairea guianensis	Amargo	19.318

UTILIZATION OF AGRICULTURAL WASTE IN POWER PRODUCTION

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Abstract

It is a goal of the Danish energy policy for the last decade to reduce energy consumption and to introduce fuels for power production with less CO_2 emission than coal. This measure has caused a considerable effort by the Danish utilities to develop technologies that reduce CO_2 emissions without causing heavy cost increases of power.

Agricultural waste in the form of surplus straw is available in an amount equivalent to 20% of the annual coal imports to Denmark. Straw firing is difficult due to its significant contents of alkaline components. Consequently its utilization presupposes the development of new technologies.

The biomass development programme is concentrated on two ways which are (1) co-firing of existing coal fired power station with a modest amount of straw and (2) development of CFB technology that allows a high share of biomass as well as coal only.

These options were tested in a coal fired 70 MW spreader stoker unit and a 125 MW PF unit. Approx. 4000 t of straw were burned. Additional tests will be launched this autumn, burning 35,000 t of straw at rates up to 20% straw.

The CFB option is pursued from the platform of a 80 MWth unit, operational early '92. This plant burns a mix of 50% straw and 50% coal and consumes annually 70.000 t of straw. Future development is aiming towards CFBs of 250 MWe, burning in excess of 50% biomass.

INTRODUCTION

ELSAM is a Danish utility group, operating approx. 4.500 MWe thermal fossil fuel fired power capacity. MIDTKRAFT and VESTKRAFT are two of the utilities. 97% of the fuel used is coal. There is no hydro nor nuclear power. Consequently the specific CO_2 emission is high. Denmark possesses considerable resources of natural gas in the North Sea. As a premium price fuel, however, it has so far not been introduced as a fuel in the major power stations.

In 1992 the Danish government committed the Danish utilities to cut the power station CO_2 emission by the year of 2005 by 20%, compared to the emission in 1988. As the power consumption has an annual growth of 1 - 2%, this commitment is very stringent and can be met only by applying a variety of means available.

Some of the important options available to ELSAM are introduction of natural gas and biomass as fuel, increase of wind power and reduction of power consumption growth. Nuclear power is not an option. ELSAM will probably have to use all options in order to meet the CO_2 goal. This paper will review the activities to introduce biomass in general and straw in particular as a fuel in the ELSAM power stations.

EXPERIENCE WITH BIOMASS

Since the 1973 energy crisis the Danish government has pursued a development programme to reduce oil dependency and energy consumption. In 1986 a CHP programme was initiated with the purpose of producing combined power and district heating. Bio energy played an important role in this programme. Table 1 gives an overview of the achievements by bio energy fired CHP plants so far. The capacity unit has ranged from 2 - 30 MWe.

Table 1: Danish Utilities CHP Bioenergy Record 1985-92

Costs		Utilities	Total
15 Co-generation plants	(mill. DKK)	2.160	3.030
Total plant output			
Electricity	(MW_e)	139	
Heat	(MW_{th})	338	
Annual biofuel consumption			
Surplus straw	(tons)	200.000	
Municipal waste	(tons)	700.000	
Wood chips	(tons)	27.000	
Solid & liquid manure	(m^3)	288.000	
Land fill gas	(m^3)	2.500.000	

A conceptual design for co-firing of utility scale boilers has been developed. Testing of biomass in such boilers has also been accomplished as a first step on the way to introducing this fuel in power stations, see table 2.

Table 2: Co-firing Coal and Straw

Plant	Firing	Year
Masnedø 75 MWe	PF	1985-87
Aarhus 70 MWe	Spreader	1992
Vestkraft 125 MWe	PF	1992

SURPLUS STRAW RESOURCES

Western Denmark is the potential supply area of straw for the ELSAM power stations. The farmland in that area is approx. 12,000 km^2 or approx. 35 % of the area. The surplus straw resources have been estimated(/1/ reports the study in more detail). Below some of the main findings affecting the amount of straw available are quoted.

Straw Production

The straw production depends on the growing conditions of each season. It is found that the actual annual amount will vary from 70 to 130% from that of the normal year.

It is believed that in future the straw production will be somewhat reduced due to the effects of the EEC MacSharry reforms, and GATT negotiations are likely to reduce the agricultural grain production.

Straw Consumption

Straw is used for traditional purposes on farms such as feeding, bedding etc. but also for heating of the farms, energy purposes, and as raw material for industrial purposes. It is estimated that this consumption is constant and independent of the yield of straw.

Total Surplus Straw

The amount of surplus straw in an average year is estimated to approx. 1.6 million tonnes. In a year of minimum yield it is, however, only approx. 0.7 million tonnes. In the future, these amounts may decrease.

Available Straw for Power Station Purposes

The total potential straw amount will not be available for energy purposes since some farmers may want to leave the straw in the field (straw acts as fertilizer) and some fields are so small that baling is not feasible.

It was estimated that only 70% of the potential surplus straw can be made available to energy purposes. This reduces the amount available to 1.1 million tonnes (15 PJ) in an average year and less than 0.5 million tonnes in a minimum year.

Geographical Distribution of Straw

There are economic limits as to how far straw can be transported. This will further reduce the amount available for combustion in existing power stations. It is therefore necessary to know the geographic distribution of the straw. Fig. 1 shows the surplus straw density.

It appears that although there is a rather high surplus amount of straw, significant areas show a straw deficit or negligible amounts of straw. Establishing straw-fired units in these areas would not be optimal.

Potential Straw Consumption for Power Station Use

Based on figure 2 which shows the location of the ELSAM power stations and fig. 1, it only seems possible to supply straw to 5 power stations. Each unit can consume approx. 150,000 tonnes of straw per year.

It should also be born in mind that the current price of surplus straw, though a waste, is at least twice that of coal (22 - 30 DKK/GJ compared to 8 - 10 DKK/GJ for coal. 1 USD = 6.5 DKK).

CHARACTERISTICS OF STRAW

Straw is a low-grade and non-homogeneous fuel. It is characterized by high volatile, chlorine, and alkaline contents. Typical data of straw are listed in table 3. **The potential problems in combusting straw are increased risk of superheater high-temperature corrosion and fouling due to chlorine and potassium, and slagging due to low ash softening temperatures. Handling requires careful developed logistic system due to the very low bulk density (the heat density is only 10% of that of coal).**

Ashes from ELSAM power stations are to a large extent utilized as raw material for cement production or for mixing in concrete. Therefore strict quality standards are to be fulfilled. One important parameter are low contents of potassium. The high potassium contents from straw may restrain or prevent recycling of the ashes.

Large scale use of straw therefore requires thorough testing before going commercial.

Table 3: Typical Fuel Data

		Straw	Coal*
Lower heat value	(MJ/kg)	13-15	24-28
Moisture(% RH)		8-23	6-14
Volatile	(%)	70-80	20-40
Ash	(%)	2-6	10-17
Sulphur	(%)	0.1-0.3	0.5-2.5
Chlorine	(%)	0.1-1.0	**
Potassium (K_2O)	(%)	0.5-2.0	**
Ash softening temperature	(°C)	800-1000	1135-1400
Bulk density	kg/m³	120-150 (bales)	700-850

Notes: *ELSAM coal range **insignificant

STRAW FIRING TECHNOLOGY

It is the opinion of ELSAM that a power plant fuelled by straw only is not feasible. The main reason for this being the poor fuel quality of straw, the variability of resources over the years and its high costs. **It has been experienced that if straw is burned with other fuels, the adverse impact of straw can be suppressed.** The ELSAM biomass firing concept is therefore based on co-firing of straw and coal.

It is expected that co-firing can be established on existing PF units, if modest amounts of biomass are to be used. If biomass is to constitute a large share of the fuel, ELSAM expects that the circulating fluid bed (CFB) is a candidate. MIDTKRAFT operates since 1992 a 80 MWth CFB unit fired with 50% straw and 50% coal.

CO-FIRING TEST OF EXISTING UNITS

During 1992 ELSAM conducted two coal/straw co-firing tests. ELSAM equipped 2 power station boilers of the 1960s' generation for short-term firing tests: a 70 MWe spreader stoker-fired unit at the MIDTKRAFT Aarhus Power Plant and a 150 MWe pulverized-fuel unit at the VESTKRAFT Esbjerg Power Plant. Main plant data are compiled in table 4. The two test programmes were designed to provide complementary information on the main aspects of co-firing in modern power boilers.

Table 4: Data of Test Plants

	Aarhus	Vestkraft
Boiler type	Spreader stoker	Pulverized
Live steam bar/°C	130/135	170/535
Reheat	None	540°C
Straw proc. equip.	Div.	Shred
Straw cap. t/h	5	7
Straw feed burner	2 off RW	6 off FW
FW = front wall		2 off cor
Max. straw load	30%	16%
Quantity of straw fired - t	2400	890

Fuel feeding to the MIDTKRAFT boiler was established by replacing 2 start-up oil burners by simple straw burners. Straw was fed pneumatically from the straw dividers of an existing CFB demo-plant nearby (see fig. 3). This straw feeding plant will deliver straw that has a length of 50 to 300 mm.

For the VESTKRAFT boiler a straw shredder was applied. The straw length is reduced to a maximum of approx. 50 mm (see fig. 4). Two test series were conducted. Initially straw were fed through one of the coal mills. A second test was performed by injecting straw cuttings pneumatically through existing burner ports located in the corners of the front wall (originally occupied by oil burners).

EXPERIENCE FROM THE MIDTKRAFT TESTS

Combustion Behaviour

A total of 2400 tons of straw was co-fired with coal during a 520 h test at 70% boiler load and straw input up to 30% (energy input). The tests were carried out in 2 shift operation. It was observed that the straw burned in suspension. It was floating in the furnace and burning in its whole length. The length of the straw did not seem to have any effect on the combustion of the straw. The combustion was finished before entering the superheater area.

The boiler is equipped with refiring from the second pass. Possible large unburnt straw particles will be collected in the collector and refired. The ash layer on the grate behaved as usual. Some caking of the grate ash was observed a couple of times but this can also happen on coal only.

After finishing the tests the furnace was inspected, and no unusual ash deposits found except on a 1 by 2 m area on the front wall. It is believed that this originates from straw ash and is the result of some initial experiments to find the best angle of the straw feeding pipe. The superheater was cleaned by soot blowers as usual for coal-firing. Due to the low ash fusion temperature of the straw ash, ash build-up was expected but none found. The condition of the economizer and the air-preheater surface was nearly unchanged. A weak tendency to some more loose fly ash deposits could be observed.

Corrosion Behaviour

Three pipe samples each 1100 mm long were installed in the superheater as shown in fig. 5. The result of the final inspection of the pipes is as shown in table 5.

The tests indicate that location of heating surfaces in flue gas temperature above 800°C may lead to heavier slagging and fouling than for coal. Due to the short duration of the tests corrosion rates cannot be quantified but the conditions for corrosion is present ($KaSO_4$, chlorine, sulphur and material temperatures above 450°C).

Table 5 - Result of Corrosion Tests

Pipe	Pipe A	Pipe B	Pipe C
Material Temp. - °C Visual Insp.	13CrMo44 370 The deposit was bonded. The main components are 60% $KaSO_4$ and 10% Fe_2O_3	13CrMo44 445 The deposit was powder-like. The main components are 70% $KaSO_4$ and 6% Fe_2O_3	10CrMo910 535 The deposit was loose. It consisted of 85% $KaSO_4$

Emissions

Emissions were measured in 3 campaigns (0, 15 and 30% straw input). The main results appear from fig. 6.

The particulate emissions increase sharply, if the share of straw is increased. The total amount of ash is reduced when straw is fired, but it is likely that all straw ash will leave the boiler as fly ash. From other precipitators on straw fired plants it is known that straw ash is more difficult to remove from the flue gas, but the precipitator can be designed to stay within particulate emission limits. The reason for the sharp increase may be that this precipitator has only one electrical zone whereas modern plants firing difficult fuels most often use 3 zones.

SO_2 emission will be reduced since straw contains less sulphur than coal. The reduction experienced can not be accounted to less sulphur in straw, but a SO_2 reduction occurs. This reduction effect is significant, as the SO_2 reduction is 30% at 15% straw and 55% at 30% straw. A similar effect has been found when firing coal and straw in fluidized beds. As there was no parameter variation, it cannot be stated, if this effect will take place over the whole load range or when using other coals.

The other emissions do not change significantly. There is a modest rise i CO emissions.

Ash Conditions

The fly ash composition is given in table 6. It is obvious that the contents of the less desirable components are increasing rapidly when the straw share of the fuel input increases. The ashes were not tested with regard to application in the cement production, but it is not likely that the ashes at 30% straw would be acceptable.

Table 6. Ash Analyses of Fly Ash and Fuel Ashes

Straw input	SiO_2 %	Al_2O_3 %	TiO_2 %	P_2O_5 %	SO_3 %	Fe_2O_3 %	CaO %	MgO %	Na_2O %	K_2O %
0%	59.0	19.8	0.77	0.43	0.72	9.4	3.5	1.7	0.70	3.1
15%	53.3	17.8	0.69	1.1	2.2	8.1	5.4	1.9	0.81	6.7
30%	48.3	15.6	0.57	1.7	5.0	6.5	8.1	1.9	1.2	11.0
Coal ash	58.3	20.6	0.78	0.21	3.0	9.3	3.1	1.6	0.49	2.2
Straw ash	22.5	0.53	<0.1	4.5	7.8	0.28	15.4	2.3	2.9	45.0

Test Evaluation

The MIDTKRAFT Aarhus test establishes confidence that co-firing of straw and coal on a spreader stoker is rather simple to install, and that operation should be satisfactory. Corrosion seems to be no serious problem. The ashes from this plant cannot be reused. Additional testing scheduled in 1993 for 3 months with 30% straw firing may confirm this assumption. The problems met in these tests are negligible compared to the problems experienced in stoker fired plants firing straw only.

EXPERIENCE FROM VESTKRAFT

Test No 1 (Straw Through Coal Mill)

It was possible to grind the coal together with the straw and achieve a good combustion. A straw share of 10% on an energy basis was obtained. No unburnt straw particles were found in the fly ash, nor in the boiler. At this straw load the coal load could not be increased above 70% of normal capacity on coal alone. The straw decreases milling capacity significantly.

Test No 2 (Separate Burners)

This test lead to a maximum of 16% straw-firing at 70% boiler load. An oil burner was operated below the straw burner. Cumulative straw quantities amounted to 890 tons. No unburnt particles were found in the fly ash. A few grains and straw knees were found in the bottom ash. The straw input was only limited by the shredder capacity.

Emissions

During the tests SO_2, NOx, particulate and HCl were measured. In fig. 7 the results from test no 2 are given. It appears that the tendencies are similar to those of MIDTKRAFT's, yet the particulate emission was unchanged.

Evaluation of the VESTKRAFT Tests

The VESTKRAFT tests were very short but it is our opinion that it should be possible to develop co-firing of coal and straw. We still lack reliable information on corrosion behaviour and reuse possibility of ash. Late 1993 we will start a new test programme in which up to 20% straw load will be achieved at 100% boiler load. During these tests we plan to burn 35.000 t of straw. The tests are supported by the EEC APAS Clean Coal Programme. We hope these tests will create the basis for launching a demonstration phase for co-firing of a 250 MWe unit.

Concept for Co-Firing

In 1992 ELSAM conducted a conceptual study for the additional plant needed to co-fire straw and coal. It is estimated to a cost of approx. 90 mill. DKK.

CFB DEVELOPMENT

The second way adopted by ELSAM for coal and straw firing is the Circulating Fluid-Bed (CFB) boiler concept, which offers the potential of co-firing at high biomass ratios (≈ 50%) at power plant scale with attractive efficiency and low environmental impact.

Previous Development

The pioneer efforts in this concept have been vested in MIDTKRAFT Power Company as a preparation to a local co-generation project, CHP Grenaa, of approx 80 MW_{th} boiler capacity (table 7).

Table 7: Coal & Biomass CFB, ELSAM Experience

	Pilot combustion tests, coal & straw
1988 :	* Risø National Lab (DK)
1989 :	* Hans Ahlstrom Lab (SF)
1991 :	**20 MW$_{th}$ demo-tests, MIDTKRAFT Aarhus Power Plant** * Coal:straw ratios up to 80% straw (by energy) * Coal:wood chip (spot tests)
1992 :	**Industrial logistics for large straw quantities**
1992- :	**80 MW$_{th}$ MIDTKRAFT CHP Grenaa** * Commercial generation of electricity, heat, and process steam * Coal: straw ratio 50:50% * 70.000 tons straw per year at full capacity
1993 :	**Preparation for EEC-APAS test at CHP Grenaa** * Coal-straw ratio 40:60%
1993 :	**Utility-sized coal & biomass CFB, advanced steam data** * Feasibility study

Pilot combustion tests 1988 at Risø National Laboratory, Denmark, and Hans Ahlström Laboratory, Finland, and associated engineering studies proved the feasibility of the coal/straw-fired CFB concept.

Supporting evidence was provided during 1990-91 by a 20 MW$_{th}$ CFB demonstration project executed in cooperation with the Danish boiler manufacturer Aalborg Ciserv International and Risø /3/. The demo plant was built at the Aarhus Power Plant. A total of 5600 operational hours at straw ratios from 0 to 80% provided comprehensive experience for all parties involved.

CHP Grenaa

The coal and straw-fired CHP Grenaa Plant, which is the first commercial installation of its kind in Northern Europe, became operational early January 1992.

Main plant data are shown in table 8. The CFB boiler (fig 8) is provided by the Consortium Aalborg Ciserv/Ahlström Boilers. The boiler is designed for straw and coal ranges up to 60% and 100%, respectively. Symmetric coal and straw feeding are adopted. No straw is allowed below 50% load level.

Table 8: CHP Grenaa, Main Plant Data

Boiler capacity	(MW$_{th}$)	78
Electric output, gr-net	(MW$_e$)	19.6 - 17.8
Main steam	(kg/s - bara - °C)	29 - 92 - 505
Process steam	(kg/s - bara - °C)	21 - 8.3 - 210
District heat	(MW$_{th}$ - °C - °C)	32 - 90 - 50

Experience with CHP Grenaa

Initial operational experience has been published /2/. Generally, plant behaviour has been satisfactory.

By the end of April 92, after 3800 operational hours, a superheater pipe failure occurred. The damaged pipe (material 10 CrMo 910) was located at the final superheater (no 3) flue gas inlet, close to the soot blower.

This failure was apparently caused by a combination of soot blower jet impact and a rather loose oxide layer. During the summer revision August 92 shields were mounted at the exposed piping, and this precaution has proved satisfactory.

4 higher alloyed pipes without shields were also installed. During an inspection April this year no significant metal loss was observed.

During December 92 full-load operation at 50:50% straw and high-sulphur coal ($\approx$ 2.5% S) resulted in heavy deposits containing K_2SO_4 at the final superheater, but also in the furnace and cyclone area. The main reason for this behaviour is probably to be found in the high sulphur contents of the coals, but we also experienced problems in controlling the combustor process (cyclone temperature was high), and this has probably increased the seriousness of the incident.

The CFB has a platen superheater at 400 - 450°C in the furnace. Its performance decreases rapidly at high straw loads. Inspection reveals that it becomes heavily fouled. If straw firing is stopped, the performance is restored.

A 40:60 coal/straw demonstration test during 93 has been scheduled for the CHP Grenaa as part of the ELSAM and EEC APAS programme.

The general evaluation of the operation has not been worse than expected. It is therefore our opinion that a CFB, which burns high alkaline fuel, must possess means for process control which will keep the combustor reactor temperature even if some of the operational parameters are not fulfilled.

Future CFB Development

It is our belief based on the experience gained from the Grenaa plant that the CFB concept is a promising candidate for burning high shares of straw (50%) in combination with coal.

ELSAM has therefore launched a development programme that has the goal of demonstrating a 250 MWe CFB in 2005 with 50 - 70% biomass (straw and wood). A 50 MWe CFB demonstrating this technology could start operation in 1998.

ELSAM is deeply involved in developing PF plants with USC data (ultra steam conditions - eg. 250 bar/580°C/580°C, see /3/) as a means to reduce CO_2 emissions. The CFB should also use USC data. This is a serious challenge.

To verify this option a verification programme at the 20 MW_{th} Aarhus CFB demo-plant has been scheduled for 1993-94. During these tests superheater elements will be tested with up to 590°C at up to 80% straw firing.

CONCLUSION

ELSAM has launched a very ambitious and costly programme with the aim of introducing biomass on a large scale in the power production. The tests and development work so far have shown that the challenges are significant but also given faith that co-firing can succeed.

This development programme will have to rely on external support such as funding, cooperation with suppliers and other utilities. The EEC APAS programme is a valuable support to this programme.

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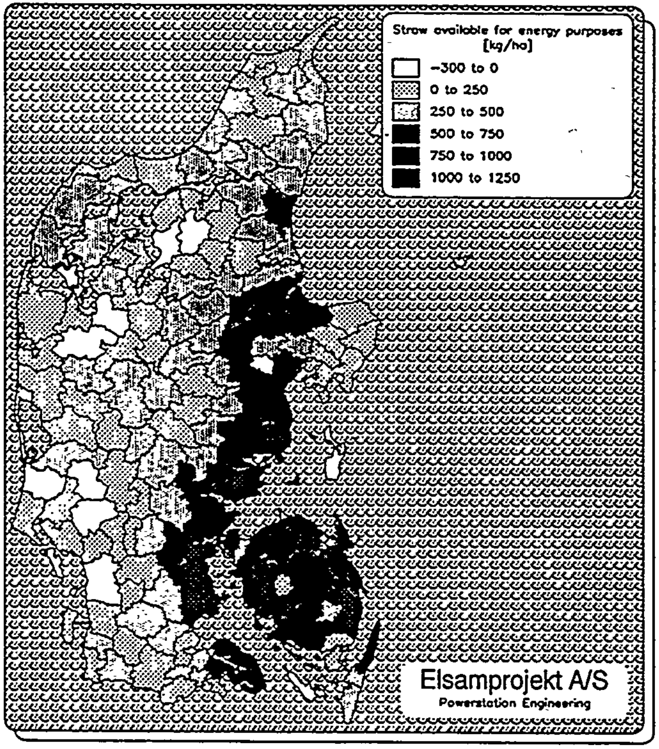

Fig. 1: **Surplus Straw Density**

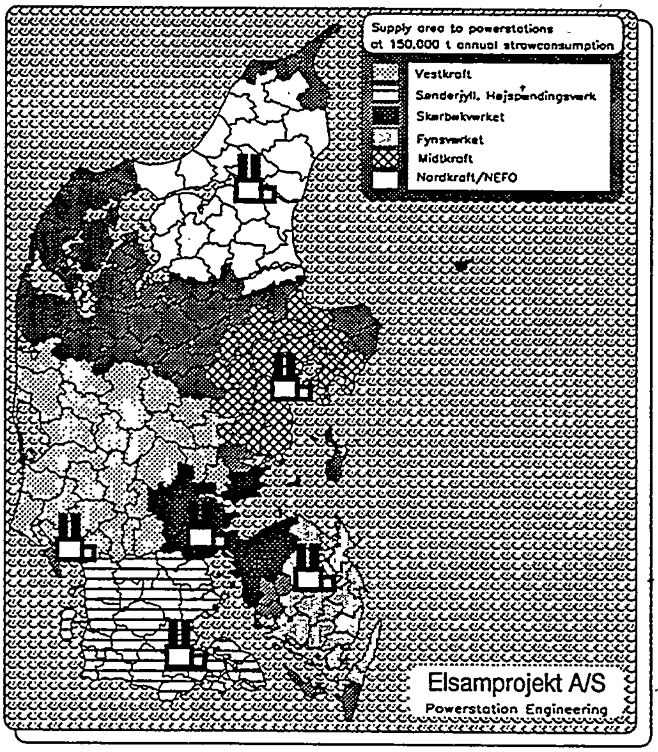

Fig. 2: **Supply Area for Straw for ELSAM Power Stations**

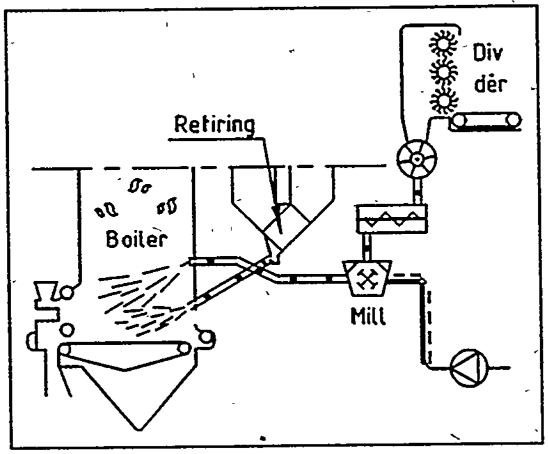

Fig. 3: Diagram for MIDTKRAFT Straw Feeding System

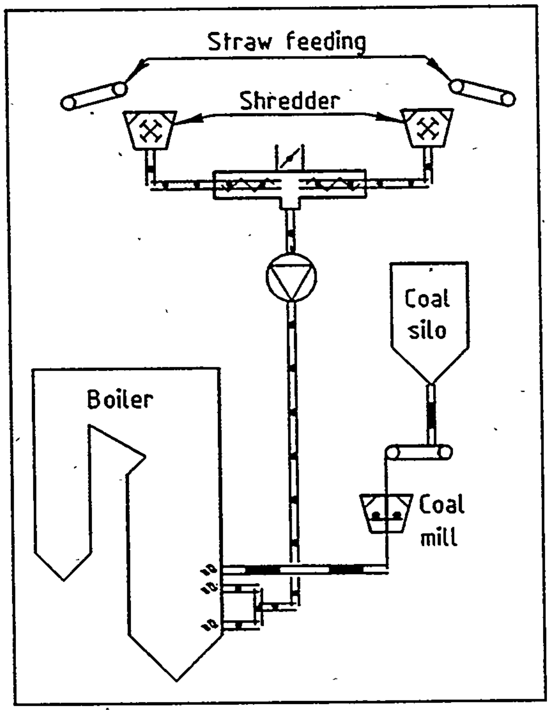

Fig. 4: Diagram for VESTKRAFT Straw Feeding System

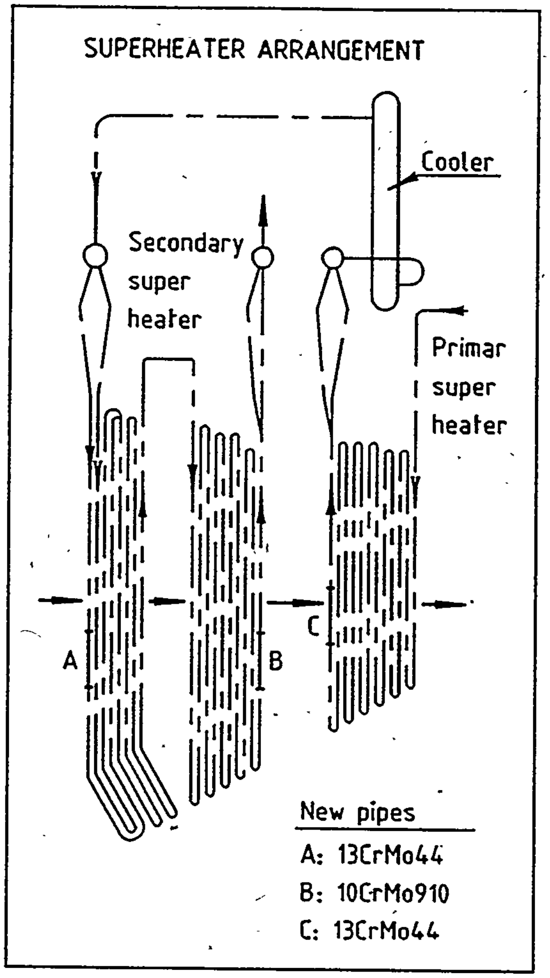

Fig. 5: Location of Material Probes in Superheater

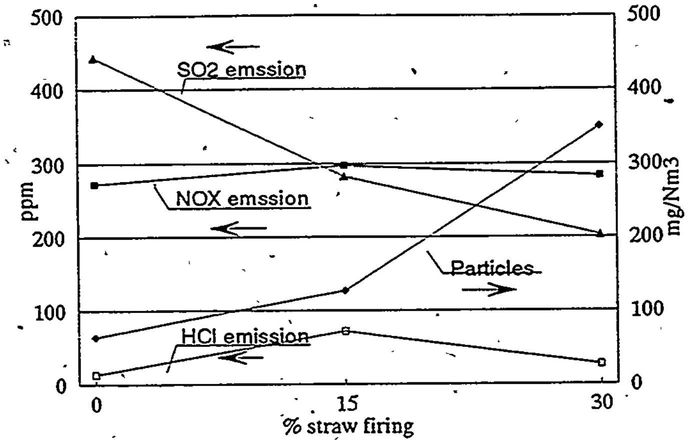

Fig. 6: Emissions as Functions of Straw Input, MK

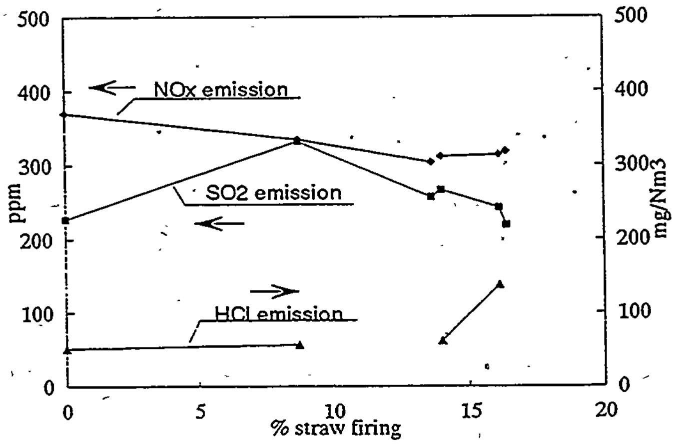

Fig. 7: Emissions as Functions of Straw Input, VK

AHLSTROM

AHLSTROM PYROFLOW

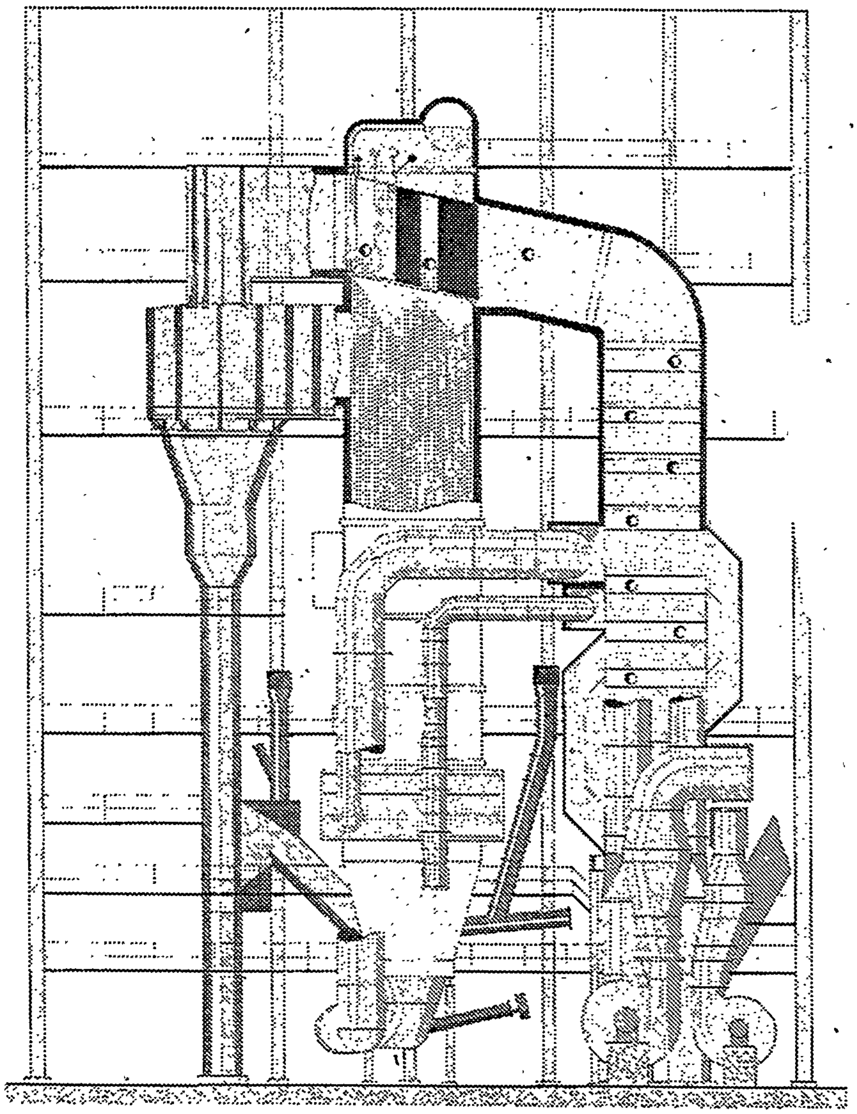
MIDTKRAFT POWER COMPANY
GRENÅ, DENMARK

Fig. 8: CFB Boiler for Grenaa

BIOMASS ASH UTILIZATION PROGRAM

CASE STUDY OF RECYCLING OPTIONS FOR NEW HAMPSHIRE GENERATORS

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ABSTRACT

The successful development of utilization programs for ash generated by the combustion of biomass in Northern New England is described, with special focus on the State of New Hampshire. With the development of over 25 large scale biomass boilers in Northern New England during the past ten years, has come the need to dispose of the over 300,000 cubic yards of ash produced as a combustion-by-product.

Resource Conservation Services, Inc., a private company, pioneered the development of various utilization options for biomass boiler ash. The major use of ash has been as an agricultural soil amendment. The high levels of calcium in wood ash make it valuable as a lime substitute for raising soil pH. Wood ash also contains significant levels of potassium, phosphorus and magnesium as well as lesser amounts of other plant nutrients which make it valuable as a fertilizer. Soil testing is used to determine application rates to agricultural land. Ash use is regulated by State environmental protection agencies. Heavy metal content of wood ash meets regulatory standards.

Wood ash has also proven valuable as a bulking and odor control material when mixed with municipal wastewater treatment plant sludge and composted. The high pH of wood ash controls odor producing compounds generated by the composting process. High carbon ash also controls odors through improved aeration and by adsorption of odor producing compounds by the "char" in the ash.

Additional uses for wood ash are as a component of concrete products such as "flowable fill" and "soil cement", as a lime substitute for sludge stabilization, and as landfill daily cover.

As higher value uses for wood ash have been developed, ash disposal costs have been reduced and ash is viewed more like a commodity than a waste material.

Key Words: Wood Ash, Biomass, Lime, Composting

I. Introduction

During the past decade in Northern New England there has been a renaissance of wood burning on a commercial and industrial scale. Wood has always been a traditional fuel in the home and for small businesses, particularly sawmills and other wood products mills. Significant changes in federal energy policy enacted into law during the early 1980s provided incentives for the production of both electricity and process steam from the combustion of biomass fuel. The result was a large scale construction effort on the part of both private industry, especially pulp and paper mills, as well as independent power producers throughout Northern New England. As the combustion of wood biomass and other solid fuels increased so did the production of the resulting ash. High cost of ash disposal might have been a disincentive to the development of biomass energy systems were it not for the development, during the same period, of utilization options for ash. The utilization options provided cost effective disposal for this by-product of electrical generation, wood ash.

At present there are over 20 large scale industrial boilers and independent power producing facilities located in the three Northern New England states. Annual production of ash from these facilities is in excess of 300,000 cubic yards. The total contribution of energy to the electrical power grid from these biomass sources is in excess of 400,000 Megawatts per year. In the state of Maine the development of wood biomass energy sources, in conjunction with the state's plentiful hydroelectric generating capacity, has resulted in Maine achieving a top ranking in the country for the use and development of renewable energy sources. The biomass industry in Northern New England has also provided needed stimulus to local economies by providing jobs both in power production and also in fuel procurement and ash disposal. Biomass energy has allowed the Northern New England region to rely on more stable locally available resources and less on potentially volatile external sources of energy.

II. Fuel Sources

While a variety of fuels are burned in biomass boilers, by far the most common fuel is the whole tree chip. Whole tree chips are derived by harvesting and chipping the entire tree, including branches and leaves, into two inch or smaller chips. Whole tree harvesting and chipping has revolutionized silvicultural practices in Northern New England. For the first time it has proven economical to harvest "cull" trees, that is, trees with low potential to produce quality saw logs or pulp wood. With the use of specialized equipment it is now possible to carry out thinning operations which both remove poor quality trees and reduce the density of the stand, allowing the remaining trees to develop more rapidly . As a management tool biomass harvesting arrived at a time in New England when large tracts of forest land were sorely in need of this type of management, having suffered years of "high grading" which resulted in stands with high stem count and a high number of low quality trees. In this sense then, whole tree chip harvesting has created a viable market for a "waste wood" which possessed little market value in traditional forest product markets..

Whole tree chips are normally chipped at the harvesting site and transported in 100 cubic yard trailers directly to the power plant. Additional sources of wood biomass include waste from wood processing operations such as turning mills, saw mills, and paper mills. The biomass, so produced, can include sawdust, bark, and chipped waste pieces such as edgings and trimmings. In the pulp and paper industry during the past decade, biomass boilers have increasingly been used as a means of disposal of the sludge produced by the mill's wastewater treatment plants. This sludge, consisting primarily of wood fiber along with inert fillers such as clay and calcium carbonate, is typically dewatered to a solids content approaching that of whole tree chips. Some mills are also burning limited quantities of waste paper generated both internally and from external sources. In the large boilers generally associated with the pulp and paper industry, fossil fuels such as oil or coal are often combusted with the biomass to produce the quantity of steam required to make paper.

III. Wood Ash Recycling

The recycling of wood ash in Northern New England began concurrently with the operation of the first large scale biomass boiler in the region. In 1983, William Ginn, recently retired as Executive Director of the Maine Audubon Society, conceived the idea of using ash from biomass boilers as a lime substitute on agricultural land. Ginn, himself a part time farmer, reasoned that the liming ability of wood ash from home stoves had always been recognized and used throughout New England's history. Why not, then, use the large quantities of ash which was beginning to be produced by biomass boilers in the same fashion, only on a much larger scale. Ginn pioneered this use of ash by developing the first environmental permits from regulatory agencies in Maine and New Hampshire. Initially the wood ash was regulated under the same rules which govern the use of municipal wastewater treatment plant sludge. As more was learned about the ash both in terms of its physical and chemical characteristics, regulations better suited to its use were developed. Beginning in 1983 with a contract to recycle the ash from the S.D. Warren Company in Westbrook Maine, Bill Ginn's company, Resource Conservation Services, Inc. (RCS) has grown during the past 10 years to the point where it now handles ash from 20 boilers in Northern New England. The New Hampshire wood ash recycling program provides an excellent case study of the development and successful implementation of a wood ash utilization program.

IV. The New Hampshire Wood Ash Recycling Program

The New Hampshire program was initiated in 1986 through a series of discussions between RCS, the University of New Hampshire and the state of New Hampshire Department of Agriculture. These discussions laid the groundwork for an agreement about how the program would be managed and regulated. The ash would be regulated by the state of New Hampshire, Department of Environmental Services (DES). RCS would manage the program on behalf of the generators of the ash with review and management recommendations provided by the University of New Hampshire, Cooperative Extension

Service. Ash would be considered a lime substitute not a fertilizer source. In order to quantify the use of ash as a lime and to further understand its benefits for crop production, a research program was implemented by the University of New Hampshire, Department of Plant Science, with funding from RCS and the ash generators.

In order to provide for public education and for acceptance by the farming community, RCS developed a series of informational brochures about the ash. Presentations were made at meetings of farming groups, as well as of community groups, in order to explain the nature of the wood ash and how it would be used on the land. Acceptance by the farming community was extremely positive and there were few problems with public opposition to this program.

The ash produced by New Hampshire biomass plants is produced almost exclusively from the combustion of whole tree chips and other "clean" wood sources. Table 1 shows the chemical characteristics of New Hampshire biomass boiler ashes.

Table 1

Agronomic Value of 6 New Hampsire Biomass Boiler Ashes

Element	Range PPM	Mean PPM
Boron	13.8 - 116	49.8
Calcium	79,920 - 219,213	154,452
Copper	51.3 - 199.3	114.3
Magnesium	7,500 - 19,540	14,597
Molybdenum	1.7 - 4.2	2.9
Phosphorus	1,000 - 13,456	8908
Potassium	27,425 - 85,260	59,383
Zinc	480 - 2,500	1,292
$CaCO_3$ Equivalence(%)	25.3 - 62.8	44.5

Calcium, and potassium are the two elements which provide the most benefit from the agricultural utilization of ash. The calcium contributes to the ash's ability to lime or sweeten the soil (by increasing soil pH). Potassium is one of the three plant nutrients required in large quantities for the production of forage crops such as hay, legumes and corn. Wood ash also contains smaller, but significant quantities of other plant nutrients such as phosphorous and magnesium, as well as plant micronutrients such as copper, zinc, boron and molybdenum. Other components of wood ash include the carbon content. This consists primarily of partially burned pieces of wood biomass. Depending upon the efficiency of the boiler operation and the nature of the ash collection system, the quantity of carbon in wood ash can vary significantly from plant to plant. Initially there were concerns raised by the University of New Hampshire that wood ash containing a high percentage of carbon or "char" might be detrimental to agronomic production systems by lessening the effectiveness of commonly used herbicides. Research conducted by the University of New Hampshire and others has demonstrated that even "high carbon" ashes are not detrimental to farm production of crops such as corn, if the ash is well incorporated into the soil. As will be discussed below, excellent alternative markets have also been developed for high carbon ash in the meantime.

Wood ash also contains heavy metals whose levels are regulated by the DES. Table 2 shows the levels of heavy metals in New Hampshire ashes as compared to regulatory standards.

Table 2

Heavy Metal Content of 6 New Hampshire Biomass Boiler Ashes

Element	Range PPM	Mean PPM	Regulatory Limit PPM
Cadmium	6.6 - 17.3	11.6	10(25)
Chromium	7.1 - 33	18.8	1000
Copper	51.3 - 199.3	114.3	1000
Lead	42.4 - 134	71.9	700
Mercury	0.06 - 0.08	0.07	10
Nickel	7.2 - 189.5	47.9	200
Zinc	480 - 2,500	1,292	2000

With the exception of cadmium, all metals are well below the regulatory thresholds. The cadmium levels will be discussed in more detail below. Once an ash has been tested and characterized as to its chemical content, a Program Approval is granted by the DES for that specific ash. In order to utilize ash on a farm site, all the soils must first be tested to determine the need for lime and the level and balance of nutrients contained on each field. Soil testing is at the heart of the utilization program. Ash is applied only at rates which correspond to the recommended need as defined by the soil test. Soil pH and lime requirements are the first consideration. Wood ashes vary in their equivalence to lime from between 20 to 75%. The differences have to do with the efficiency of the burn at the power plant, the type of fuel, and the quantity of carbon in the ash. The ash from boilers which re-inject their ash, or burn it twice, has a lower carbon content and a correspondingly higher lime equivalency.

In addition to meeting the lime requirements, it is important to maintain a proper balance between the nutrients in the soil. The major cations, consisting of calcium, magnesium and potassium, must be maintained in the soil at correct levels in relation to each other. For example, if potassium levels are high compared to levels of magnesium, there will be an imbalance of nutrients in the plant and possible ill health for livestock consuming the forage produced on the field. Wood ash is no long applied to a field if the calcium saturation exceeds 80%, nor if the potassium saturation level exceeds 50% of the magnesium saturation level. Generally it is the calcium saturation and pH level of the soil which limit further application of ash to a site. With most farm fields in Northern New England, two applications of ash over a 5 year period are sufficient to achieve target fertility and pH rates.

Once the soil tests on a farm confirm the need for ash, the ash is delivered in large trucks to each field according to the amounts required to provide the lime needs of each field. As an example, if a field required 2 tons of lime per acre, and the ash had a 50% $CaCO_3$ equivalence and came out of the plant at 50% solids, the farmer would receive 8 wet tons of wood ash per acre of field to be fertilized. When ash is top dressed on an existing crop, the rate is limited to the equivalent of two tons of lime per acre. When ash is incorporated into the ground for growing a row crop or for reseeding a field a rate of lime equivalent to three tons per acre is utilized. Prior to discharge from the power plant the ash is mixed with sufficient water to condition the ash thereby preventing blowing and dusting problems. At the farm site wood ash is stockpiled on locations of the field that are level, out of the wind and with specified buffer distances from houses, wells, and water bodies.

Buffers for spreading ash are maintained in order to ensure environmental integrity. Table 3 shows the buffers or setbacks maintained in the New Hampshire wood ash program.

Table 3

New Hampshire Ash Utilization Program: Buffer Distances for Ash Applications

Feature	Distance(feet)
Houses, Wells	300
Water Bodies	100
Seasonal Waterways	25
Property Boundaries	25
Public Roadways	25

V. Problems With the Program

Although the New Hampshire wood ash program has been extremely successful, it has not been without problems encountered due to both physical and chemical characteristics of certain ashes. One of the major ongoing problems in handling any wood ash is the physical condition of the ash when it leaves the plant and when it is stockpiled in a field prior to spreading. As was described above, ash is routinely mixed with water to condition it in order to prevent the formation of dust. Ash however, because of its high calcium content, will undergo a series of chemical transformations once it is conditioned with water which can result in the formation of a primitive cement. This can cause the ash to solidify, forming large lumps or clinkers. These lumps create havoc with spreading equipment and can also be a true hazard to the harvesting of hay when lumpy ash is spread on grasslands. Another problem which can result from improper conditioning of ash is the carryover of live embers from the boiler into the ash itself. There have been occasions when ash has been delivered to a field as a glowing red mass which has on one occasion burned and caused serious damage to the truck delivering the ash to the field. Finally, the presence of metal objects can result in operational problems. These can range from bolts, tools, and other hardware from the chipping operation or from maintenance at the power plant to the presence of metal slag resulting from the melting of metal in the boiler. As with the lumps, metal objects in ash are a serious problem for farmers harvesting hay off of grassland and can be a threat to animal health when ash is spread on pasture land. RCS has worked closely with the power plants to address these problems. Close monitoring of the conditioning systems and installation of magnets and screens has eliminated these ash quality problems.

As noted above, the level of heavy metals in wood ash is below regulatory levels with the exception of cadmium. Cadmium in ash is the result of cadmium which is present in the wood itself. Those power plants which achieve an extremely efficient burn that is, plants which produce a low carbon ash, will have correspondingly higher concentrations of cadmium. Initially, this led to a problem in the program because cadmium from several power plants was routinely exceeding the state regulatory level of 10 parts per million. Research, however, demonstrated that the health risks of cadmium at these levels was minimal for several reasons. First, as ash is more concentrated due to more efficient burn, it's liming value is also proportionately higher. Therefore, the loading rate of this type of ash would be lower in terms of tons per acre than from a less concentrated material. The risk analysis which established heavy metal regulatory limits was based on work conducted with municipal wastewater treatment plant sludge landspreading programs. Typically, the loading rate in terms of dry tons per acre for the sludge program is significantly higher than the loading rate for wood ash. Further, RCS limited the annual application rate to 8 dry tons per acre, which effectively ensured that cadmium would not exceed any loading limits when the metal concentration was below 25 parts per million. For these reasons the New Hampshire DES provided a variance mechanism which effectively raised the allowable cadmium concentration in wood ash, from 10 parts per million to 25 parts per million. All wood ashes produced in New Hampshire are able to easily meet the 25 parts per million standard.

Another problem with a heavy metal developed with one power plant due to the lead content of its ash. Routine monitoring of ash delivered to farm sites detected a lead level in excess of the state regulatory standards. Samples of each load of ash are routinely obtained for every delivery to a farm site. From these "grab samples" composite samples are assembled for routine ongoing analysis. When the regular analytical data was received for the ash which showed elevated levels of lead, it was possible to trace the problem to a specific quantity of ash generated by the power plant and to isolate where that ash had been delivered. The stockpiled ash was removed from the field and not spread. The problem was traced to a "trial" that the power plant had initiated. As it turned out, the trial wood contained a significant quantity-wood which had been coated with lead based paint. Careful monitoring of fuel supplies has precluded a reoccurrence of this problem.

Another issue which has been raised about wood ash during the past two years involved the discovery that wood ash from New England contains measurable amounts of the radioactive isotope Cesium 137. When compared to the levels of radioactivity found in low level waste from the nuclear power industry which are commonly handled by special disposal, it appeared that the levels of radioactivity in wood ash, were quite high. In response to this question all New Hampshire ashes were tested to determine the level of radioactivity. The testing program carried out by the University of Maine Physics Department showed that the levels in biomass boiler ashes were roughly equal to levels already present in New England soils. A literature search showed that there was excellent laboratory, greenhouse, and field data to demonstrate that the radioactive elements present in ash and in soil which had resulted from the fallout from weapons testing during the 1950s & 1960s was unlikely to pose a threat to human health. Cesium 137, which is the major radioactive isotope discovered in wood ash, remains firmly fixed to soil particles. There is very little uptake of this element into plant tissue, and therefore a very small potential for transfer to the human food chain. Various risk analyses carried out to assess the risk of wood ash utilization demonstrated that, compared to background levels of radiation, exposure to the radioactivity in ash represents a very small incremental risk.

VI. Alternative Utilization Options

While agricultural utilization has remained the backbone of the ash recycling program, additional uses and markets for ash have also developed. The most successful of these new markets involves the use of wood ash in the composting of municipal wastewater treatment plant sludge. Beginning with pilot projects in Scarborough Maine in 1985, the use of wood ash to compost municipal wastewater treatment plant sludge has grown steadily. The Scarborough Sanitary District, located in a coastal community in southern Maine, operates a waste water treatment plant and static pile composting facility to process the sludge resulting from the treatment process. Due to its proximity to residential neighborhoods the compost facility at Scarborough was encountering serious opposition to its operation due to odors generated by the composting process. This led the District to investigate the use of wood ash in its composting process as an odor control material. Ash was used in a mixture with the sludge in place of wood chips. In addition, ash was used as an odor control "blanket" for each pile. The results were exceptional. Not only was odor greatly reduced, but the composting process was also very successful, with piles heating up rapidly and maintaining required temperatures throughout the composting cycle.

Ash can be used in a variety of ways to aid in the composting process, both for odor control and to provide texture or bulking of the sludge mixture. High carbon ashes are useful as a bulking agent for sludge and can provide a 100% replacement for wood chips or other bulking material. Low carbon ashes can also be effectively utilized for odor control in composting by substitution of up to 25% of the bulking material. Odor control from the use of wood ash in composting is the result of higher pH in the piles which discourages the formation of odor producing compounds. Odor control may also be achieved with high carbon ashes by means of better aeration and by absorption of odor on the char which has properties similar to activated carbon. One of the negative aspects of using wood ash as a composting amendment is the initial production of ammonia from the compost piles due to the high pH of the wood ash. Nevertheless, the market for ash as a compost bulking material and odor control agent has been growing rapidly and now accounts for a significant proportion of RCS's ash utilization picture.

Forest application of wood ash would seem like a logical utilization option for this material. After all, what would make more sense than returning the nutrients and minerals in the ash to the very land from which they originated. Research conducted by the University of New Hampshire has demonstrated that there is a benefit to forest soils from the application of wood ash. There has, however, been no large scale forest land application program for wood ash in New Hampshire due to economic considerations. Specialized forest spreading equipment has been developed and utilized successfully in Maine, but, the cost of spreading ash on this type of site far exceeds the cost of utilizing ash on agricultural land and as a compost bulking material. Therefore, there has been an economic disincentive for this utilization option.

There have also been research and demonstration projects carried out recently to develop additional uses of wood ash, particularly related to its use in the construction industry. RCS has successfully used wood ash to produce a soil cement. In this application the ash is tilled into native soil along with Portland Cement, compacted with a roller, and allowed to harden to form a low cost pad for the storage of waste material. Another use of wood ash is as a component in a controlled low strength material or "flowable fill". A flowable fill is a construction material somewhat similar to concrete. It is used to replace native soils as a backfill material around culverts, pipelines, foundations, etc. RCS has successfully used wood ash as a component of flowable fill. Flowable fill is currently a major utilization option for coal ash in the Mid West and Mid Atlantic regions of this country.

Some wood ashes my also be utilized as a replacement for lime in the production of cement and for the stabilization of municipal wastewater treatment plant sludges. Wood ash has also been successfully used as a material to mix with sludge to provide a higher solids content for landfill disposal. Wood ash alone or blended with soil can be used as a daily cover material for landfill disposal of municipal solid wastes.

VII. Conclusion

With the development of a broad spectrum of utilization options for wood ash during the past 10 years, the cost of ash disposal for biomass power plants in New Hampshire and other New England states has steadily decreased. While once viewed as a waste, and at best something to sweeten the soils on farm fields, wood ash is increasingly recognized as a valuable mineral resource and is in the process of becoming a valuable commodity rather than as a waste material. The development of utilization programs for wood ash has helped the biomass industry to remain a viable power source while at the same time eliminating the need to use valuable and scarce secure landfill space for disposal of this material.

ENVIRONMENTAL ISSUES:
NEW TECHNIQUES FOR MANAGING AND USING WOOD FUEL ASH

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ABSTRACT

Continued research and development of environmentally-acceptable and cost-effective end uses for wood ash is having a significant affect on the ability to use wood and wood waste for fuel. This is particularly true for ash resulting from treated wood combustion. Concerns about the contents of ash from wood containing paint, stain, preservatives, or other chemicals is one of the largest regulatory barriers to its use as fuel. The purpose of this paper is to:

- Identify the physical and chemical characteristics of ashes produced from the combustion of untreated and treated wood.
- Explain the types of "clean, untreated" and "treated" wood that are likely to produce ash that can be beneficially used.
- Describe existing and potential products and end uses for untreated and treated wood ash.

Definitions

In this paper, "untreated wood" is defined as wood that does not contain additives or chemicals such as harvesting residue, wood product industry waste, landclearing waste, stumps, and untreated dimensional lumber. Untreated wood also includes materials containing nails, bolts, and other items that can be removed. Pallets are generally considered to be untreated wood. However, some pallets are constructed with treated wood, are painted, or become contaminated during use.

"Treated wood" is defined as wood that contains additives or chemicals such as glues, resins, binders, preservatives, surface coatings, metal, roofing material, insulation, fiberglass, plastic, and laminates. Examples include plywood, particleboard, painted wood, stained wood, varnished wood, pressure-treated wood, creosote-treated wood, railroad ties, telephone poles, and wood laminates.

WHY IDENTIFY END USES FOR WOOD ASH?

Increasing pressure on existing solid waste disposal facilities is encouraging new approaches to reducing waste generation and increasing reuse and recycling throughout the U.S. In particular, interest is growing in implementing source reduction programs, identifying reuse options, developing recycling facilities, and expanding end use markets for wood waste.

The growing emphasis on wood waste is important, because the material represents a significant portion of the solid waste stream and is often not addressed by recycling programs instituted at the local level. The decreasing availability of permitted solid waste disposal facilities in certain parts of the country is causing substantial increases in tipping fees. This escalates operating costs for businesses and industries that generate wood waste, results in higher prices charged to customers, and may lead to more illegal "backyard dumping".

A variety of energy production, solid waste management, and environmental benefits can be achieved through the source reduction, recovery, and processing of wood waste. Such efforts can:

- Decrease the amount of solid waste generated and needing to be disposed of;
- Help control solid waste hauling costs and tipping fees paid by generators of wood waste;
- Stretch the limited capacity of existing landfills;
- Decrease the need to site new landfills;
- Alleviate a variety of economic and regulatory issues that result in wood waste being discarded illegally;
- Recover wood waste that can be used in another way;
- Create a new supply of fuel for existing or proposed wood-fired power plants, industries, businesses, and institutions; and
- Demonstrate that end users of recycled wood material can obtain environmentally acceptable, cost-competitive products that meet their specifications and end use requirements.

KEY ISSUES AFFECTING THE USE OF WOOD AND WOOD WASTE FOR FUEL

Since 1986, CTD has conducted an ongoing research program that tracks the development, operation, and regulatory experience of major wood and wood waste combustion and processing facilities throughout the U.S. This research has consistently revealed several issues that have major impacts on existing and potential facilities that use, or would like to use, wood and/or wood waste for fuel.

- There is substantially more wood waste generated than is represented in most federal, state, and local solid waste assessments. This is because a significant amount of wood waste never enters the municipal solid waste (MSW) stream, and is therefore not counted in MSW analyses. Instead, the wood is buried on-site, burned outdoors, or discarded in the "back 40".
- In many urban locations in the U.S., numerous wood waste generators, processors, and solid waste facilities have substantial volumes of wood waste for which they would like to find new end uses and markets. This is especially true in states and regions that have limited solid waste disposal capacity. It is not true in portions of California where there is a relatively large demand for wood fuel, but where there is a decreased supply of wood residue from the forest, due to reductions in the amount of federal land available to harvest.
- One of the largest <u>potential</u> markets for wood waste is fuel. This is especially true for "clean," untreated wood waste, such as forest management residue, landclearing debris, primary wood industry mill residue, pallets, some types of agricultural residue, and dimensional and other untreated lumber. This is often not true for common treated wood materials such as plywood, particleboard, pressure-treated wood, creosote-treated wood, or other wood containing non-wood materials.

BARRIERS TO THE USE OF WOOD WASTE FOR FUEL

The combined experience of wood waste processing facilities, operators of existing wood-fired facilities, and developers of new wood-fired power plants indicate there is substantial interest in using wood waste as fuel. However, concerns about environmental regulations and ash disposal costs are cited as key barriers preventing the use of wood waste as fuel.

Environmental Regulations

In many states, it is uncertain whether regulatory agencies will permit existing or new wood-fired facilities to burn wood waste, especially if the material potentially contains treated wood. This was originally due to concerns about air emissions. However, more recently concern has grown about the potential contents of ash produced by facilities burning treated wood waste.

Although several states have approved the "beneficial" use of ash from untreated wood fuel as soil amendment, compost bulking agent, or fertilizer material, uses of ash from fuel containing significant amounts of treated wood are largely unknown and untested. This is primarily because there is minimal information on the characteristics of ash from the combustion of treated wood. Regulators tend to be most concerned about the potential concentration of heavy metals, organic compounds, and pH in ash produced from the combustion of treated wood.

Ash Disposal Costs

Ash generated by the combustion of treated wood is likely to be required to meet more stringent environmental regulations than untreated wood ash. Regulations regarding treated wood ash may require that the ash be:

- Disposed of in a solid waste facility, specialized landfills, monofills, or monocells;
- Tested periodically to determine the physical, chemical, and environmental characteristics; and
- Tested to determine if it is hazardous. If the ash is hazardous, it must be managed and disposed of as a "manifested" waste.

The impact of environmental regulations on the management or disposal of treated wood ash is significant and can add substantial permitting and testing costs to wood-fired facilities. This in turn may cause it to not be economically feasible to use treated wood for fuel.

In many states, environmental agencies are willing to review data and information from applicants who would like to utilize waste materials such as treated wood ash (rather than dispose of the material.) However, it is generally the applicant's responsibility to supply sufficient information to demonstrate the proposed use of the wood ash will not pose a risk to humans or the environment.

THE REGULATORY PERSPECTIVE ON WOOD ASH

A variety of federal and state regulations address the definition or classification of ash produced from the combustion of untreated or treated wood. Some regulations contain specific definitions and classifications for various types of wood feedstock and ash, while others do not. Regulations that do not specifically address these issues are interpreted through subsequent rulemaking procedures, internal administrative guidance documents, or on a case-by-case basis by regulatory and permitting staff.

Federal Solid Waste Regulations

Federal regulations that apply to wood ash are contained in the Resource Conservation and Recovery Act of 1976 (RCRA) and the Hazardous and Solid Waste Amendments of 1984. RCRA and the 1984 amendments define what materials are classified as "solid" and "hazardous" waste, and establish the regulatory framework under which waste must be managed or discarded.

RCRA defines solid waste "as any discarded material". RCRA does not specifically define wood ash as a solid waste. However, under RCRA all types of discarded material are classified as solid waste, unless the material exhibits any one of four hazardous characteristics (in which case, the material is then classified as hazardous waste). The four characteristics that determine whether a material is hazardous include:

- Ignitability, i.e. the ability to spontaneously combust;
- Reactivity, i.e. the ability to detonate or react violently under normal conditions or when mixed with water, or to release toxic fumes at a pH between 2.0 and 12.5;
- Corrosivity, i.e. does the material have a pH less than or equal to 2.0 or more than or equal to 12.5, or does the material corrode steel at a rate greater than 1/4-inch per year at 55 degrees Centigrade?; and
- Toxicity, i.e. is the material listed by EPA as being toxic, or does it generate a leachate that is deemed to be toxic when tested with the Toxicity Characteristic Leaching Procedure (TCLP)?.

The characteristics that affect whether wood ash is hazardous are corrosivity and toxicity. Although corrosivity generally applies to liquids, in some cases it may also apply to ashes. Many ashes generated during the combustion of wood in utility-scale facilities are wetted (or "quenched") with water to extinguish live embers and to control dust emissions. In addition, ash may be stockpiled outdoors and exposed to precipitation. Free water may leach from ash stockpiles, and the resulting leachate may have a pH in excess of 12.5. Due to the potential for leachate to be produced by ash stockpiles, at least one state (Washington) has established regulations for wood ash that include testing for pH.

RCRA contains an exclusion or exemption for solid waste that may otherwise be classified as hazardous. The exclusion is for resource recovery facilities that manage either household waste or non-hazardous waste from commercial and industrial sources. The exemption has created some controversy, since MSW ash is not specifically included in the exclusion, and MSW ash may otherwise be classified as hazardous under RCRA. The U.S. Environmental Protection Agency (EPA) issued a policy statement in September 1992 (<u>OSWER Policy Directive #9573.00-01</u>) stating that EPA intends to regulate MSW ash as solid, not hazardous waste. This exclusion has implications for facilities that burn treated wood, since they may be permitted as "resource recovery" facilities by state environmental regulators.

State Solid Waste Regulations

Although RCRA applies to all solid (and hazardous) waste generated in the U.S., most states have promulgated solid waste programs and regulations to manage solid waste in their state. State solid waste regulations must be equivalent to, or more stringent than RCRA. Aspects of state regulations that apply to wood ash include:

- Definitions of wood ash. Some state solid waste regulations contain specific definitions for untreated or treated wood ash.

- Provisions for the beneficial use of solid wastes. Some state regulations provide for the beneficial use of a solid waste. An example is the use of wood ash as a liming agent, replacing other materials such as ground limestone. Solid waste that is beneficially used may be exempt from solid waste regulations. However, in order to be beneficially used, the material must not be hazardous, and its use must have minimal or no potential to contaminate groundwater, surface waters, or soil.

WOOD ASH CHARACTERISTICS

A variety of research has been done during the past decade to identify the characteristics of, and potential uses for ash produced by facilities that burn wood fuel. Since most wood-fired facilities currently in operation burn primarily untreated wood, until recently most research has focussed on untreated wood ash.

This is changing, however, due to an ash testing project completed in 1992 and another project that will be completed in 1994. A key research and testing project on treated wood ash was completed by Environmental Risk Limited (ERL) and C.T. Donovan Associates, Inc. (CTD) for the New York State Energy Authority (NYSERDA) in 1992. The final report, Wood Products in the Waste Stream: Characterization and Combustion Emissions contains a comprehensive analysis of technical, regulatory, and public policy issues that affect the processing and combustion of treated wood waste for energy. The report contains data on the physical and chemical characteristics of a variety of wood waste ashes. Much of the ash tested for the study was ashed in a laboratory oven, not in a full-scale, combustion facility. Laboratory ashing produces ashes with different characteristics (i.e. higher levels of potential pollutants) than are expected for ashes generated in full-scale combustion facilities that burn the same types of treated wood.

A new project is now underway by CTD and Resource Conservation Services, Inc. that involves burning various types of treated wood in full-scale utility boilers or in combustion research laboratory boilers. The ash is being sampled and tested for a variety of physical, chemical, and environmental characteristics. The purpose of the project is to determine the potential for beneficially using untreated and treated wood ashes for land application and ash-concrete products.

Presented in Table 1 is a comparison of key characteristics of coal, MSW, and various types of wood ashes. Information in the table is based on the results of multiple research and testing programs compiled by C.T. Donovan Associates, Inc. Based on information presented in the table, the following conclusions regarding ashes from untreated and treated wood can be made.

- The chemical and physical characteristics of wood ash produced by the combustion of treated wood in utility- and industrial-scale boilers differs significantly from other solid fuel ashes (including untreated wood) in several ways. These include: the minerals content such as aluminum and sodium oxides; certain metals such as chromium, copper, and lead; and the ash content when measured as a percent of fuel.

- Wood ashes produced by laboratory ashing procedures do not typically reflect actual boiler operating performance. This is due to differences in combustion efficiency, temperature, rates of fuel drying and pyrolysis, and/or different levels of excess air and in-bed turbulence. In some cases, laboratory tests may yield higher values for certain parameters, while for other parameters values may be lower than ash from actual boilers.

- Some wood products, such as creosote-treated wood and particleboard (which contains organic-based adhesives) may produce ash containing acceptable levels of metals or organics. However other wood products, such as CCA-treated wood (which contains inorganic, metallic-based preservatives) may contain levels of metals or organics that are significantly higher than untreated wood ash.

- Wood ashes generally have higher pH values than coal ash, and lower ash contents (measured as a percent of fuel). Due to the lower ash content, larger proportions of heavy metals and other contaminants may appear in wood ashes than occur in coal or MSW ash.

- The presence of certain mineral oxides in treated wood ash (particularly aluminum, ferric, and silicon oxides) indicate cementitious properties that may have value for use in concrete and other end use products.

- The chemical and physical characteristics of mixed C/D wood ash and specific types of treated wood ash in various products and end uses are generally untested.

WOOD ASH CHARACTERISTICS AFFECTING BENEFICIAL USES

The TCLP analysis is often the first test state regulators require when determining the appropriate management of a waste material, such as wood ash. According to RCRA, waste is considered to be hazardous if the TCLP analysis results in one or more metals exceeding limits established by EPA.

In addition to RCRA, EPA has promulgated regulations pertaining to the use and disposal of sewage sludge and septage (40 CFR Part 503). Commonly referred to as the "Part 503 regulations", the regulations establish the minimum standards sludges from wastewater treatment facilities must meet in order to be land applied. The Part

503 regulations must be adopted as minimum requirements by states. However, states can promulgate more stringent regulations, if it is deemed necessary.

The Part 503 regulations contain two sets of numerical limits for elemental metals that pertain to sludges that are to be land applied. The "ceiling concentrations" establish the upper limit for metals concentrations. The "pollution concentrations" establish more stringent metal concentrations, and sludges that meet these limits receive less regulatory oversight.

In many states, the numerical limits in the federal Part 503 regulations will be adopted and used to regulate the land application of other solid waste materials, such as wood ash, in addition to sewage sludge and septage. Since one of the largest existing and potential end uses for wood ash is land application as a liming agent and/or source of nutrients, the Part 503 regulations are expected to have a direct impact on future wood ash land application activities.

Presented in Table 2 is a compilation of TCLP metals and elemental metal data on various types of treated wood and treated wood ashes. Also presented are regulatory limits for TCLP metals and elemental metals. Regulatory limits for the metals are provided so the data can be compared to the limits, and conclusions can be made regarding the capability of treated wood to meet the limits. Pollution concentrations established in the Part 503 regulations are also presented. Key conclusions are discussed below.

- Both creosote-treated wood feedstock and creosote-treated wood ash produced in a combustion facility (referred to as "facility ash" in the table) meet federal and state regulatory standards for metals and Part 503 concentration levels for land application. This suggests that the feedstock can be regulated and managed as solid waste, and the resulting ash may be land applied or possibly beneficially used in some way.

- Laboratory ash from wood waste feedstock typically meets federal and state regulatory standards for metals and Part 503 concentration levels for land application. Since laboratory ashing tends to produce ash with higher concentrations of metals than a combustion facility, this indicates that ash generated by the combustion of this feedstock in a combustion facility may also meet TCLP requirements and Part 503 concentration levels.

- CCA-treated wood typically exceeds the TCLP limit for arsenic. However, RCRA contains an exclusion from hazardous waste regulations for wood materials that fail TCLP for arsenic, barium, cadmium, chromium, lead, mercury, selenium, silver, endrin, lidane, and methoxychlor. Wood ash may not be classified by states as hazardous solely due to arsenic levels.

- Ashes from the laboratory combustion of feedstock from wood waste processing facilities often exceed TCLP limits for chromium and lead, and may be at the TCLP limit for silver. However, this may not be true for wood waste combusted in full-scale boilers, since the laboratory ashing process does not accurately depict or duplicate combustion conditions in utility- or industrial-scale combustion facilities.

- Elemental analyses of CCA-treated wood indicate concentrations of arsenic and chromium that exceed minimal levels established in Part 503 regulations for land application. Of interest are the levels of arsenic and chromium in CCA-treated wood ash. However, it is not possible to predict the amount of these metals that will be present in ash from full-scale combustion. A useful comparison is the percent concentration of arsenic and chromium in ash from laminated wood, which is 127% and 581%, respectively. If these percentages are applied to CCA-treated wood, the calculated concentrations of arsenic and chromium in the ash will exceed levels established in the Part 503 regulations. A similar comparison for copper suggests that the concentration of copper in CCA-treated wood ash will also exceed levels established in the Part 503 regulations. However, test burns of CCA-treated wood in a full-scale combustion facility are needed to determine this.

- Ash from the combustion of laminated wood in a combustion facility contained a concentration of lead that exceeded levels established in Part 503 regulations. It is unclear what this means, since chips of paint were noted in the laminated wood feedstock and paint is not used in the lamination of wood.

WOOD ASH END USES

Presented in Table 3 is information on existing and potential end uses for ash from untreated and treated wood. The information is based on multiple surveys and interviews of wood ash generators and end users throughout the U.S.

Ash produced from the combustion of untreated wood has been used as a liming agent, source of potash, and nutrients on agricultural land for nearly a decade in several states. The amounts of carbonates, hydroxides, and high pH of wood ash can reduce soil acidity. The application of wood ash can improve agricultural productivity; improve soil conditions for growing turf, shrubs, trees, flowers, and other ornamentals; and may reduce the adverse impacts of acid rain. Other uses, such as sludge compost amendment, sludge odor control, and landfill cover, are expanding as landfill capacity becomes scarce and more expensive.

Existing end uses for ash from treated wood are limited due to concerns regarding contaminants that may potentially be in the ash. A potential large use for wood ash, and in particular treated wood ash, is as an admixture in concrete. Wood ash contains certain cementitious properties. When wood ash is combined with hydraulic cements (i.e. Portland cement), concrete products can be created with various compressive strength characteristics. The resulting ash-concrete product can potentially be utilized as either a low strength concrete or as "flowable fill". Flowable fill is a term that refers to a structural fill material that can be poured into place. An advantage of flowable fill over other structural fill materials is that compaction is not required. This reduces both the time and labor costs required to place the fill.

The combining of treated wood ash with cement may reduce, or eliminate, the potential for heavy metals contained in the ash (i.e. arsenic and chromium) to leach from the ash-concrete material. As hydraulic cement reacts with water (or hydrates), it forms a complex crystalline structure which can bind with or "tie up" metals, thus preventing their potential release. The high pH of ash combined with the lime content of cement also helps prevent the leaching of metals. This is because the metals are maintained in their insoluble hydroxide forms, rather than in their soluble elemental forms.

Potential end uses for low strength concrete include concrete fill for bridge or building decking, and cast concrete products such as road barriers, floor slabs, and concrete fill. Potential end uses for flowable fill include: fill around foundations; structural fill under concrete slabs and footings; structural fill in dams and bridge abutments; fill under or around pipes that are below grade; fill for utility cuts in roads; base material for sidewalks, parking areas, and low-traffic roads; and stream bank stabilization and erosion control.

CONCLUSION

The beneficial use of wood ash is expected to increase in the future as the physical, chemical, and environmental characteristics of the material become better understood. This will be especially true for ash produced from the combustion of untreated wood in state-of-the-art utility- and industrial-scale facilities. It may also be true for various types of treated wood ashes, pending results of further research and testing that is currently underway.

Overall, RCRA regulations and TCLP metal limits are expected to be used by states when developing guidelines and regulations for beneficially using wood ashes for a variety of end uses. The federal Part 503 regulations addressing sewage sludge and septage are expected to provide guidance for states specifically interested in developing guidelines and regulations concerning the beneficial use of wood ashes for land application.

TABLE 1: COMPARISON OF SELECTED CHEMICAL AND PHYSICAL CHARACTERISTICS OF COAL, MSW, AND VARIOUS WOOD ASHES (a)

CHARACTERISTIC	COAL BOILER ASH (b)	MSW INCINERATOR ASH (c)	UNTREATED WOOD BOILER ASH (d)	MIXED C/D WASTE WOOD BOILER ASH (e)	LABORATORY ASH FROM SELECTED WOOD PRODUCTS (f) Creosote Wood	Particle Board	CCA-Treated Wood
1. METALS (Mg/Kg)							
Arsenic	2.3 - 34.0	12.0 - 3,500.0	16.0 - 38.2	23.0 - 78.8	.75 - 15.8	BDL - .38	290.0 - 64,000
Cadmium	0.3 - 10.0	0.18 - 2,840.0	0.63 - 26.3	0.21 - 2.7	0.1 - 5.0	BDL - .1	BDL - .2
Chromium	14.0 - 218.6	12.0 - 5,710.0	12.5 - 92.0	20.0 - 209.0	BDL - 32.5	BDL	1740.0 - 41,000
Copper	1.5 - 820.0	40.0 - 10,900.0	40.0 - 154.5	258.0 - 1,050.0	4.0 - 191	BDL	1040.0 - 39,000
Lead	3.1 - 210.7	31.0 - 13,500.0	3.0 - 133.0	29.2 - 671.0	8.0 - 717	BDL	2.1 - 13.0
Mercury	BDL - 1.37	BDL - 300.0	BDL - 0.65	BDL - 0.63	BDL	BDL	BDL - .11
Nickel	4.5 - 330.0	13.0 - 12,910.0	9.0 - 55.5	45.0 - 109.0	BDL - 47	BDL	BDL - .73
Zinc	0.9 - 1,500.0	92.0 - 46,000.0	26.0 - 800.0	44.4 - 1,320.0	8.0 -1,200	8.0 - 11.5	3.6 - 20.0
2. MINERALS (Percent Dry Weight Basis)							
Aluminum Oxide	20.0 - 60.0	5.9 - 13.0	8.7 - 11.2	4.32 - 14.0	4.0 - 7.1	1.5 - 6.0	0.4 - 6.6
Ferric Oxide	5.0 - 25.0		4.0 - 5.9	3.7 - 10.8	21.1 - 22.6	1.7 - 4.0	0.7 - 7.0
Silicon Oxide	40.0 - 90.0	19.0 - 62.9	38.2 - 76.9	26.5 - 65.5	19.7 - 33.0	7.0 - 25.6	0.4 - 7.3
Sodium Oxide	0.5 - 3.0		1.5 - 1.6	1.5 - 5.0	1.6 - 16.0	4.0 - 21.1	0.4 - 0.6
Potash	0.5 - 3.0		1.7 - 8.0	1.8 - 5.6	2.0 - 2.4	7.0 - 13.4	2.0 - 2.6
3. ASH CONTENT (As % of Fuel)	4.1 - 40.8	15.9 - 30 (h)	0.5 - 5.0	0.24 - 31.2	1.2 - 1.7	0.20 - 0.90	0.9 - 3.8
4. pH	3.5 - 5.0	9.0 - 11.8	9.0 - 13.5	8.0 - 13.0	11.0 - 13.5		
5. LOSS ON IGNITION (% organic carbon)	3.5 - 16.2	0.4 - 5.32 (g)	1.1 - 73.9	NT	NT	NT	NT
6. MOISTURE CONTENT (% weight)	1.8 - 7.3%	20.0 - 37	35.5 - 67.0%		1.01		
7. GRAIN SIZE (in millimeters)	.015 - .30		.075 - 75.0	NT	NT	NT	NT
8. SPECIFIC GRAVITY	2.53 at 20 deg C	2.5 - 2.6	1.5 - 2.5	NT	NT	NT	NT

BDL = Below Detectable Limit

NT = Not Tested

(a) Prepared by C.T. Donovan Associates Inc., Burlington, VT, 1993.

(b) Based on data from Envirosphere Company, Sacramento, CA, 1985; Tillman, D.A. Ebasco Environmental, Bellevue, WA, 1991; Coleman, P.M, RCS Inc., Brunswick, ME, 1992.

(c) Based on data from Envirosphere Company, Sacramento, CA, 1985; Tillman, D.A. Ebasco Environmental, Bellevue, WA, 1991; Coleman, P.M., RCS Inc., Brunswick, ME, 1992.

CHARACTERISTIC	PLYWOOD (Facility Ash)	FURNTITURE WASTE (f)	LAMINATE (f)
1. METALS (Mg/Kg)			
Arsenic			
Cadmium			
Chromium			
Copper			
Lead			
Mercury			
Nickel			
Zinc			
2. MINERALS (Percent Dry Weight Basis)			
Aluminum Oxide	0.75 - 1.93	15.0	9.5
Ferric Oxide	1.03 - 1.71	6.5	2.5
Silicon Oxide	4.0 - 9.2	12.4	18.4
Sodium Oxide	2.88 - 7.96	4.8	1.6
Potash	0.92 - 18.4	6.0	2.9
3. ASH CONTENT (As % of Fuel)	0.36 - 1.38	0.96	1.35
4. pH			
5. LOSS ON IGNITION (% organic carbon)	19.6	7.2	

BDL = Below Detectable Limit

NT = Not Tested

(d) Based on data from Coleman, P.M., and Peterlein, W., RCS, Inc., Brunswick, ME, 1991; Campbell, A.G., University of Idaho, Moscow, ID, 1991; Envirosphere Company, Sacramento, CA, 1985; Tillman, D.A. Ebasco Environmental, Bellevue, WA, 1991; Coleman, P., RCS Inc., Environmental Risk Limited, Bloomfield, CT, 1990; White, R.K & Rice, J.S., Tennessee Valley Authority, 1992; Greene, W.T. OMNI Environmental, Beaverton OR, 1988; Naylor, L.M. and Schmidt, E.J., Dept of Agricultural Engineering, Cornell Univesity, Ithaca, N.Y.; and Etigieni, L., et al., Univeristy of Idaho, Moscow, ID, 1990.

(e) Based on data from: Coleman, P.M., RCS, Inc. 1992; Enseco Inc., West Sacramento, CA, 1987; Commercial Testing & Engineering Co., Long Beach, CA; 1986; Environmental Risk Limited, Bloomfield, CT, 1991; and Miles, T.R., Portland, OR, 1992. This represents ash data from several wood-fired facilities that burn a mixture of C/D or "urban" wood waste.

(f) Based on data from Energy Factors, Marysville, CA, 1988; and, Environmental Risk Limited, 1991. These data are from laboratory ash tests in graphite furnaces of specific wood product fuel samples. For several reasons, the values of wood ash burned in a laboratory may not resemble actual boiler operating conditions. This is a result of differences in temperature, rate of pyrolysis, amount of excess air, and other factors.

(g) Measured via total organic carbon (TOC).

(h) Varies greatly depending on if iron-based materials are removed, and if over-sized materials are removed.

TABLE 2: TCLP METALS AND ELEMENTAL METALS ANALYSES FOR VARIOUS TYPES OF TREATED WOOD AND ASH (a)

METAL	REGULATORY LIMITS	CREOSOTE-TREATED (b)		PRESSURE-TREATED (c)		PARTICLEBOARD (d)		PLYWOOD	
		Wood	Facility Ash (i)	Wood	Laboratory Ash (j)	Wood	Ash	Wood	Ash
TCLP METALS (mg/l) (k)									
Arsenic	5	BDL - 4.3	BDL	BDL - 8					
Barium	100	0.076-0.140	0.35	BDL					
Cadmium	1	BDL	0.22	BDL					
Chromium	5	BDL -0.93	BDL	0.4 - 4.1					
Lead	5	0.010-0.042	1.44	BDL					
Mercury	1	0.031-0.084	BDL	BDL					
Selenium	5	BDL	BDL	BDL					
Silver	0.2	BDL	BDL	BDL					
Aluminum	N/A		3.93						
Beryllium	N/A		0.002						
Copper	N/A		0.76						
Iron	N/A		0.69						
Manganese	N/A		13.5						
Nickel	N/A		0.40						
Zinc	N/A		40.4						
ELEMENTAL METALS (mg/kg) (l)									
Arsenic	41	0.75 - 1.5	BDL -15.8	BDL -2,050	26000-64000	BDL -0.38		BDL - 7.2	
Barium		14.5 -25.2	196 - 580	3 - 580		9.1 -27.4		1.2 -11.1	
Cadmium.	39	0.1 -0.14	0.72 - 5	BDL - 5.0		BDL - 0.1		BDL - 0.1	
Chromium	1,200	BDL	20 -32.5	20 -2,357	4000 -41000	BDL		0.3 - 8.5	
Copper	1,500	4 - 8.5	55 -191.0	64.5 -1,073	24000-39000	BDL		1.1 - 2.5	
Lead	300	8 -39.5	45 -71.7	1.2 - 13		BDL - 6.5		0.7 - 75	
Mercury	17	BDL	BDL	BDL -0.11		BDL		BDL -0.16	
Titanium		2.5 - 2.9		BDL - 18		BDL -0.87		0.2 - 1.2	
Nickel	420	BDL	17 - 47	BDL -0.85		BDL		BDL - 0.5	
Zinc	2,800	8 -91.5	157 - 820	3.7 - 20		7.5 -11.5		7 - 8.5	
Silver		BDL -0.05	BDL	BDL -20.1		BDL		BDL	
Selenium	36		BDL						
Boron			230						
Molybdenum	18								

(a) Data compiled by C.T. Donovan Associates, Inc. from published and unpublished ash characterizations, 1993.

(b) Creosote-treated railroad ties and telephone poles.

(c) Chromated copper arsenate (CCA) treated wood, including some CCA-treated fire retardent wood.

(d) Both soft and hard wood particleboard.

(e) Laminated wood panels.

(f) Scraps from furniture manufacturing including glued sheets, hardwoods, laminated wood, and wood composites.

(g) Combined data from six different wood waste processors.

(h) Combined data from two facilities permitted to burn wood waste.

TABLE 2: (Continued)

LAMINATED WOOD (e)		FURNITURE (f)		PROCESSOR (g)		WOOD WASTE FUEL (h)	
Wood	Facility Ash	Wood	Ash	Wood	Laboratory Ash	Wood	Laboratory Ash
					BDL - 3.7		BDL
					BDL - 1.1		1.4 - 2.4
					BDL		BDL
					1.1 - 46		0.26 -0.94
					BDL - 14		0.006-0.42
					BDL		BDL
					BDL		BDL
					BDL - 0.2		BDL
3.3	7.5	BDL		0.46 -262.5	158 - 2933		28.5 -78.8
70	2,330	10		15 - 630	1067.5-10658.9		875 -1465
0.08	1.3	BDL		0.25 -2.00	9.7 - 43.9		0.025-0.21
21	143	BDL		2.5 - 233	340 -5760.9		82 - 209
3	69.5	2.5		4.0 -3300	329.8 -2536.6		258 -1050
85	1,850	BDL		22.91-1300	2281.6-21413.3		86 - 438
BDL	0.45	BDL		0.03 -0.13	1.2 - 6.1		0.125
2.8	168	2.9			6413.6-11148.8		250 -4790
BDL	35.5	BDL		2.0 - 53	96.9 - 390.2		45.5 -61.5
16	400	7		2.5 - 800	1864.8-8843.5		280 - 850
0.6	0.22	BDL		0.03 - 2.5	1.9 - 69.8		0.31 -2.35

(i) Facility ash refers to ash generated by the combustion of wood in an industrial, commercial, or utility facility.

(j) Laboratory ash refers to ash generated by ashing wood in a laboratory setting with little or no control of operating parameters such as excess air and fuel feed rate.

(k) Concentration of metals in the Toxicity Characteristic Leaching Procedure (TCLP) extraction fluid following extraction. Regulatory limits established by the U.S. EPA and promulgated in 40 CFR Part 261 on March 29, 1990 as part of the Resource Conservation and Recovery Act (RCRA).

(l) Elemental metals in ash on a dry weight basis. Regulatory limits have been established by the U.S. EPA and promulgated in 40 CFR Part 503 on February 19, 1993 as part of the Clean Water Act.

TABLE 3: EXISTING AND POTENTIAL END USES FOR WOOD ASH

PRODUCTS	END USES	MARKETS
	UNTREATED WOOD ASH - EXISTING USES	
Agricultural liming agent	Increases soil pH	Sold or given to farmers
Fertilizer	Adds macro and micro nutrients to soil	Sold or given to farmers
Sludge compost amendment	Increases solids content of compost mixture Odor reducing agent	Sold or given to municipal or private compost facilities to replace sawdust or wood chips
Charcoal binding agent	Charcoal production	
Landfill cover	Cover material for landfills	Direct or partial replacement for native soils
	UNTREATED WOOD ASH - POTENTIAL USES	
Water treatment	Clarifying agent for drinking water or other water	Replacement for clarifying agents
Wastewater adsorbent	Treatment of domestic and industrial wastewaters, including landfill leachate	
Liquid waste absorbent	Absorbent for liquid spills including gasoline and oil	As carbon content increases, absorbancy increases
Hazardous waste solidification agent	Solidifies semi-solid hazardous wastes	Replacement for lime, clay, and cement kiln dust
Lightweight fill	Fill in roadway bases, parking areas, and structures	Replaces other fine aggregates
Asphalt mineral filler	Fine aggregate in road asphalt	Use depends on gradation and
Mine spoil amendment	Added to coal and clay mine spoil to adjust pH	Amended spoil is used during mine reclaimation
	TREATED WOOD ASH - EXISTING USES	
Road base aggregate	Fine aggregate in road bases	Replaces fine aggregate
Landfill cover	Cover material for landfills	Direct or partial replacement for native soils
Filler in adhesives	Added to plywood adhesive to decrease the total amount of adhesive required	Filler in adhesives for wood products
Agricultural liming agent	Increases soil pH	Sold or given to farmers
	TREATED WOOD ASH - POTENTIAL USES	
Ash-concrete	Mixed with cement to produce low strength concrete products	Replacement for concrete in low strength applications

Prepared by C.T. Donovan Associates, Inc., 1993.

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WOOD ASH TO TREAT SEWAGE SLUDGE FOR AGRICULTURAL USE

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Abstract

About 90 percent of the three million tons of wood ash generated in the United States from wood burning facilities is being landfilled. Many landfills are initiating tipping fees and/or restrictions on the disposal of special wastes such as ash. The purpose of this work was to evaluate (1) the feasibility of using wood ash to stabilize sewage sludge and (2) the fertilizer and liming value of the sludge/ash mixture on plant response and soil pH.

Research showed that wood ash, when mixed with sludge, will produce a pH above 12.0, which meets U.S. EPA criteria for pathogen reduction for land application on non-direct food chain crops. Different ratios of wood ash to sludge mixtures were tested and the 1:1 ratio (by weight) was found to be optimal. Five replications of wood ash from four sources were tested for moisture content, pH and fertilizer nutrients. The pH of the ash/sludge mixture (1:1) on day one ranged from 12.4 to 13.2. In most cases the pH remained the same over a 21 day test or only dropped 0.1 to 0.3 units. Analyses of the mixtures showed that heavy metal concentrations (As, B, Cd, Co, Cr, Cu, Mn, Mo, Ni, Pb, S, Se, Zn) were low. The 1:1 ash/sludge mixture had a calcium carbonate equivalency of 17 percent. Green house pot studies using tall fescue grass were loadings of 300 to 750 pounds per acre of TKN-N than for 500 lb/acre of 10-10-10 commercial fertilizer. Plant tissue analysis showed N, P, K, Ca, and Mg levels to be within the sufficiency range for tall fescue.

Wood Ash to Treat Sludge for Agricultural Use

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Introduction

It is estimated that three million tons of wood ash are produced each year in the United States by wood burning facilities. About 90% of wood ash generated is landfilled. The physical and chemical properties of the wood ash present problems in landfills.

The most widely used alternative to landfills is land application as a soil amendment. Research has shown that wood ash has a liming effect on land. Normally, no organic chemical or heavy metal limitation exists for land applying wood ash. The major constraints to land applying wood ash are transportation costs, low fertilizer analysis and handling constraints, e.g. dustiness when dry or caking if wet.

Processes have been developed utilizing alkaline material to stabilize and/or reduce the moisture content of sewage sludge prior to use as a soil amendment. Alkaline stabilization has been approved by the U.S. EPA as meeting the pathogen reduction criteria for a Class B sludge. Class B criteria requires that the sludge/alkaline material mixture maintain a pH of 12.0 for at least 2 hours.

The land application of sewage sludge (biosolids) has become a common practice in which the application rate is controlled by the amount of nitrogen, phosphorus or heavy metals in the sludge. The U.S. EPA has developed criteria for the beneficial and safe application of biosolids to cropland. When applying an alkaline stabilized sludge an additional constraint may be the liming effect in which the soil pH is raised above 7.0 where deficiencies of some plant nutrients may occur.

The objective of this research was to evaluate the feasibility of using wood ash to stabilize sewage sludge, i.e. determine what mix ratio of wood ash to sludge is needed to meet the elevated pH requirements for Class B biosolids. A secondary objective was to evaluate the fertilizer and liming value of the wood ash to sludge mixture on soil pH and plant response.

Results and Discussion

The pH of the wood ash from five different sources ranged from 10.4 to 13.5. It was noted that the fly ash usually has a higher pH than the bottom ash.

Ash/Sludge Analyses

Screening tests were conducted to determine which mix ratios (1:3, 3:5, 1:1, 5:3, 3:1) of wood ash to sludge gave suitable handling characteristics and what was the resultant pH. It was determined that a mixing time of 1.5 minutes provided the blending of the ash and sludge to give a pH above 12. Mixing times of three minutes or longer should be avoided because the mixture would 'ball-up.' The optimum mix ratio of ash to sludge based on handling characteristics and pH adjustments was 1:1. Tests using five replications were conducted using fly ash from four sources. Table 1 presents the average values for moisture content, pH and fertilizer elements of the ash/sludge mixtures on day one and after three weeks.

The pH of the ash/sludge mixture (1:1) on day one ranged from 12.4 to 13.2. In most cases the pH stayed the same or only dropped from 0.1 to 0.3 units in 21 days. For the Craven County ash (electric power plant), the pH dropped from 12.8 to 11.8 in 21 days.

A review of the fertilizer elements in the ash/sludge mixture shows that the relative amount of potassium is high in relation to the nitrogen and phosphorous. Nitrogen is low relative to the phosphorous. The amount of calcium and magnesium in the material gives the ash/sludge mixture good liming properties.

Mixtures of bottom ash and sludge were prepared and tested. Dry (unquenched) bottom ash had similar pH reaction to fly ash. The values for the fertilizer elements were similar to the fly ash/sludge mixtures.

Table 1. Average values for fertilizer parameters of sludge and different fly ash with sludge (1:1) mixture[1].

	Day	Moisture Content	pH	TKN	NH3	PO_4	K	Ca	Mg
		%		mg/g(wet basis)					
Sludge	-	86.4	6.2	10.1	-	4.13	2.0	2.02	1.4
Prosperity Ash	1	41.3	12.4	2.64	0.12	4.90	23.1	76.0	6.84
	21	33.3	12.3	4.94	0.09	5.89	22.4	65.0	7.24
Macon Ash	1	35.6	13.2	2.37	0.12	6.19	52.7	290	10.9
	21	34.0	13.2	4.92	0.07	6.86	54.3	252	10.3
Rabun Ash	1	37.2	12.2	2.41	0.16	2.77	18.2	94.0	4.08
	21	27.9	12.1	8.36	0.13	4.76	20.4	128	4.92
Craven Ash	1	43.2	12.8	3.82	0.03	4.43	18.7	75	5.0
	21	47.6	11.8	4.88	0.048	4.61	20.8	75	4.5

1. Five replications for each treatment, except two for sludge.

Metal Analyses

A series of metal analyses are presented in Table 2. A comparison of the Prosperity and Macon fly ash and bottom ash data indicated an increase in the bottom ash concentrations of Cd, Cu, Pb and Zn. Selenium was the only metal with a markedly higher concentration in the bottom ash than in the fly ash. Metal analyses of a 1:1 mixture of four fly ashes with sludge are also reported. A comparison of metal levels for fly ash alone with the levels in the ash/sludge mixture showed that the sludge contributed to an increase in Cd, Cr, Cu, Ni, Pb and Zn levels. The level of metals in the wood ash/ sludge mixture are all well below the level that would restrict land application.

Table 2. Metal analyses of fly ash and 1:1 mixture of fly ash/sludge

Metal	Fly Ash[1]	1:1 Mixture[1]
As	8	<6.8
B	135	135
Cd	3	7
Co	7	6
Cr	14	21
Cu	52	102
Mn	0.43%	0.42%
Mo	<0.1	<0.3
Ni	14	18
Pb	39	52
S	0.38%	0.51%
Se	<0.5	<2.8
Zn	187	318

1. Mean values for wood ash from four sources.

Soil and Plant Studies

Prosperity fly ash was mixed with sludge on a 1:1 basis for soil and plant growth tests. The ash/sludge mixture was held for 21 days prior to conducting the soil and plant tests. The concentration of the fertilizer and liming parameters in the mixture were as follows: moisture content = 25.9%, pH = 12.3, TKN = 5.08 mg/g, ammonia-N = 0.04 mg/g, P =

3.25 mg/g, K = 48.7 mg/g, Ca = 91.5 mg/g and Mg = 48.7 mg/g. Rates of 1 to 10 ton/acre of wood ash/sludge mixture were applied to 6 soils of varying textures (pot study). Lime applied to 2 of the soils revealed that the mixture had a calcium carbonate equivalency of approximately 17%.

On lighter texture soils, a pH of 7.0 is exceeded with relatively low rates of the wood ash/sludge mixture. The maximum amounts which can be safely applied would be 4 ton/acre for the sand, 5 ton/acre for the loamy sand, and 7 ton/acre for the sandy clay loam.

A greenhouse pot study was conducted with wood ash sludge mixture applied to tall fescue grass at rates equivalent to 0 to 750 lb TKN-N/acre in 150 lb increments on Iredell sandy loam and Cecil sandy clay loam. A fertilizer treatment of 500 lb/acre of 10-10-10 with 1 ton/acre lime was included. The study was replicated 4 times. The above ground plant material was harvested when the average height was 12 in. Statistical analysis revealed no interactions with soil; average results across soils are reported in Table 3.

Dry matter yields increased with increasing rates of TKN-N. No toxicity symptoms were observed in any of the pots.

Table 3. Dry matter production of tall fescue with various rates of wood ash/sludge applied to give the shown TKN-N rates in lb/acre. Dry matter yields are in grams/pot.

TKN-N rate (lb/acre)	Ash/Sludge (1:1) Application Rate (tons/acre)	Harvest 1 dry matter (g/pot)	Harvest 2 dry matter (g/pot)
0	0	0.21c*	0.47e
150	15	0.88b	2.80cd
300	30	0.89b	4.11c
450	45	1.18ab	5.86b
600	60	1.22a	6.84b
750	75	1.38a	9.22a
Fertilizer	N.A.	0.88b	1.80de

* Means within columns followed by different letters are significantly different at the 0.05 probability level.

Plant tissue samples were analyzed for N, P, K, Ca, and Mg. No interaction with soil was detected in the analysis. Most of these values were within the sufficiency ranges for tall fescue. The N contents for the 750 lb of TKN-N/acre and fertilizer treatments are slightly below the range. Some K values are below the lower end of the sufficiency range, although only the fertilizer treatment was significantly below 1.5. These results suggest that the expected toxicity of the higher rates of the wood ash sludge mixture may not occur.

Conclusions

Mixing wood ash with sewage sludge cake on a 1:1 basis raised the pH of the mixture above 12.0 in most cases. The pH remained above 12.0 for an extended period of time, up to 25 days in some of the tests conducted. Wood ash can be used for alkaline stabilization to meet Class B pathogen reduction.

The potassium level in the ash/sludge mixture was high relative to nitrogen and phosphorous fertilizer nutrient levels. Metals in the ash/sludge mixture were determined and their levels allow land treatment without any major constraints.

Large applications of the ash/sludge mixture to sand, loamy sand and sandy clay loam soils should be controlled so that the pH is not raised above 7.0. The ash/sludge mixture had a calcium carbonate equivalency of 17%.

Greenhouse pot studies using tall fescue plants with loadings of TKN-nitrogen up to 750 pounds per acre showed increasing dry matter yields. Yields were significantly higher than 500 pounds per acre of commercial fertilizer for loadings of 300 to 750 pounds per acre of TKN-N in the ash/sludge mixture. No toxicity symptoms were observed in any of the pots. Plant tissue analysis for N, P, K, Ca and Mg showed these values to be within the sufficiency range for tall fescue.

Pilot Scale Cotton Gin Trash Energy Recovery

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Abstract

During the summer of 1992 a 520,000 kcal/h (2,064,400 Btu/hr) biomass combustor was installed at a cotton gin in southwestern Oklahoma. The gin has a capacity of approximately 35 bales per hour. Each bale of cotton ginned weighs about 227 kg (500 lb) and produces about 68 kg (150 lb) of trash. Therefore, this gin produces about 52,360 kg (115,500 lb) of trash per day during a typical ginning season. Approximately 2 million kg (4 million lb) of gin trash are produced at this site each year.

Cotton must first be dried to about 3-5% moisture content before the ginning process is begun. To accomplish this at this gin, two six million Btu/hour direct fired gas heaters are used to heat air for drying the cotton. The biomass combustor was installed to operate in parallel with one of the heaters to supply heated air for the drying process. A pneumatic conveying system was installed to intercept a portion of the gin trash and divert it to the burner. The burner was operated during the 1992 ginning season, which lasted from September through November, with few problems.

This project was supported in part by Western Area Power Administration, Oklahoma Department of Commerce and the Oklahoma State University Center for Energy Research.

Introduction

Ginning of cotton produces a large quantity of waste materials commonly called gin trash. This gin trash consists of cotton plant parts such as leaves, stems, burs, cotton lint, immature seeds, and soil particles. The amount and makeup of gin trash are a function of the harvesting method used. There are two types of mechanical harvesters commonly used, spindle pickers and strippers. Spindle pickers use rotating spindles to remove the cotton lint from the cotton boll while strippers remove the entire boll from the plant. Consequently, spindle picked cotton contains much less foreign matter than does stripper picked. In general, for each bale of spindle picked cotton ginned approximately 68 kg (150 lb) of gin trash will be produced while stripper picked cotton will yield about 318 kg (700 lb) of gin trash. Table 1 lists components of typical cotton gin wastes and Table 2 describes some of the chemical properties.

Table 1. Components of Cotton Gin Waste *

Lint (%)	11.1
Burs (%)	48.6
Sticks (%)	8.4
Fine (%)	32.1

* from Schacht and LePori (1978)

Table 2. Chemical Properties of Cotton Gin Trash (dry basis) *

Volatile Matter (%)	85.0
Carbon (%)	42.0
Hydrogen (%)	5.4
Nitrogen (%)	1.4
Sulfur (%)	1.7
Arsenic (%)	
areas applying arsenical desiccants	0.02
areas not applying arsenical desiccants	0.001
Oxygen and Error	34.5

* from Schacht and LePori (1978)

The ginning of seed cotton is essentially a process of removing unwanted materials from the cotton lint. This is a highly mechanized process using numerous pieces of rotating machinery to separate the lint from foreign materials. Each piece of ginning machinery is designed to remove specific types of foreign materials from the lint. The waste streams from these machines are usually transferred out of the gin by a combination of augers and pneumatic conveying devices. Cyclone separators are used to remove the gin trash from the pneumatic conveying system. The waste is usually stored in a gin trash facility called a bur house which is typically remote from the gin. The bur house consists of overhead bins which store the gin trash to be loaded into trucks for disposal.

In 1991 slightly more than 17 millions bales of cotton were produced in the U.S. on approximately 12 million acres of cropland (United States Department of Agriculture, 1992). About 250,000 bales of cotton were produced on 380,000 acres in Oklahoma in 1991 (Oklahoma Department of Agriculture, 1991). Since most cotton in Oklahoma is stripper harvested, at approximately 318 kg (700 lb) per bale this represents 91 million kg (175 million lb) of gin trash that must be disposed of. Common methods of disposal include land filling, land application and as cattle feed. Until air pollution regulations all but stopped the practice, a large amount of gin trash was burned in incinerators or open pits at the gin site.

Using an adiabatic bomb calorimeter, Griffin (1976) determined that the gross heat value of gin trash ranged from 16.67 to 19.59 MJ/kg (7167 to 8422 Btu/lb) with an average value of 18.44 MJ/kg (7929 Btu/lb). To correct for moisture content at typical harvest conditions he recommended multiplying the average value of 18.44 MJ/kg by .87. This yields a net fuel value of 16.04 MJ/kg (6897 Btu/lb) which is consistent with results published by Schacht and LePori (1978) who suggest a value of 15.5 MJ/kg (6664 Btu/lb) for engineering design purposes. A mean ash content of 14.47 % reported by Schacht and LePori (1978) from west Texas stripper harvested seed cotton is somewhat higher than values reported by Griffin (1976) from gin trash collected from mid-south gins.

During the summer of 1992 a commercially produced pyrolytic combustor was installed at a newly constructed cotton gin located in southwestern Oklahoma. The combustor was purchased from a German firm sold under the trade name of ***Bioflamm.*** The model purchased is rated at 520,000 kcal/h (2,064,400 Btu/hr).

System Description

The prototype trash combustor system consists of five components or subsystems:

1. Pneumatic conveyor
2. Fuel storage and metering
3. Combustor
4. Heat exchanger
5. Cyclone particulate collector

A schematic in plan view is shown in Figure 1 and in cross section in Figure 2.

Pneumatic Conveyor

The pneumatic conveying subsystem consists of a rotary air lock metering device to intercept gin trash from the bottom of a U-tube auger conveyor and introduce it into the suction side of the pneumatic conveyor. The material is then transported to a cyclone separator that feeds the material directly into the fuel storage bin. The rotary air lock is activated by a controller at the fuel storage bin that signals the rotary air lock to operate when the bin level falls to a pre-selected level. The storage bin has a capacity of .5 m^3 (17.6 ft^3) and has an inclined variable speed metering auger. The metering auger supplies fuel to the combustor through a rotary air lock that also serves as a fire lock.

Pyrolytic Combustor

After the fuel passes through the rotary fire lock it is conveyed directly into the combustor by a feed auger. The fuel is placed directly onto the first of three moving grates that move the material through the combustor. The operating principles are as follows: The pyrolytic reaction occurs in an oxygen deficient atmosphere where a fraction of the volatiles are withdrawn from the reactor and mixed with a small amount of combustion air and is then reintroduced back into the hot floor grate where heavy gas components are cracked into light molecules. At the exhaust end of the combustor secondary air is introduced into the gas stream for combustion. Both primary and secondary air is supplied with a blower. Adjustable dampers are used to regulate total air flow as well as the ratio between primary and secondary combustion air. The heat of reaction is used to heat an air-to-air heat exchanger.

Heat Exchanger

The exhaust stream from the combustor is directed into the combustion chamber of a modified King Model TDM 200 D hot air furnace. The furnace was obtained without a burner and is used as an air-to-air heat exchanger. The TDM 200 D has a rated input value of 2636 MJ (2,500,000 Btu). The heat exchanger uses a 7.46 kW (10 hp) blower to move the air. This air is ducted into the cotton dryer duct system of the gin. An adjustable damper is used to regulate air flow through the heat exchanger.

Cyclone Particulate Collector

Exhaust from the heat exchanger is directed into a double cyclone particulate collector. The cyclone collector not only removes some of the patriculates but also has a blower that acts as a draft stabilizer for the combustor.

Conclusions

The combustor was operated during the 1992 ginning season which lasted from September through November. The harvest was considerably shorter than normal due to nearly perfect weather conditions. The system performed with few mechanical problems. One problem encountered was plugging of materials as they left the metering auger. Gin trash usually contains some cotton lint and is therefore highly compressible. When using auger conveyors to move gin trash, it is customary to provide some space for the material to expand after exiting the auger. The metering auger of this system did not provide this expansion space and consequently tended to plug occasionally. The equipment was designed to detect plugging and included a safety switch to automatically shut down the fuel feed mechanism when it occurred. A modification to the metering auger to provide an expansion chamber will correct this problem.

The exhaust cyclone particulate collector is rated for a maximum inlet temperature of 350 °C

(662 °F) and this was easily reached at low fuel feed rates. This appears to be a fairly serious limitation in that the combustor could not properly gasifiy the biomass at such low feed rates. This led to some smoke production and thus limits the amount of biomass that can be utilized by the system. Slag formation reported by other investigators did not occur with this equipment. This is probably due to the relatively low operating temperature required by the exhaust cyclone.

No attempt was made to measure fuel feed rate or heat output from the system during the first year of operation. This is scheduled to be done next ginning season. In addition the fuel metering auger will be modified to prevent plugging.

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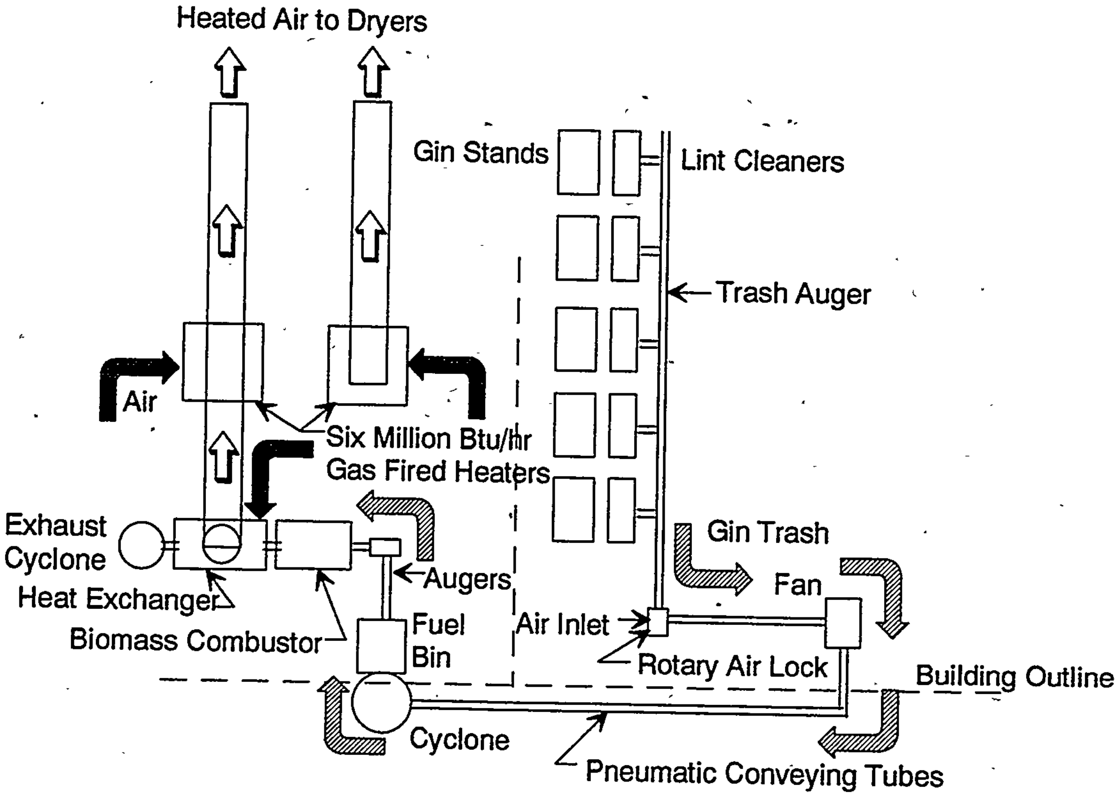

Figure 1. Schematic plan view of equipment

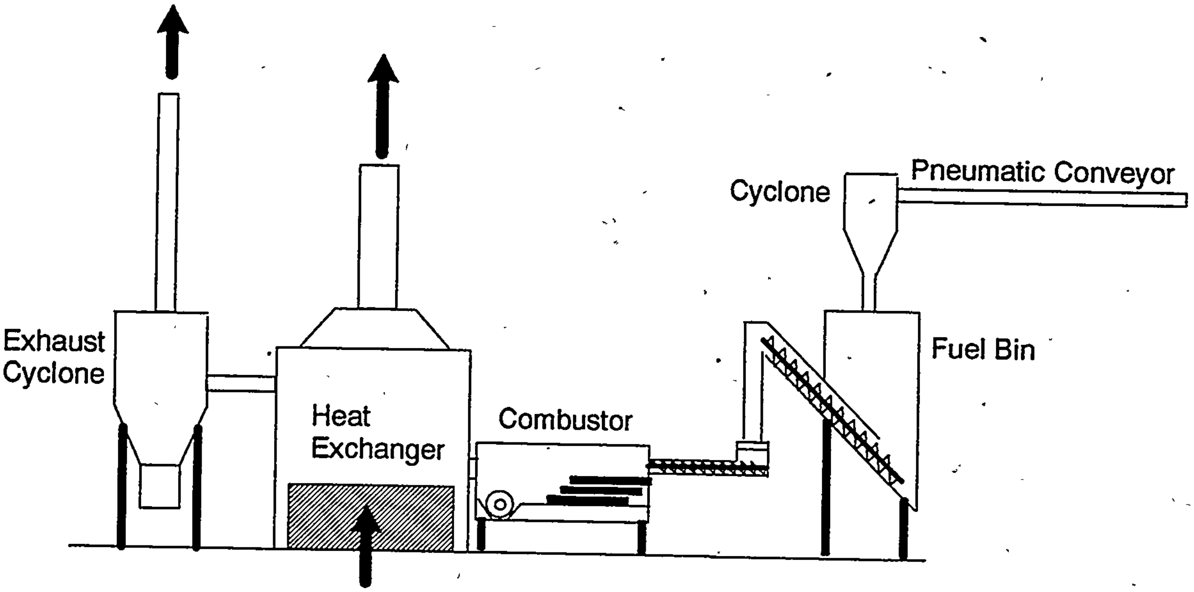

Figure 2. Schematic cross-section view of equipment

Direct Observation of the Release of Alkali Vapor Species in Biofuel Combustion and Gasification

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Abstract

The largest present use of biomass for energy is in combustion for steam and electrical power. Biofuels have an acknowledged advantage over coal as a solid fuel because of their low sulfur and ash content. However, some forms of biomass have substantial quantities of alkali metals and chlorine. In addition, evidence indicates that the alkali in biomass is largely atomically dispersed, resulting in its facile mobilization into the gas-phase. Gaseous alkali compounds aggravate problems of slagging, fouling, and corrosion on heat transfer surfaces in present-day boilers. These problems can be particularly severe when mixed and variable agricultural residues are burned. Furthermore, the next generation of biomass-to-power systems will likely involve combined cycle gas turbines, where alkali tolerances are especially restrictive.

In this paper, we report on laboratory studies in which biofuels are combusted under simulated turbine or boiler-firing conditions. Gaseous alkali, sulfur, nitrogen, and halogen-containing species are measured by direct extraction from the hot gases through molecular-beam mass spectrometry (MBMS). The experimental apparatus will be described and its capability illustrated with results of time-resolved evolution of species like K, KCl, KOH, SO_2 and NO_x from small samples of biomass in combustion environments. The nature and release of such species will be explicated by referring to thermodynamic equilibrium predictions and information on the form of alkali in solid, gaseous, and liquid biofuels.

Introduction

Biomass residues have been combusted in boilers for many years to raise steam for heat or electricity. Most often such use has been within the primary or secondary forest products industry burning fairly consistent and characterized feeds. More recently, under the stimulus of the Public Utilities Regulatory Policies Act (PURPA), a dramatic increase in grid-connected, biomass-fired power plants has occurred.(1) One consequence of this increase is the use of lower quality fuels instead of the "good" wood fuels of choice. In particular, crop residues such as wheat straw can have considerable alkali and chlorine, both of which are known to foul, slag and corrode (2). A special conference contains papers giving a broad overview of problems experienced in California (3) and a special issue of Biomass and Bioenergy (2) includes papers on mineral matter behavior.

Based on coal experience, the likely nature of alkali in biomass and a model of the mechanisms of alkali transport to hot surfaces (4), we expect that vapor release of alkali in biomass combustion could be a significant factor. Such a release is even more critical at the higher temperatures experienced in turbine based systems. (5) As a consequence of these issues, the Biomass Power Program of DOE (6) is supporting a laboratory study to identify and measure the alkali and chlorine containing vapor species released from a wide variety of feedstocks under simulated combustion and gasification conditions. This poster describes the experimental approach and preliminary screening results for a number of representative feedstocks.

Experimental Approach

Our approach to alkali vapor speciation is to apply the nearly universal detection capability of direct, molecular-beam, mass spectrometry (7) to extracting and identifying species from laboratory flow reactors. Small samples (about 30-50mg) of solid biomass are inserted into flowing He - O_2 preheated to 1100°C (for preliminary screening) and the evolution of vapor species with time is monitored.

Results

Figure 1 shows typical evolution profiles for the major species from switchgrass, a favored dedicated energy crop, but also representative of high alkali, high chlorine crop residues. The relative scales of the intensity axes are meaningless: only the time evolution is to be interpreted. In later work, the instrument will be calibrated to give actual partial pressures of species. Figures 2 and 3 show the overall spectrum of products in the char burning phase, following the combustion of volatiles. The partial ultimate analysis of the six fuels is given in the figures. The samples represent a range of likely feedstocks, from clean, ash-free wood to ash-laden crop residues or herbaceous energy crops.

Discussion

The most significant aspect of these results is simply the ability to sample the highly condensible alkali vapor species and observe their evolution with time and conversion conditions. In figure one an early, volatiles combustion phase can be seen, followed by the char burnout phase. Note that a majority of the potassium is released at the higher temperatures of char burning. The extreme variations in alkali species release shown in figures 2 and 3, due to changes in composition of the feedstock, particularly the effect of chlorine, promises that systematic screening studies of many feedstocks will yield a predictive method for correlating fouling and slagging with composition. The levels of alkali released in combustion at the rather modest temperature of 1100°C, (tens to hundreds of ppm wt) gives a warning that some form of hot gas clean up may be needed for high-alkali materials. Future studies, under gasification conditions, may indicate more favorable retention of alkali on char or particulates.

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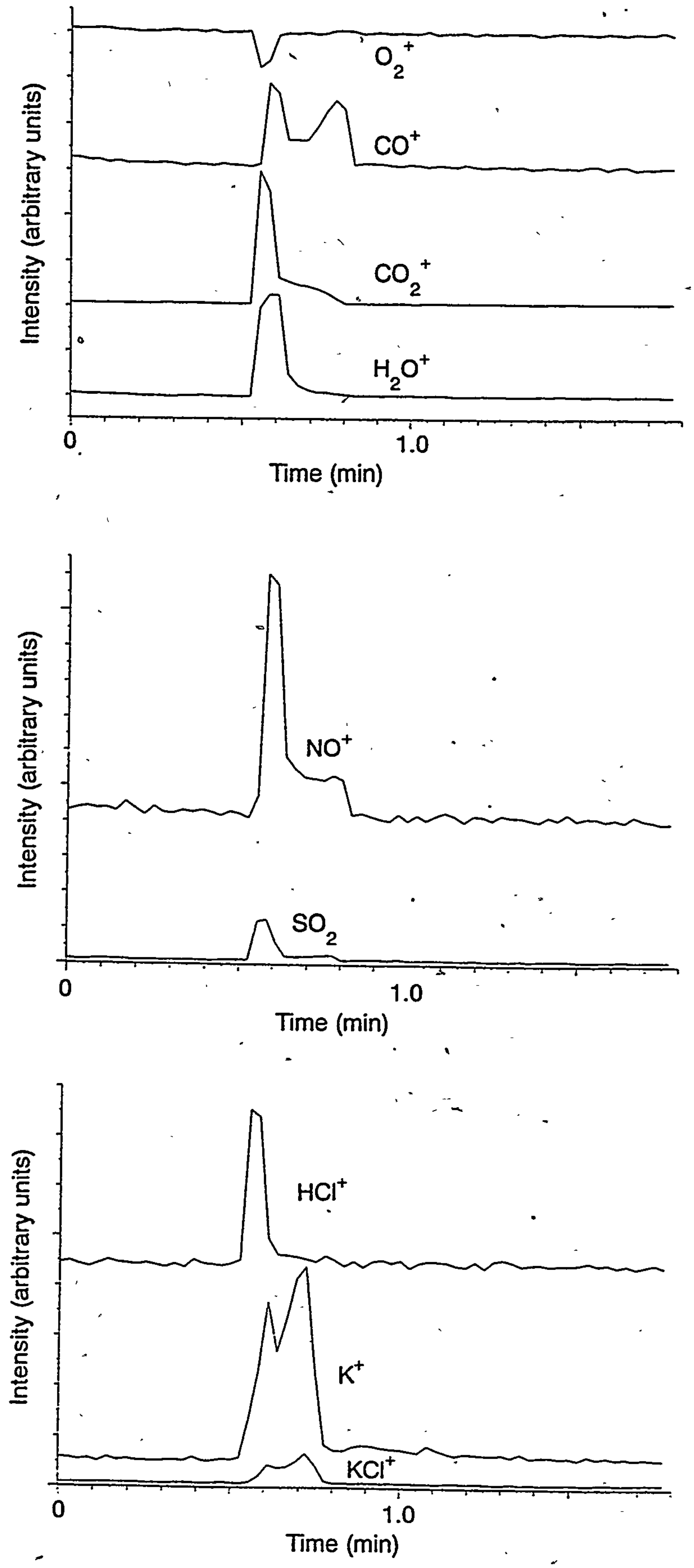

Figure 1. Evolution of major and minor species in the batch combustion of switchgrass in 80% He, 20% oxygen at 1100°C

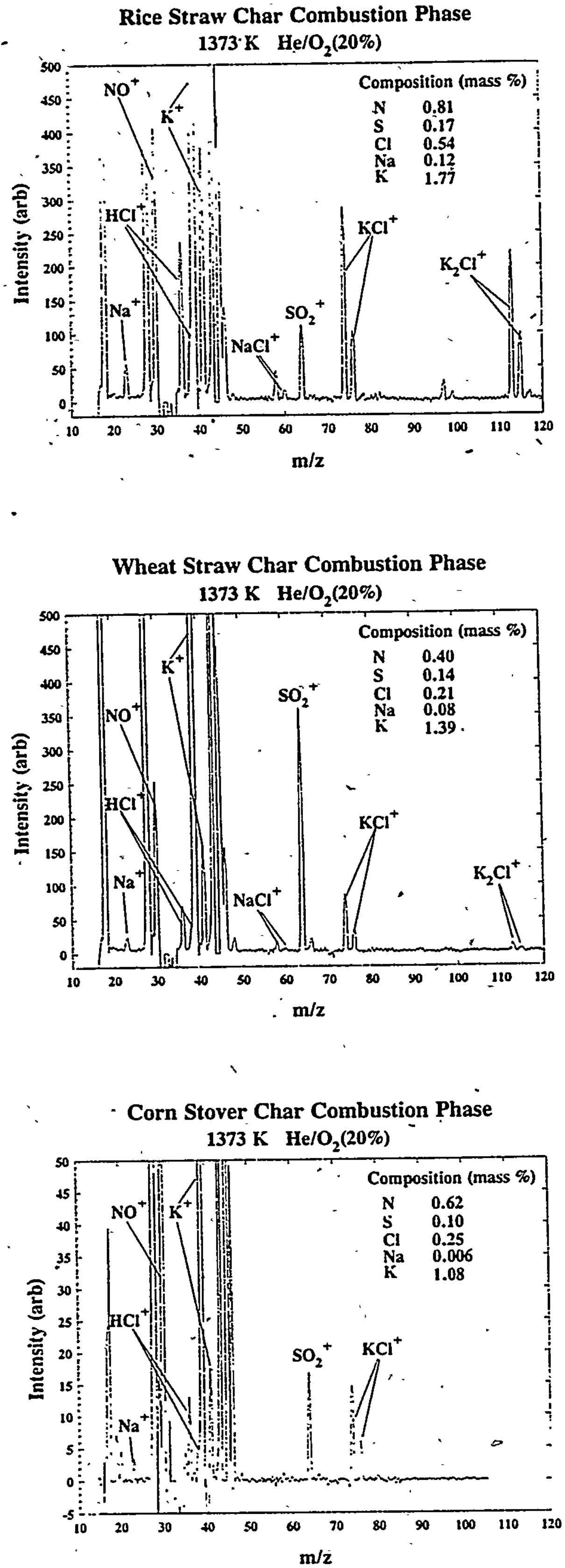

Figure 2. Mass spectra of three feedstocks, averaged over the char combustion phase of batch combustion. Rice straw, wheat straw and corn stover.

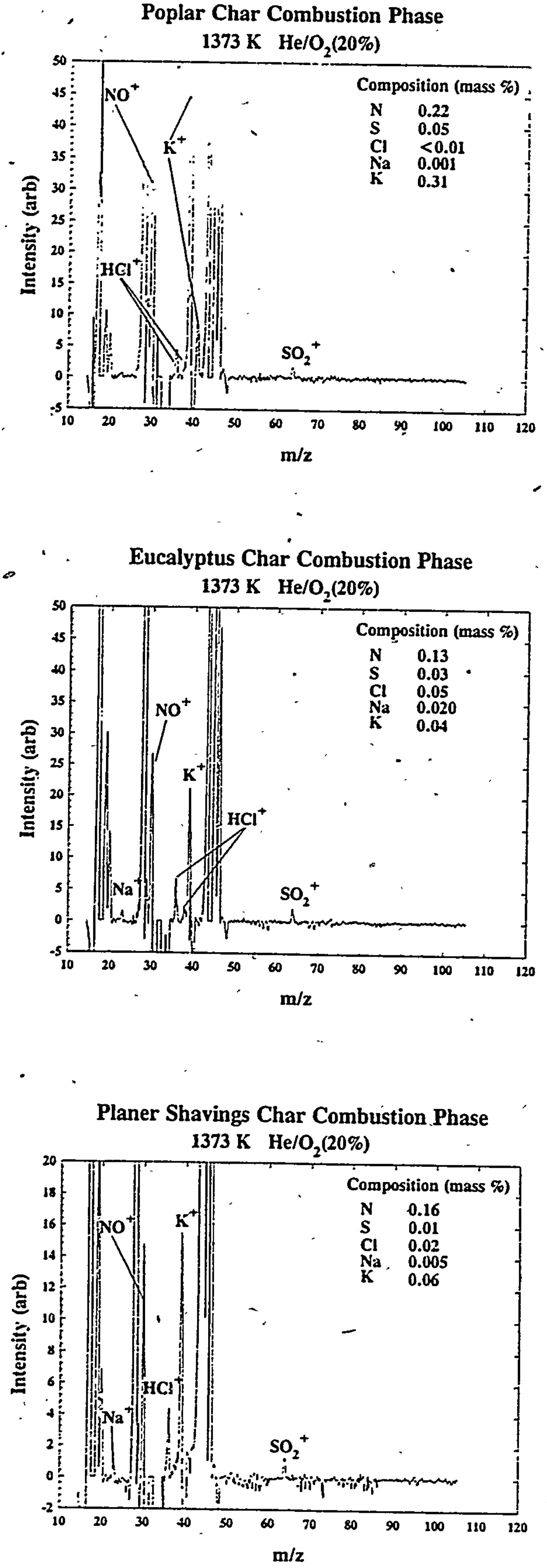

Figure 3. Mass spectra of three feedstocks, averaged over the char combustion phase of batch combustion. Lodgepole pine planar shavings, eucalyptus and poplar.

EMISSIONS FROM LABORATORY COMBUSTOR TESTS OF MANUFACTURED WOOD PRODUCTS

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ABSTRACT

Manufactured wood products contain wood, wood fiber, and materials added during manufacture of the product. Manufacturing residues and the used products are burned in a furnace or boiler instead of landfilling. Emissions from combustion of these products contain additional compounds from the combustion of non-wood materials which have not been adequately characterized to specify the best combustion conditions, emissions control equipment, and disposal procedures.

Total hydrocarbons, formaldehyde, higher aldehydes and carbon monoxide emissions from aspen flakeboard and aspen cubes were measured in a 76 mm i.d. by 1.5 m long fixed bed combustor as a function of excess oxygen, and temperature. Emissions of hydrocarbons, aldehydes and CO from flakeboard and from clean aspen were very sensitive to average combustor temperature and excess oxygen. Hydrocarbon and aldehyde emissions below 10 ppm were achieved with 5% excess oxygen and 1200°C average temperature for aspen flakeboard and 1100°C for clean aspen at a 0.9 s residence time. When the average temperature decreased below these levels, the emissions increased rapidly. For example, at 950°C and 5% excess oxygen the formaldehyde emissions were over 1000 ppm. These laboratory tests reinforce the need to carefully control the temperature and excess oxygen in full-scale wood combustors.

INTRODUCTION

Manufactured wood products contain wood, wood fiber, and non-wood additives such as adhesives. Manufacturing residues can be used to replace fossil fuels at the industrial site. Eventually the manufactured products are discarded, and rather than going to a landfill, the wood products may be burned in a boiler. Emissions from combustion of these manufactured wood products have not been adequately characterized to specify the best combustion conditions, emissions control equipment, and disposal procedures.

Primary wood product industries include lumber, plywood, composition board, and pulp and paper. Primary residue is in the form of edge trimmings, sawdust, sander dust, shavings, and fiber sludge. At the pulp and paper mills waste fiber containing additives and dyes accumulate. During secondary manufacturing, adhesives, plastic overlays, paints, varnishes, lacquers, fillers, strength additives, and dyes are applied to the wood products [Atkins and Donovan, 1992]. Wood preservatives and fire retardant chemicals may also be added.

In this paper aldehyde, total hydrocarbon and carbon monoxide emissions from combustion of flakeboard made from aspen are compared with emissions from "clean" aspen in a laboratory-scale, fixed bed combustor. Exterior grade flakeboard is made from thin flakes of wood and 3-7 % phenol-formaldehyde resin solids. Depending on the application, the phenol-formaldehyde resin contains 1-7 % sodium hydroxide which acts as a catalyst, maintains resin solubility, and helps the resin to penetrate the wood. In some flakeboard potassium hydroxide is substituted for part of the sodium hydroxide. Approximately 1 % wax is added to the flakeboard as a water repellant. Proximate analysis (Table 1) shows that the flakeboard used in this study has more fixed carbon and less volatiles than than the aspen. The ultimate analysis shows that flakeboard has slightly more hydrogen and carbon and less oxygen. The mineral analysis was similar for the two fuels except that the flakeboard had 608 ppm of sodium, whereas the aspen had only 6 ppm of sodium. This raises separate issues concerning slagging and fouling due to the sodium.

Because of the phenol formaldehyde resin in the flakeboard, there is concern that the formaldehyde emissions may be higher than in pure wood. Formaldehyde is considered a hazardous air pollutant by the 1990 Clean Air Act. Under proper operating conditions a wood-fired, spreader-stoker boiler has low formaldehyde emissions, however when the temperature and/or excess oxygen are too low, the formaldehyde emissions can be very high [Hubbard, 1992, Atkins and Donovan, 1992]. Larson, et.al., 1992 measured hydrocarbon and formaldehyde emissions of clean woodchips and woodchips impregnated with phenol formaldehyde resin in a rotary kiln combustor which was fired with natural gas (35% gas and 65% wood on an energy basis). The products of incomplete combustion were higher for the impregnated wood than for the pure wood.

Table 1. Analysis of the Flakeboard and Aspen

Proximate Analysis (as-rec. %)	Flakeboard	Aspen
moisture	6.56	6.64
volatiles	77.44	81.57
fixed carbon	15.46	11.50
ash	0.57	0.29
Higher Heating Value (kJ/kg)	20,030	19,192
Ultimate analysis(dry, ash free %)	Flakeboard	Aspen
hydrogen	6.47	6.21
carbon	51.12	50.77
oxygen	41.89	42.23
nitrogen	0.50	0.43
sulfur	0.02	0.05

TEST SETUP AND TEST PLAN

The combustor consists of a 76 mm i.d. by 1.5 m long, heated alumina oxide tube with a grate on the bottom (Fig. 1). A Kanthal heating wire element controlled by a 220 V, 30 A variable-voltage transformer was wrapped around this tube, and a moldable refractory board was wrapped around the heating wire. Approximately 10 cm of high temperature Kaowool insulation surrounds the refractory board and insulates the combustion chamber from a stainless steel tube which acts as the outer most shell of the combustor. Flakeboard in the form of 6 mm cubes was introduced into the top of the combustor by a specially designed variable-speed feeder. The cubes fall by gravity down the combustion tube onto a bed of alumina oxide chips supported by a stainless steel grate. Air is introduced from beneath the packed bed of chips (underfire air) and from two opposing jets located 30 cm above the bed (overfire air), and is monitored by flow meters and controlled by adjustable valves. As the combustion products exit the combustion chamber, they enter a 10 cm diam. stainless steel exhaust duct. An exhaust fan downstream in the duct pulls the exhaust gas through a pyrex cyclone collector.

Temperatures, oxygen, and carbon monoxide were monitored continuously and recorded on a computer every 5 s. Thermocouples were located 15 cm above the bed, at the exit of the combustor tube, in the exhaust duct, and immediately after the particulate filter assembly. A 3 mm stainless steel probe at the exit of the combustion tube was connected to carbon monoxide and oxygen meters. Also at the exit of the combustor tube, a heated 1.5 mm stainless steel probe and sample line were connected to a Hewlett Packard 5890 Series II gas chromatograph which used a glass wool packed column and a flame ionization detector to measure total organic carbon (TOC) emissions. In the exhaust duct, two 3 mm quartz probes were inserted - one probe is heated and connected to a particulate filter assembly and impinger train, and the other is connected to a separate impinger train and is used to capture aldehydes in a DNPH solution according to the Boiler and Industrial Furnace (BIF) Method 011 [EPA, 1990]. The cyclone collector with a removable flask collects flyash, and after a test run the underfire air is increased and the bottom ash is blown into the cyclone. Further details are given in the M.S. thesis by Wilkening, 1993.

TEST RESULTS AND DISCUSSION

Combustion tests were run at nominal excess oxygen levels of 2.5 %, 5 % and 10 % corresponding to excess air levels of 15 %, 40 % and 90 %. The calculated adiabatic flame temperatures were 1860°C, 1600°C and 1070°C, respectively. The ratio of overfire air to underfire air was about 2:1. The residence time in the reactor was held at 0.9 s by adjusting the fuel and air flows. The fuel flow rate ranged from 0.33 g/s to 0.11 g/s, while the air ranged from 1.75 g/s to 2.5 g/s. Exhaust temperatures ranged from 500°C to 1100°C. Lower temperatures required higher air and fuel flows to maintain the 0.9 s residence time. To achieve constant conditions it was important the feed the wood cubes at a constant rate; while this was achieved, there were some fluctuations in the CO and O_2 levels.

Total organic carbon emissions (TOC, Fig. 2) were very sensitive to temperature and excess oxygen. The data correlated better with average combustor temperature (referred to as average temperature) than with exhaust gas temperature. This is because the walls of the combustor were heated, and thus the flame temperature and exhaust temperature were independent. The average combustor temperature was defined as the weighted average of the lower combustor temperature (measured 15 cm above the grate), the calculated flame temperature, and the measured exit temperature. For both fuels the TOC was less than 10 ppm when the average temperature was above 950°C with 10% excess oxygen, and above 1050°C with 5% excess oxygen. At 2.5% excess oxygen the TOC was always above 10 ppm. As the temperature was reduced below these levels, the TOC increased markedly. For the 5% and 10% excess oxygen levels the difference between the pure aspen and the flakeboard was not significant. However, for 2.5% excess oxygen the flakeboard had higher TOC emissions than the aspen. The maximum level measured was 4000 ppm at 920°C.

Formaldehyde emissions (Fig. 2) were also very sensitive to average temperature and excess oxygen. The formaldehyde emissions were less than 10 ppm when the average temperature was greater than 1200°C. When the average temperature dropped below 1200°C the formaldehyde emissions increased rapidly. For example at 950°C and 5% excess oxygen the formaldehyde concentration was over 1000 ppm. Excess oxygen levels of 10% allow a lower temperature to prevent formaldehyde emissions. The flakeboard appears to require a slightly higher temperature (about 50°C) than clean aspen to prevent formaldehyde emissions. Acetaldehyde emissions (Fig. 2) are similar to formaldehyde, but the levels were a factor of 2 to 10 lower. Acrolein and propionaldehyde were observed at the 100 ppm to 1000 ppm level when the average temperature was below 1000°C. No butylaldehyde was ever detected.

Carbon monoxide emissions (Fig. 2) were also very sensitive to average temperature and excess oxygen. For CO there is a clear distinction between the clean aspen and the flakeboard. At higher temperatures the CO emissions were at a low level which depended on the amount of excess oxygen. As the average temperature dropped below 1200°C, 1100°C and 1000°C for excess oxygen levels of 2.5%, 5%, and 10%, respectively, the CO level increased rapidly for the flakeboard. These temperature regions were about 100°C lower (1100°C, 1000°C and 900°C) for the clean aspen. Thus the flakeboard requires approximately 100°C higher temperature than the aspen to burn cleanly. The burnout of CO at levels below 500 ppm appears to take more time than the available 0.9 s.

CONCLUSION

Emissions of hydrocarbons, aldehydes and CO from flakeboard and from clean aspen were very sensitive to average combustor temperature and excess oxygen. Hydrocarbon and aldehyde missions below 10 ppm were achieved with 5% excess oxygen and 1200°C average temperature for aspen flakeboard and 1100°C for clean aspen at a 0.9 s residence time. When the average temperature decreased below these levels the emissions increased rapidly.

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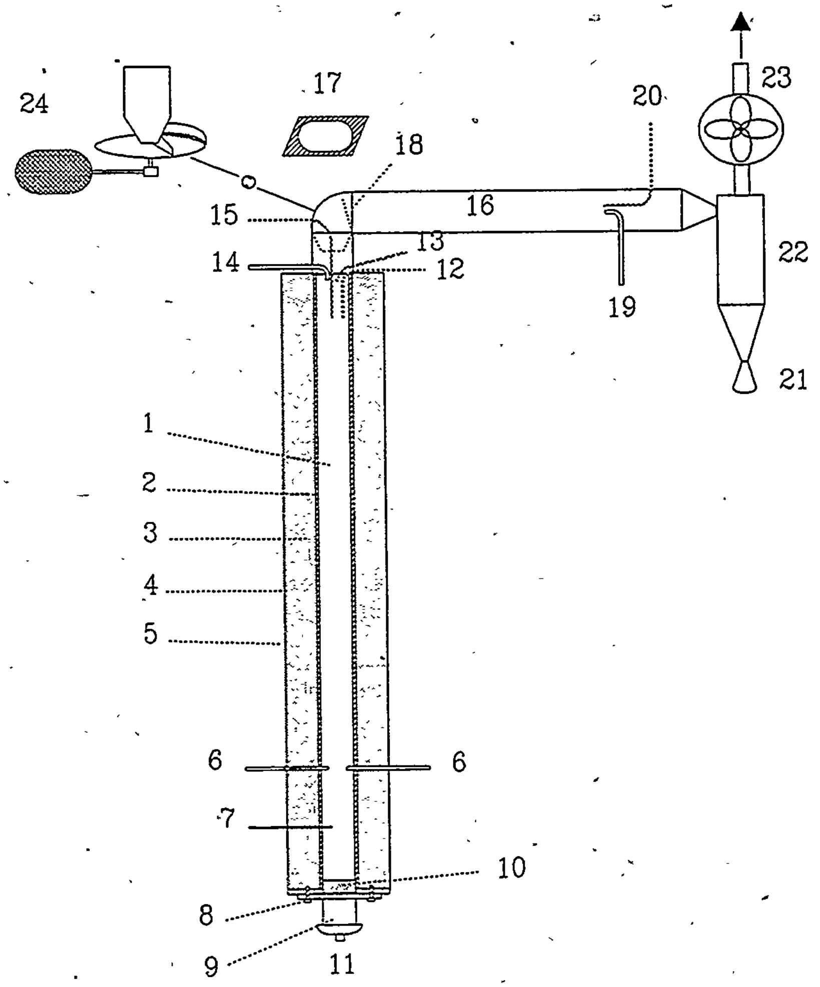
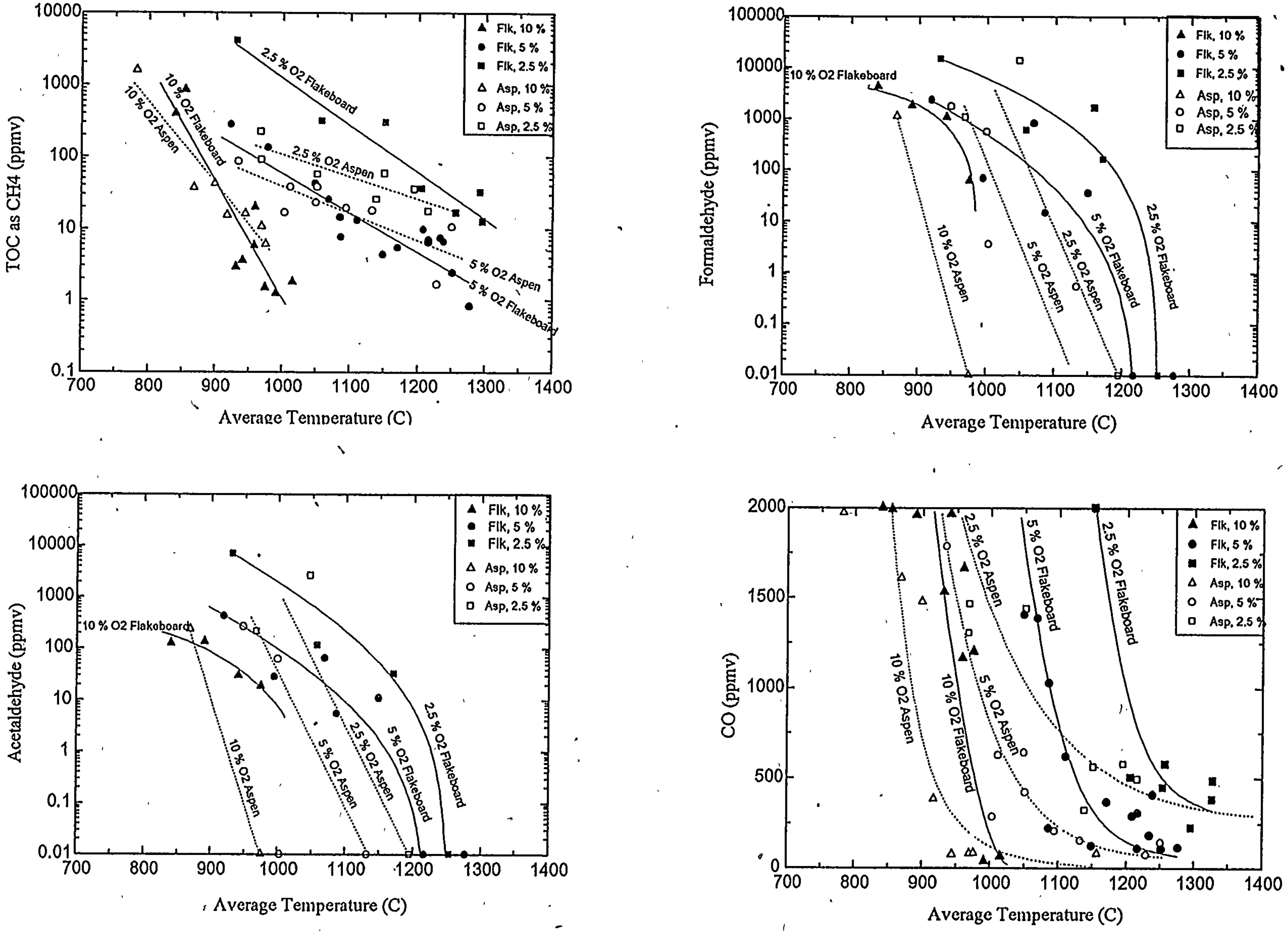
1. combustor tube
2. heating wire
3. refractory sheet
4. insulation
5. stainless steel tube
6. overfire air jets
7. thermocouple
8. stainless steel grate
9. air plenum
10. packed bed
11. underfire air
12. gc probe
13. thermocouple
14. aldehyde train probe
15. O_2/CO train probe
16. exhaust duct
17. mirror
18. support screen
19. particulate probe
20. pitot tube
21. collection flask
22. cyclone
23. exhaust fan
24. feeder



1. **Schematic of test setup.**



2. Emissions data

DRYING WOOD WASTE WITH A PULSE COMBUSTION DRYER

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ABSTRACT

There is a vast amount of wood waste available to be used as an alternate fuel if its moisture could be reduced efficiently. Tests have been conducted to assess an industrial dryer using pulse combustion as a heating source for drying wood waste; specifically sawdust and pulverized wet hog fuel. Pulse combustion offers the advantage of high heat transfer, efficient combustion, and low NOx emissions. The material is injected into the exhaust gases in the tailpipe of the combustor which uses natural gas or propane as a fuel. The turbulence created by the pulsations enhance the drying process by reducing the boundary layer thicknesses. The material is further dried in a rotary drum.

The material has been dried without scorching or burning in tests where the inlet moisture content has been as high as 60% on a wet basis. The outlet moisture contents achieved have typically been 10%. Analysis of the test data and cost estimates of the equipment indicate that the pulse combustion drying system is at least comparable to existing systems in terms of operating costs, and offers very significant savings in capital costs. Testing with various other materials such as wood pulp, sludges and peat is continuing to further assess the equipment's performance.

1.0 General

There is an abundance of wood byproducts from the lumber, and pulp and paper industries which represent a significant source of fuel. The byproducts however normally contain a substantial amount of water which renders the burning of them inefficient. Efficiency is improved with the drying of the wood waste to moisture levels of 15% or less before being fed into boilers or other heating equipment.

Research has proven that dehydration of a material is both accelerated and improved by sound waves that are superimposed on the heated air that is normally used for evaporating the moisture contained in the material.[1] The improvement in the material results from the shorter time of exposure to the heat and to the effect of the sound waves which separate the particles of the material. In practice, sound waves are rarely used in dehydration processes because of the cost of the energy that is required to produce them.

Pulse combustion provides the ideal combination of heat, high velocity air and intense sound pressure waves without prohibitive electrical and equipment costs for drying. This conclusion is derived from the following:

- Pulse combustion used as a heat source has been shown to improve heat transfer over conventional steady state combustion. This has been proven to result from the sonic pulsations which reduce the heat transfer coefficient. Hence, a drier based on pulse combustion is expected to be smaller and less costly, for the same material throughput. It may also be transportable, where others are not.
- The products of combustion from pulse combustors has been proven to be lower in NOx, since pulse combustion operates at a lower temperature. The lower flame temperature occurs from previous combustion gases being mixed with the newly admitted fuel charge at the time of ignition of the charge. The result is an environmental benefit.

A development program was initiated to design, fabricate and test a pulse combustion dryer to determine its performance. Interest from Energy, Mines and Resources Canada led to a test program to assess its effectiveness on wet hog fuel and other wood waste materials.

2.0 Equipment Description

The drying equipment which has been used for conducting the tests consists of pressurized cabinet, a combustor, material hopper, agitator and feed mechanism, rotating drum, exhaust blower and exhaust cyclone.

The combustor consists of a combustion chamber in the form of a short pipe with an air and fuel admitting valve at one end and a length of reduced diameter pipe at the opposite end. The valve, which allows flow in only one direction, admits air from a blower, to the combustion chamber where it mixes with the fuel to form an explosive charge. Ignition is provided by a spark plug and a rapid increase in pressure follows. The gases are driven out through the small diameter tail pipe. A vacuum follows the explosion and a new charge of fuel and air are drawn into the combustion chamber. Ignition is provided from the previous combustion and the cycle is repeated at approximately 80 times per second. The rated capacity of the combustor used in the testing is 1,000,000 BTU/hr. The turndown ratio is 3:1, however for this set of tests, full capacity was maintained.

The material to be dried is injected directly into the tail pipe. Here it is subjected to the extreme turbulence of the hot gases as well as rapidly changing positive and negative pressures. The pulsations created would have the ability to breakdown viscous materials such as sludges and manures. Moisture is driven out of the material by the rectifying action of the pressure fluctuations. Evaporation takes place in the heated air stream, producing steam. The material flows into a rotating drum where the excess heat further evaporates moisture in the material. A blower lifts the material into a cyclone where it is separated from the airstream. A flowsheet is shown in Figure 1. Note that the rate at which the material is injected is determined by a thermocouple sensor, T_D, which regulates the speed of the feed auger in the tailpipe using a variable speed drive motor. Hence injection is slower for wetter materials and faster for drier materials.

3.0 Equipment Performance

Many tests have been conducted using sawdust, milled sawdust and pulverized wet hog fuel. Typical test data is given in Table 1.

Table 1: Summary of Test Data for Pulse Combustion Dryer

Inlet air flow	235-375 l/m (500 - 800 cfm)
Inlet air temperature	ambient
Inlet air humidity	ambient
Gas input	293 kW (1,000,000 BTU/hr)
Material input (wet basis)	317 - 544 kg/hr (700 - 1200 lb/hr)
Moisture content of mat'l at injection	40 - 60%
Moisture content of mat'l at outlet	5 - 15%
Evaporation rate	200 kg/hr (440 lb/hr)
Electrical power utilization	approx. 3.7 kW (5 HP)
Drying set temperature, T_D	121 - 177°C (250 - 350°F)
Temperature in the combustor tailpipe	815°C (1500°F)
Run duration	15 - 30 minutes
Efficiency	48 - 52%
Energy used per mass H_2O evaporated	.27 - .32 kW/kg H_2O (.6 - .7 kW/lb H_2O)

Efficiency is defined as the heat required to raise the temperature and evaporate the water in the material relative to the total heat used. Much of the test data was recorded on a data logger which assisted in the analysis of the performance of the dryer.

4.0 Analysis and Discussion

Over the course of testing several trends were noted that are worthy of discussion. Furthermore, a comparison between pulse combustion drying and other systems was conducted, based on a hypothetical scenario where the wet hog fuel feed rate was 5000 kg/hr with a moisture content of 60%. An evaporation rate of 2680 kg/hr produced a product with 15% moisture. The fuel was natural gas. Preliminary costing and performance data were received for three types of flash drying systems (2, 3, 4).

Most tests were conducted using green sawdust containing particles 6 mm or less. The optimum set temperature was determined to be 121°C (250°F). This represents the temperature of the mixture of the combustion gases, wood waste and evaporated water at the outlet of the tail pipe. Tests with pulverized hog fuel (2mm or less) showed a lower set temperature to be adequate. It was concluded that a lower set temperature and therefore a higher efficiency could be achieved by increasing the dwell time in the drum.

The material at the outlet of the dryer showed no signs of scorching or carbonizing. There was a discoloration present, indicating an oxidation of the material's surfaces.

The efficiency of any drying system is dependent upon the amount of air used in the process. The pulse combustor requires primary air to provide oxygen to support combustion. Secondary air is used to cool the combustor. These requirements are fuflilled by a relatively small amount of air. Conventional dryers require substantial amounts of air to subject the material to high velocities and turbulence to enhance heat transfer. Using pulse combustion, the heat transfer is accomplished using pressure waves. The result is that significantly less air is required, and therefore less heat and less fan horsepower should be required; hence operating costs should be lower. Furthermore, the relatively low requirements for air allow for a reduction in the size of the system components such as baghouses, ducting, cyclones, etc. In comparing the test data from the pulse combustion dryer to that of the flash dryer, the overall energy usage was in fact similar, being about .27 kW/kg water evaporated, however, the amount of air on a prorated basis was in the order of 50% that of the flash dryer. Pulse combustion drying had a slight advantage in terms of operating cost, since there is a lower use of electricity. These results were seen as promising, since the optimum parameters regarding the drum design were not identified. (ie. drum dwell time, drum rotation speed).

The existing combustor is fabricated from black carbon steel pipe and relys on secondary air to provide sufficient cooling so that the yield temperatures of the material are not reached. It was found during testing however that the combustor turned red hot which indicated that the running temperature was higher than expected. The next combustor will be fabricated from a high temperature stainless steel which, although increasing the cost slightly, will allow for a significant reduction in secondary cooling air, thus increasing the efficiency of the unit. Calculations suggest an increase in the overall efficiency of well over 70%.

Detailed calculations were performed to determine where the input heat is utilized in the system. Table 2 provides a breakdown.

Table 2: Estimate of Heat Utilization in the Pulse Dryer

		Existing Data	Projected
Energy used to	evaporate water	50%	75%
	heat water vapour above boiling	3%	3%
	heat material	4%	4%
	heat dry air	27%	10%
Heat radiation and other losses		16%	8%
		100%	100%

Reducing the amount of air has been discussed above. Insulating the entire rig will also increase the efficiency of the unit by reducing the radiation losses, since the current system is poorly insulated. These improvements allow a projected performance as given in Table 2.

Pulse combustion allows for smaller components due to the improved heat transfer; hence the system capital cost is lower than for conventional systems. A definitive analysis has not been completed at this time, however preliminary estimates for competing flash drying systems based on the data in Table 2 indicated that purchased packages were in the order of $US 230,000 to $US 290,000 for the basic drying systems less baghouses, feed systems, hoppers, structural supports, commissioning, installation, etc. For a pulse combustion unit with a similar capacity a figure of $US 170,000 was estimated.

5.0 Conclusion

Pulse combustion drying has been demonstrated to be at least as efficient as conventional flash drying systems and to offer significant savings in capital costs.

The specific application of drying hog fuel and waste wood with a gas fired pulse combustion dryer is useful for comparison purposes, however there are currently many installations which use boiler flue gas to accomplish this task. This represents a low operating cost, hence the usefulness of any gas fired drying system is questionable. Pulse combustion does offer high heat transfer capabilities and therefore the testing of hybrid designs may prove worthwhile in reducing capital costs.

Development and testing on the pulse combustion dryer is continuing, with materials such as manure, wood pulp, sludges, peat, grain, etc. It promises to render smaller more compact and transportable drying systems in the future.

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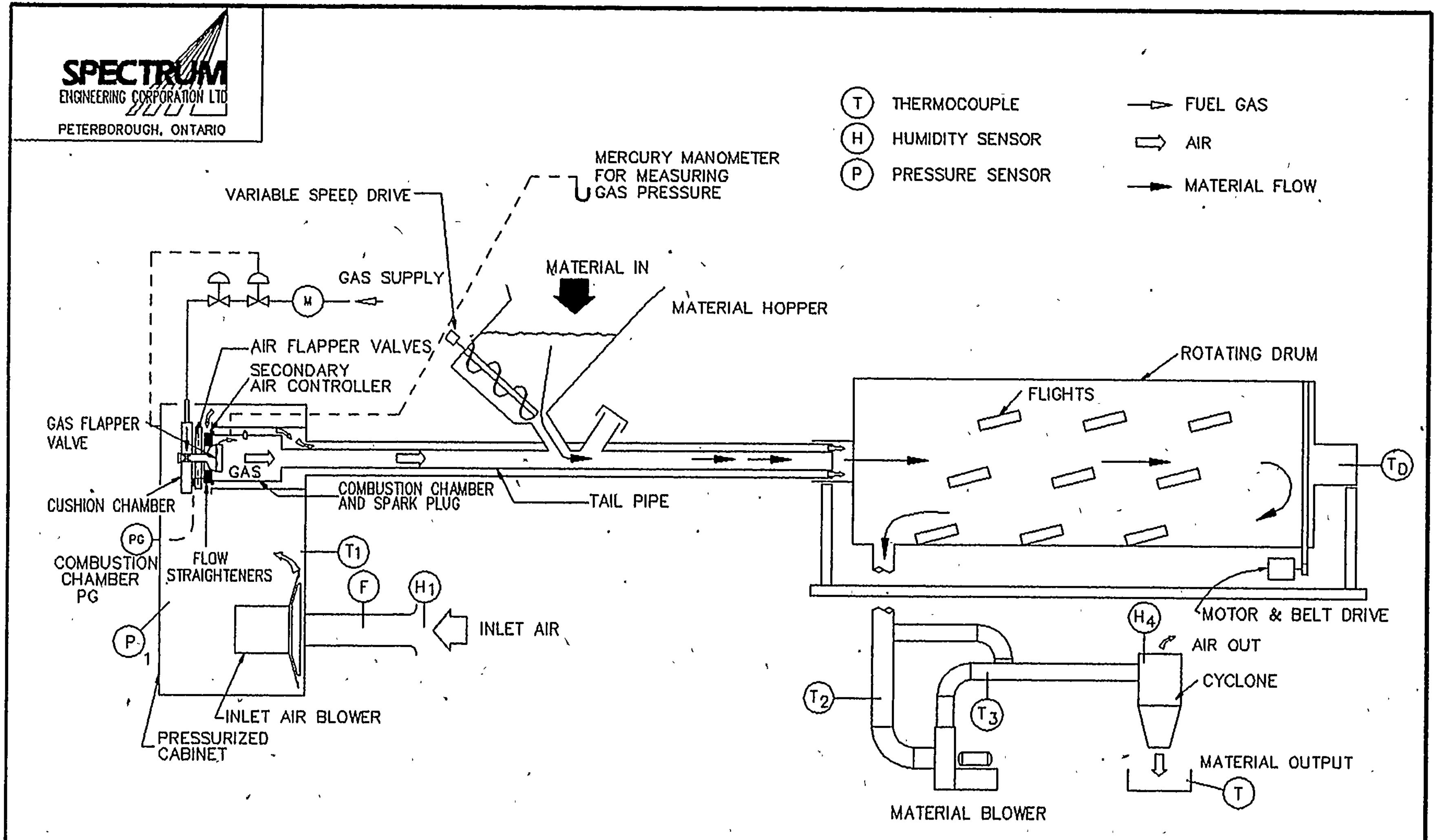

FIGURE 1 : PULSE DRYER PROCESS FLOWSHEET

BIOMASS ASH UTILIZATION

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Abstract

This paper demonstrates that with careful analysis of ash from multiple biomass and waste wood fired power plants that most of the ash can serve a useful purpose. Some applications require higher levels of consistency than others.

Examples of ash spreading for agricultural purposes as a lime supplement for soil enhancement in Maine and North Carolina, as well as a roadbase material in Maine are discussed. Use of ash as a horticultural additive is explored, as well as in composting as a filtering media and as cover material for landfills. The ash utilization is evaluated in a framework of environmental responsibility, regulations, handling and cost.

Depending on the chemical and physical properties of the biomass derived fly ash and bottom ash, it can be used in one or more applications. Developing a program that utilizes ash produced in biomass facilities is environmentally and socially sound and can be financially attractive.

BIOMASS ASH UTILIZATION

The United States obtains approximately 2.7 quads of energy per year from biomass while producing 1.5 - 3.0 million tons of ash. Ash residue continues to be a significant disposal problem as environmental regulations become more stringent and landfill sites become less available and more expensive. Recent regulations (EPA Resource Conservation and Recovery Act, Subtitle D, Part 258 RCRA) will also escalate tipping fees. It is obvious from an economic standpoint alone that alternatives to landfilling must be in place before RCRA is fully implemented.

This paper demonstrates that with careful analysis of ash from the burning of biomass in a traveling grate stoker system and cooperation with various agencies, most of the ash can serve a useful purpose. Experiences from three facilities are summarized: Fort Fairfield, ME, Craven County, NC, and Stratton, ME.

Fort Fairfield

Fairfield Energy Venture, L.P. is a 30 megawatt, (net) wood fired electrical generating facility located in Fort Fairfield, Aroostook County, Maine. Electricity produced at the station is sold to Central Maine Power Company.

As a result of the combustion process, an annual average of 350,000 tons of wood fuel is consumed. The annual volume of wood ash produced is approximately 10,000 conditioned tons, (50% moisture). The ash is conditioned with water and angrued into an enclosed trailer of an ash transport vehicle. Most of the ash is landspread as an agricultural supplement from the facility. The ash is either transported directly to the site designated for utilization, or to a storage bunker, where it is stored for future landspreading.

The wood ash contains appreciable amounts of potassium, magnesium and phosphorus and is free of dioxins and furans or their subisomers. In addition, the ash contains concentrations of micronutrients, making this material an excellent soil amendment and liming agent. Added to its neutralizing capabilities, (especially important in mineral soils where low pH is of concern) the ash provides substantial amounts of calcium, as well as other macronutrients for plant growth and production. Available nitrogen is negligible.

Figure I, below, illustrates typical loading rates of macro and micronutrients at an application of four tons per acre.

Nutrient	Pounds Provided	Nutrient	Pounds Provided
Calcium	783.2	Sulfur	0.1
Potassium	259.4	Sulfate	64.4
Magnesium	60.2	Boron	0.7
Phosphorous	30.7	Zinc	5.1
Iron	276.6	Manganese	46.8
Copper	0.3	Molybdenum	0.1

Note: Pounds per acre ÷ 0.892 = kilogram per hectare, (kg/ha)

Application programs of wood ash to agricultural land should at a minimum, consider baseline soil nutrient availability, nutrient requirements of the crop(s) to be grown and method of application, (topdress or incorporation).

Typically, soil nutrient availability is determined by collecting and analyzing composite soil samples representative of the site designated for utilization. Analysis conducted on soil samples should include, soil pH, buffer pH, concentrations of macronutrients, (Calcium, Magnesium, Phosphorous and Potassium) base saturation calculations for Calcium, Magnesium and Potassium, as well as soil Cation Exchange Capacity (CEC), % Organic Matter and recommendations for lime and fertilizer, based on the crop to be grown.

Once the above determinations are ascertained, application of the wood ash should be initially based on the liming needs as directed by the target pH of the crop to be grown. However, consideration should also be given to the other nutrients provided by the wood ash. Fertilizer blends and concentrations should therefore be adjusted accordingly. Once the target pH is reached, application should be based on nutrient uptake and removal by the crop. At this point, a maintenance dosage is recommended.

Two standard methods of wood ash application include topdressing and incorporation into the soil. Due to the significant mineral hydroxide availability, formed from mineral oxides after the addition of conditioning water, wood ash pH values of 13 to 14 standard units are not unusual. It is therefore recommended that topdress application be at a rate of no greater than 75% of the incorporation rate. Field application of wood ash is usually performed using a standard agricultural lime spreader or rarely, a manure spreader.

Craven County

Craven County Wood Energy L.P., operated by HYDRA-CO Operations, is a 45 MW biomass fired facility located in Craven County, North Carolina. The plant burns approximately 540,000 tons of clean waste wood (approximately 33% each of wood chips, bark and sawdust) and generates about 16,000 tons of ash per year. Ash from the facility is currently being landfilled. New RCRA regulations dictated the need for a new landfill and subsequent higher tipping fees are anticipated.

Anticipating these changes, the facility engaged in what was to become a three year campaign to reduce the dependency on landfills by researching known alternatives and drawing from the success of the Northeast region in fly ash spreading (Northeast Governors Association, 1988). The intent was threefold: first, to declassify fly ash as a waste product (note: it was never classified as a <u>hazardous</u> waste); second, to investigate the feasibility of using the ash as a lime substitute (given the fact that local soils are highly acidic); and thirdly, to investigate any and other viable alternatives to landfilling. These actions, when brought to fruition, would improve the overall environment of the area as well as reducing facility costs.

After carefully considering all of the options, it was decided to concentrate the greatest effort towards agricultural land application.

During this planning period the facility was contacted by Dr. Joe Zublena, Specialist in Charge, Soil Fertility, North Carolina State University (NCSU), Dr. Bob Rubin, Extension Specialist and Associate Professor NCSU, and Mr. J.W. (Billy) Dunham, County Extension Director, Craven County, NC. In 1991 these gentlemen conducted a small replicated test on soybeans and found when used in a small replicated test, the fly ash treated land showed an increase in soil pH and plant yields equal to the plots that were treated with a commercial lime product (Rubin, 1992). The end goal of their project was to get the material registered as a liming material. Therefore, the facility plan was aligned with their proposed two point project as summarized below.

Facility Plan Description

The Plan involves two demonstration projects for the use of fly ash. Both of these projects are in progress.

Project I

- Set up replicated plots on a one to two acre site to monitor wood ash application compared to dolomitic lime. Treatment rates are: wood ash at ½, 1 & 2 times the recommended rate, a control area, and lime at ½, 1 & 2 times recommended rate.
- The neutralizing value of wood ash at these three rates will be compared to dolomitic lime at equal rates.
- Soil samples will be pulled from the entire plot before applications of any product and rates will be based on soil sample recommendations.
- Soil samples will be pulled from each plot prior to application of materials. This will be used as a comparative base for the next two years. Three components will be evaluated (1) Soil pH changes, concentrations of potassium, calcium, manganese, magnesium, metals and other macro and micro nutrients will be monitored every three months for two years, (2) tissue analysis will be pulled from each plot twice per year to monitor nutrients and metal uptake and (3) crop yield will be determined. Reports will be compiled at the end of each growing season.

Project II

Set up a large scale demonstration program on a variety of soil types throughout Craven County to demonstrate the neutralizing value of wood ash to dolomitic lime and to monitor the exchangeable concentrations of macro and micro nutrients as well as metals. Fields needing lime will be identified and ash will be applied at recommended rates to bring the pH up to desired levels. A portion of each field will have dolomitic lime applied as a comparative. Soil samples will be pulled from each field before application of materials, another sample will be pulled after harvest and another in the spring before planting. If lime is required for a second year, materials will be applied according to NCDA recommendations and soil samples will be pulled at the end of the second harvest. After harvesting of the second crop, a final report will be written for each demonstration site.

For additional monitoring, tissue analysis will be pulled each growing seasons to look at nutrient and metal uptake.

Bi-monthly lab testing of ash (including EPTOX and TCLP) on a 500 acre test site to establish a neutralizing valve and to determine the concentrations on nutrients is ongoing.

In May, 1993, the DEHNR Solid Waste Director provided a verbal indication that the fly ash produced at the Craven facility was no longer considered a waste product but indicated that continued testing, monitoring and reporting will be required. The next step will be the registration of fly ash as an agricultural amendment. Permission was granted to temporarily spread fly ash on farms selected by the County Extension Agent.

There are still a significant number of details to be worked out before the program is in full operation. Fly ash is only spread on farm land from September through May, so a suitable storage site has to be obtained. Storing ash uncovered on farm sites before spreading has resulted in "chunks" that are not easily broken up. Temperature and humidity are obviously contributing factors. Stored ash will need to be processed to meet the finners and gradation requirements for lime in order to become a lime supplement product in North Carolina.

In summary, there appears to be an excellent market for fly ash as an agricultural amendment. The problems in delivering the product are primarily bureaucratic. The farmers want the ash, the facility is willing to work with the farmers, and both have the backing of NCSU and the County Extension Agent. This material has tremendous potential for beneficial reuse. Wood ash has been recycled through forested systems since the first lightning caused forest fire. Land application of wood ash mimics this natural process in a planned, controlled manner.

Stratton

Stratton Energy Associates (SEA) owns a biomass energy generating facility in Eustis, Maine. Two ash residuals are the result of the combustion and environmental containment processes, fly ash and bottom ash. Stratton Energy Associates has contracted with A.L.E.N.A.G., Inc. to transport and dispose these waste residuals. Currently the fly ash is transported to Canadian sites for either land applications, land filling, or incorporation into sewage sludge. The bottom ash is transported to Norridgewock, Maine for disposal at the Consolidated Waste Services.

S.E.A/A.L.E.N.A.G., with the help of Brown & Michaud, are investigating alternative strategies to productively use the bottom ash including: meeting M.D.O.T specifications for use as a borrow material; agricultural use to lighten heavy soils; and use as a roadbase material in forestry and agricultural management situations. The latter is the focus of this discussion.

In a preliminary meeting with D.E.P. staff, it appeared that due to a number of unknowns, an experimental program should be implemented to determine the impact of leaching from the bottom ash or in combination with other materials.

The bottom ash from the Stratton Energy Facility has characteristics similar to medium textured gravel. The material however does not appear in a laboratory situation to have enough cohesive qualities to insure good compaction. However it is believed that the material is suitable enough for use in a road sub-base in a unamended state. A test program to more accurately predict what will happen in a field road base was developed.

A test strip near the Stratton Energy Associates plant site was secured. The program involved the initial construction of 600 feet of road, approximately 24 feet in width, with 3:1 sloped shoulders. The existing loam was stripped and stockpiled on site for potential future use as an additive to the bottom ash if necessary. A 36 inch subbase/base material comprised solely of bottom ash was constructed. Surface collection devises were used to collect run off from the exposed surface. Upon completion of the control strip the monitoring program was implemented.

A sampling program has been designed to collect 3 samples during significant rainfall events. The samples are analyzed for pH, aluminum, calcium, iron, magnesium, phosphorus, potassium, and sodium. A metals test will be done on a composite sample of all the samples. The metals composite sample will be acidified to a pH of <Z with nitric acid prior to collection. Data needs to be collected and analyzed after one more significant storm before the study can be completed.

The study will determine whether excessive leaching of phosphorus occur from bottom ash residual used in road construction versus normally occurring leaching of phosphorus from newly constructed gravel roads. The study will also determine the suitability of the bottom ash for use as a road sub-base and base material.

This alternative when used in development of logging roads could minimize the need to truck in additional quantities of gravel for sub-base development.

Other Uses

Presently a portion of SEA fly ash is utilized in Valoraction, Inc. "Mediafeed" filter. These filters are successfully used to treat municipal landfill leachate. The filter consists of several layers of filtration media (Stratton fly ash being one of the components). Leachate is sprayed into the top of the filter bed. Filtrate is collected from the bottom and again sprayed onto a secondary filter bed of similar composition. This secondary filtrate is then aerobically digested in an aerated pond.

SEA fly ash has been mixed with sand and municipal sewage treatment sludge and used as a landfill cap. Two purposes are accomplished; the sludge is deodorized, and the cap material is very supportive of grass growth. The mix material makes a good bank slope stabilizer as well and becomes an excellent soil amendment which can also be used for bank stabilization and topsoil in municipal planting projects.

Ash from Fort Fairfield has demonstrated beneficial uses of composting as it pertains to the Industrial Waste Utilization Facility and the agricultural/industrial community. In Arroostook County, the closing of starch factories has compounded the potato and potato waste disposal problem. Through the heating and aeration process of composting, the pathogenic organisms are killed off resulting in a material which is free of disease and can be spread directly back in to the soil.

Wood ash, an essential compost ingredient, provides a nutrient source as well as stimulates the temperature rise required by providing mineral oxides and hydroxides to the compost material. During the composting process, pH will increase as a result of wood ash addition. The final product is typically neutral or slightly alkaline. When applied to the low pH mineral soils of Aroostook County, the finished product assists in increasing soil pH and maintaining this pH through its organic buffering capacity.

Conclusion

Depending on the chemical and physical properties of the biomass derived fly ash and bottom ash, it can be used in one or more applications. Developing a program that utilizes ash produced in biomass facilities is environmentally and socially sound and can be financially attractive.

THE BIOMASS ENERGY INDUSTRY OF NORTHERN NEW ENGLAND:

LESSONS FOR AMERICA

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Abstract

The successful development of biomass energy for electricity generation in Northern New England (Maine, New Hampshire) was launched by new innovative public policies and the relative competitive advantages of ample supplies of wood residues and forest biomass. Since 1980 over 600 megawatts of wood-fired capacity has been developed, and generates nearly 20% of the two state electricity supply.

What are the factors that account for this dramatic development, and what are the lessons for the rest of the America's?

This paper summarizes the influences of public policies, the importance of extensive resources, the power needs of utilities, the business/investment opportunities for IPP's, and native strengths in fuel procurement and wood combustion experience.

Conclusions are drawn in the form of lessons for other regions and jurisdictions concerned with attaining the benefits of biomass energy development.

Introduction

The production of electricity from wood is a relatively new and increasingly important source of energy in northern New England (Maine, New Hampshire, and Vermont). Since 1980, the wood-fired electric generating industry has grown from a few cogenerators producing electricity mostly for self consumption to a complex of nearly thirty cogeneration and free standing plants capable of providing over 700 megawatts of generating capacity for utilities in Maine, New Hampshire, and Vermont.

What accounts for this successful development of biomass power, and what can we learn from the development of the industry in Maine and New Hampshire? In these states, the industry is characterized by a large number of stand alone plants, in addition to typical cogeneration facilities, established solely for the production of electricity.

This paper discusses the importance of supportive public policies in creating the opportunities for biomass power development, and explains why a wood-fired electric power industry developed in the region.

Setting

By 1980 the stage was set for the development of wood-fired power plants in the region, as well as the rest of the country. New federal and state laws and associated regulations designed to encourage the development of renewable energy resources by non-utility producers were in place and being implemented through state regulatory commissions. At the same time, many of the region's utilities faced increasing needs for new capacity to meet growing demands for electricity at a time when traditional sources of power were increasingly difficult to develop. The combination of new power needs, with conducive public policies, and ample wood resources provided the impetus for the development of the biomass energy industry.

Underlying these circumstances was widespread support for appropriate action to assure future energy security and independence, brought on by the traumatic experiences of the energy crisis of the 70's. An experience still fresh in the public mind. This support for action cut across partisan, economic, and social interests. In Maine and New Hampshire this interest took the form of support for renewed emphasis on hydropower development and the potential for biomass energy, two traditional energy resources.

The Biomass Power Industry in Maine and NH.

The biomass power industry in Maine and New Hampshire is comprised of (27) cogeneration and free standing facilities located in a variety of saw mill and pulp and paper mill settings, and other strategic locations on the power grid. The smaller (one to four megawatt) cogeneration plants are associated with saw mill and solid wood processing mills, while the larger (40 to 60 megawatts) cogeneration facilities are fully integrated into the power systems of pulp and paper mills. Free standing plants, ranging in size from 12 to 40 megawatts, are located at strategic positions with access to the power transmission network.

Public Policies and Opportunities for Biomass Power Development

Structure of The Policy Environment

The opportunity for non-utility producers to generate and sell electricity produced from woody biomass was created by the enactment of the Public Utilities Regulatory Policies Act (PURPA) of 1978. Ostensively, PURPA was passed by Congress with the intention of encouraging the development of cogeneration and small power plants using renewable energy resources as a means of improving energy security and lowering dependence on foreign oil imports. In political reality, the PURPA provisions were created in response to the unwillingness of utilities to purchase at fair prices the excess electricity produced by non-traditional sources typically located in manufacturing facilities. The idea of encouraging cogeneration using renewable resources serves to advance national energy objectives and fits well with the energy strengths of the northeast region.

PURPA is implemented at the state level, guided by federal regulations. State enabling authority and associated regulations establish responsibility in each state's Public Utilities Commission (PUC) to administer alternative power programs. Although ME and NH are neighbors, each took a distinctly different approach to implementing its alternative energy programs. Consequently, the details of implementation vary reflecting each state's effort to tailor the process to meet its own objectives, but the results are similar.

In Maine, rules implementing PURPA purposefully create an "arms length" regulatory relationship between the PUC and a utility. The intent of these regulations is to guide the actions of utilities in arranging a power purchase by setting forth rules to guide the process, without creating a direct role for the Commission in a "before-the-fact" contract review or approval. The Maine PUC relies on subsequent rate setting processes and prudence review as a control mechanism. As a further control on the process, the rules allow either party in a negotiation to partition for Commission intervention to ensure good faith efforts. This approach stands in strong contrast with states opting to maintain an active role for regulatory bodies in power development decisions. The Maine model creates the arena, with ground rules, in which utilities and independent power producers (IPP) can strike a deal.

In New Hampshire, the Public Utilities Commission is much more actively engaged in the planning and approval of alternative power projects. Initially, the PUC maintained an active role in the process of developing alternative power projects through a policy of long term levelized standard offers. Under this process the commission exercised its responsibility by establishing long term rates, based on an avoided cost calculation, and then approving "mature" proposals negotiated between an IPP and a host utility by issuing a rate setting order. In recent years, following a two year investigation of avoided cost and a review of the commissions experience, a new more flexible system has been instituted that encourages direct negotiation for private contracts between a utility and an IPP. Under the new system alternative sources of power are evaluated within the context of an accepted utility power plan and selected on the basis of the least cost alternative.

Policy Implementation: Fulfilling Policy Goals and Objectives

The enactment of PURPA, as part of the National Energy Act, was part of a broad public policy response to the oil supply disruptions and price increases of the early and mid 1970's. In the Northeast, energy plans and reports emphasized the potential of the region's wood resources as an important component of an indigenous energy supply. Maine and New Hampshire adopted the development of indigenous renewable resources as a key objective of state energy plans and in supporting legislation. Predating the passage of PURPA, the New Hampshire legislature enacted the Limited Electrical Energy Producers Act (LEEPA), RSA 362-A, in June 1978 (revised in 1983) to encourage "small-scale and diversified sources of supplemental electrical power to lessen the state's dependence upon other sources which may, from time to time be uncertain." Similarly, the Maine legislature enacted the Small Power Production Facilities and Cogeneration Act in 1979, MRSA Title 35, (revised as The Maine Energy Policy Act of 1988). These legislative actions contributed significantly to establishing a public policy environment conducive to the development of native energy resources.

These national and state energy policies enjoy broad public support for improving energy security and opened the door for alternative energy options. In both Maine and New Hampshire the expanded use of hydropower and wood energy sources were viewed as consistent with these policies and desirable as a redevelopment of traditional energy resources. State energy plans identified the energy development potential of these indigenous resources and the benefits that could accrue from their use.

The implementation of PURPA and related laws provided the opportunity, if not the imperative, for hydro and wood development in the two states consistent with public energy objectives. Since the policy objectives of PURPA and related laws are consistent with state energy policies in the area of energy efficiency and development of alternatives to oil the implementation of these laws served to also fulfill state energy objectives.

Guided by established energy objectives that included the use of wood, the Public Utilities Commissions in the two states implemented alternative energy programs with an expectation that hydro and biomass options would be viable alternatives. In Maine, some Commission members actively worked to encourage the development of alternative energy projects, especially early biomass cogeneration projects. In NH the PUC anticipated a big role for hydro with a definite potential for wood. As it turns out in the two states, the energy potential for hydro has been rather limited, while woody biomass options have far exceeded expectations.

While the structure of the opportunity for wood- fired generation was framed by the rules implementing PURPA and related laws, the inherent competitiveness of biomass as an energy alternative set the pace for alternative energy projects. Independent developers responded to the generally positive environment of supportive public policy with a host of proposals based on the relative competitive advantages then existing with woody fuels. In a period of high oil prices and potentially more expensive alternative sources of electricity wood-fired generation facilities were cost competitive in Maine and New Hampshire. This competitive advantage was supported by ample supplies of mill residues and forest biomass, opportunities for cogeneration in existing wood products mills, a well developed supply network, a good forest inventory data base, and a tradition of burning wood for on-site energy needs.

To the independent power developer a biomass energy project is strictly speaking a business opportunity. Each wood-fired power plant is carefully designed to fill a power purchase contract agreement, with a plant sized and fueled to be run efficiently. In cogeneration settings the power facility is operated to meet internal needs with sales of excess power to a utility, while stand alone plants are designed and operated to produce electricity strictly for sale.

With up to ten years of operational experience on some plants, the biomass energy industry has proven the technical feasibility of generating electricity from wood and demonstrated the high degree of reliability of these plants. In both states energy planners, Utilities Commissions, and utilities now recognize the technical viability of wood biomass energy options, but declining oil prices, and economic recession have eliminated the cost competitiveness of wood energy in the current marketplace.

Lessons for America

The development of the wood biomass energy industry in Maine and New Hampshire has contributed significantly to attaining greater energy self-sufficiency, while enjoying the economic benefits and energy security that accompanies indigenous resource development. This experience is the ultimate out come of bold new policies created in national and state energy legislation. Policies widely supported and implemented through the utility regulatory process.

Supportive public policies were essential to the development of the wood biomass energy industry in Maine and New Hampshire. Direct and clear policy objectives in the form of legislation and state energy plans expressed wide spread support for the development of local energy resources. The energy crisis of the 1970's sent a strong message to the US and the people of Maine and New Hampshire, an area highly dependent on imported oil supplies, that fundamental changes in energy use and sources were needed to assure energy security in the future. The enactment of state and national energy legislation established new energy policies positioning the region for changes in its energy mix. Aggressive implementation of PURPA through the actions of state regulatory commissions lead directly to the development of biomass energy plants.

The emergence of independent power producers, especially with stand alone facilities, fundamentally changed the structure of the electricity supply in the region. The business community response to an economic opportunity was stimulated by new energy policies, and resulted in the establishment of a whole new industrial sector in the regional economy.

NORTH PLANT CO-GENERATION PROJECT
for
SOUTH DAVIS COUNTY SEWER IMPROVEMENT DISTRICT

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Abstract

In the summer of 1988, the South Davis County Sewer Improvement District (SDCSID) learned of a grant/loan program being administered by the Utah State Department of Energy(DOE) for projects that demonstrate new and innovative ways of conserving energy or utilizing renewable energy sources. The SDCSID applied for and received from the DOE both a grant and a no-interest loan to finance half of the cost of a co-generation project at the North Wastewater Treatment Plant. This co-generation project utilizes methane gas, a by-product of the anaerobic digestion process, to generate both electricity and heat that is used at the plant.

The SDCSID calculated that at the current anaerobic gas production rate, a 140 KW engine generator could be run almost 24 hours a day. Approximately 75% of the current electrical needs at the North Plant are supplied by the 140 KW engine generator. Also, all of the heat necessary to raise the temperature of the incoming sludge to 95° F., and to heat four large buildings is supplied from the heat recovery system of the engine.

The system utilizes an induction type generator to supply electricity, which is somewhat simpler to design and less expensive to install than a synchronous type system. An induction system utilizes the Electrical Utility's incoming power to excite the generator to correct the phase so that it can be used by the loads in the plant. In addition, the SDCSID installed a second identical engine generator as a back-up and to peak shave. Plant effluent is used to cool the engines instead of air-cooling through radiators.

Start-up of the system was not without its problems as the engines' cooling systems needed to be changed both by the engine manufacturer and by the SDCSID in order to properly cool the engines. In addition, a major problem with the power factor as measured by the Electrical Utility was causing all savings by the reduction of the load from the Utility to wiped out. Capacitors had to be installed both at the engines and at the main feed from the Utility to the main bus in order to bring the power factor to above 0.90.

Currently, the SDCSID has reduced its electrical bills from an average of around $7000 per month to around $2000 per month. With further improvements in the peak shaving capabilities, the monthly bill is expected to go down even further. Expenses to operate the facility are estimated to be around one cent per KWH. The total project cost was $520,000. After making financing payments, and subtracting O&M expense, there is a net profit of around $10,000 per year. Based on a total capital cost of $520,000, a discount rate of 6%, and a net benefit after O&M of $44,500, the pay-back period for the project is 9 years.

COGENERATION PROJECT
AT
SOUTH DAVIS COUNTY SEWER IMPROVEMENT DISTRICT

In the summer 1988, the South Davis County Sewer Improvement District learned of a program being administered by the Utah Department of Energy(DOE) concerning the funding of energy projects which demonstrated new and innovative technologies for conserving energy or which utilized renewable energy sources. During the design of the expansion and rehabilitation of the District's North Plant, an engineering firm had looked at cogeneration and had concluded that cogeneration was about a break-even prospect on a plant the size of the North Plant. Construction of the expansion and rehabilitation of the North Plant had started in the fall of 1988 and the District knew that any cogeneration project would have to be coordinated closely with the present construction. The District decided to take a closer look at cogeneration with the idea that some of the costs of the facility would be funded by the DOE.

After analyzing the prospect of cogeneration at the North Plant, the District then applied for a $250,000 grant from the DOE to cover approximately half the estimated cost of the project. Soon after the District learned that the DOE had approved the project and had awarded a grant of $125,000, and a ten year, no-interest loan for $125,000.

The District put a considerable amount of research into the design of the facility with the idea that it must be reliable, fairly easy to operate, and within the budget. After completing the design, the District started construction on the facility in the spring of 1991 and completed construction by the end of the fall of that year. Start-up of the project continued through the end of the fall of 1991 and was not without its problems. However, today, the District has seen the electrical bills go down from approximately $7000 a month to about $2000 a month and is currently working on utilizing the second engine for peak shaving capabilities.

Design Decisions

Previous to starting the design, the District looked at several existing cogeneration facilities in the intermountain area and also looked at several sites in the San Francisco Bay area that were of similar size. From those visits, the District made the following general observations:

- Air-cooled radiators which removed excess heat from the cooling system seemed to be a very high maintenance item to the point that almost every installation was having problems with them.
- Those facilities that experienced a lot of maintenance problems with the engines quite often were those that had bought a "surplus" enginator that was not designed for burning digester gas and which had been converted from some other fuel to burn digester gas.
- The operations of the treatment plant played a very important part in the quality and quantity of digester gas produced.
- The method of supplying the electricity to the plant for utilization varied greatly and could be as expensive as the enginators themselves.

- The attitude of the staff toward the systems played a very important part in whether the system was successful or not.

After observing the experience of other installations, and after taking a closer look at the quality and quantity of digester gas being produced, the District started the design process.

Selection and Sizing of Enginators.

The District had not had very reliable gas metering previous to the expansion of the North Plant. In the construction project, the District was going to install a "mass-gas flow meter" that had received good references from numerous other installations, but the meter was not going to be installed soon enough to allow for an analysis of the existing gas flows. Therefore, the District decided to look at both "text-book" values for gas production and to look at other plants who had seemingly accurate gas meters. Table 1 shows the a summary of the information gathered

Table 1
Gas Production Summary

	North Plant[1]	Orem Plant[2]	Napa Plant[3]	Pinole Plant[4]
Level of Treatment	Second.	Second.	Primary	Primary
Flow (MGD)	5.72	4.00	4.00	3.00
Estimated Population	38,100	32,000	40,000	16,000
Digester Gas Production (Cu.Ft. /Day)	57,734	57,300	54,600	22,000
Gas Production				
Cu.Ft. /Cap. Day	1.52	1.79	1.37	1.38
Cu.Ft. /MGD	10,093	14,325	13,650	7,333

[1] North Plant Records September 1987 to January 1989.
[2] Orem Wastewater Plant records May 1988 to Dec. 1988.
[3] Plant records from Napa, Cal. plant 1985-86.
[4] Plant records from Pinole, Cal. plant 1985-86.

The District looked at the present flows into the plant and made the decision to size the enginator on the growth of the next five years and to not do a "twenty-year" design based on gas flow projections. It had been noticed that many small plants had overestimated the amount of gas available and were forced into burning a large amount of natural gas to make electricity and to keep the engines on line. Secondly, the District had to look at the heating requirements of the primary digester and the four buildings that would be heated by the hot water. Figure 1 shows the existing system that the District was using to heat the digerster and two of the plant's buildings. Figure 2 shows the proposed flow schematic of the cogeneration system along with the design criteria of the enginators.

Based on the fact that the most of the installations that had been visited were using Waukesha Enginators, the District also decided to use that make of engine. The engine selected based on the design criteria was a turbo-charged Model No. VSG11GSI. One item that concerned the District was that this engine would turn at 1800 rpm. Industry in the past had recommended that slower engine speeds be used to allow a longer life for the engine. However, after looking at the "life-cycle costs" of both purchasing and maintaining the engine, the VSG11GI was selected. This engine would supply approximately 85% of the plants electrical needs over the next five years. It would also burn all of the gas produced by the plant for the next 5 years, but most importantly, would supply all of the heating requirements for both the sludge and the buildings for the next twenty years. A summary of the specifications for the engine is as follows:

Table 2
Enginator Specifications

Manufacturer	Waukesha Power Systems
Model No.	VSG11GSI
Speed	1822 RPM
Type of Generator	Induction
Voltage	480
Kilowatts/KVA	140/166.7
Power Factor	0.85
Heat Rejection	813,000 BTU/hr.

Electrical/Control Design.

Due to the fact that the North Plant Expansion was well underway, the electrical and control design was somewhat controlled by the new equipment being installed. The new Motor Control Center for the entire plant was already installed, and there was a new 600 KW stand-by generator on-line that was capable of running everything in the plant at once. Basically, there were two alternatives available to the District on how to configure the tie to the electrical system from the generators. The first, and most common, was to supply a synchronous type generator that would require a division in the motor control center such that a portion of the equipment would be run by the generator and the remainder would be run through the utility. It would also require that either an auto-transfer switch be supplied to switch the equipment over to the utility should the cogeneration system fail or that a load shedding device be installed that would drop out the equipment that was being run by the utility's supply.

The second type of system is an inductive type system that allows the feed from the generator to go directly to the bus on the motor control system through a breaker. This system requires that the utility's feed correct the phase and synchronize the power from the generator on the engine. The main problem with this system is that if the utility goes down, so does the cogeneration system. But with the size of the stand-by generator, loss of both the utility and the cogeneration system was not a problem.

Since the cost of the synchronous type switch gear was about $40,000 more than the cost of the control panels for the inductive type system (this includes both controls and MCC modifications), and since the District had already installed a new motor control center which would be difficult and expensive to modify, the decision was made to go with an inductive type system.

Heating and Cooling System

It was rather easy to tie the cogeneration system into the heating system that was being installed in the new plant upgrade. The upgrade included a new boiler, heat exchangers for heating the sludge, and a new hot-water distribution system. One major decision made was not to use a fan-cooled radiator to cool the temperature of the return water that in turn cooled the water circulated through the engines. It was decided to use a plate-&-frame type heat exchanger with plant effluent being pumped through the exchanger to bring the temperature of the water down. As an added benefit, the cooling water, which was chlorinated effluent, was then discharged into the sludge gravity thickener. The application of chlorinated effluent to the thickener has worked very well in reducing odors from the thickener.

The cooling water system is controlled by a PLC that has a set point temperature of the water going back to the engine's cooling system. A set of variable frequency drives control the speed of the pumps that send the plant effluent to the cooling water heat exchanger.

Gas Handling Equipment

Since the cogeneration facility was to be built onto the existing stand-by generator building, the distance from the digesters was too far for the pressure from the digester gas holding system (14"W.C.) to supply the gas at an adequate pressure. It was decided that a water seal type gas compressor would be used and that would bring the pressure of the system up to about 2 p.s.i. A liquid ring compressor was chosen since it has been industry experience that the water used in the compressor will wash out up to 70% of the hydrogen sulfide in the gas. The district had found that the gas at the North plant contained below the recommended limit for hydrogen sulfide (0.20%), but felt that using the liquid ring compressors was a cheap way to reduce the hydrogen sulfide level to an even safer level. Hydrogen Sulfide is one of the major problems in using digester gas. Its presence can break down the lubricating oil of the engines, corrode rings and valves, and condense in the exhaust system and cause extensive corrosion. After the compressors, a coalescing filter was installed to remove any solids entrained in the gas and to reduce the water content.

Utility Rates

One of the major items that concerned the district was the decision of whether to stay on its current rate schedule with the utility, (rate schedule 6), or to go with what the utility recommended, rate schedule 31. This was a special back-up rate schedule designed for cogeneration systems. A careful analysis showed that the back-up rate would run around $1000 per month. This would allow the District to have scheduled down times for maintenance and repair without paying a penalty for the increased power demand. With rate schedule 6, the District pays a demand charge which is based on a moving 15 minute average over the entire billing period. This demand charge could negate any reduced power bill that the cogeneration system would give to the District if the engine was to drop out for at least 15 minutes. Therefore, the District investigated the possibility of purchasing a second engine. This engine would serve as a back-up to the system and would come on line automatically if the first engine was to go down. The monthly cost of the engine, based on the financing that the District was using for the plant expansion, was $670/month. Because this was considerably cheaper than using the backup rate, it was decided to purchase a second enginator identical to the first. Besides saving money on utility billings, the second engine also gave the additional following advantages:

- Allows the operators the time to change the oil and do other monthly maintenance items wihout being rushed for time.

- Provides for the possibility of doing peak-shaving with the second engine.

- Callouts to make repairs on the engines will be reduced since the second engine will come on line automatically if the first one fails.

- Almost doubles the life of the engines since each one will only be running half as much.

- The District has an asset for its investment in the form of a second engine.

Misc. Items

One unique aspect that was designed into the system was that of environmental control. A fairly sophisticated air handling system was designed that would keep the air temperature in the cogeneration room below 80 deg. F. This not only improves the performance of the engines, but increases the life of both the engines and the electrical gear in the room.

Another item, that was picked up from another plant was that of providing for a make-up oil system. By installing a holding tank next to the engine, and by supplying a make-up valve, a constant level of oil in the crankcase is always provided. And, when the oil is to be changed, a little pump is attached to the drain pipe coming from the crankcase, the oil pumped out, and the new oil drained in from the make-up tank. Oil changes, which are done on a monthly basis, are done quite easily.

Construction and Start-Up

The cogeneration facility was finished in the fall of 1991. Construction went fairly well with the engines being installed in a building that was an addition to the stand-by generator building. The District had made all of the heating water system changes to allow for the cogeneration system during the North Plant Construction Project. In addition, all of the electrical changes necessary were also done during the construction project. Start-up of the system did not go as smoothly. It seemed that just as soon as one problem got solved another one would crop up. The following describes the problems that were involved with the start-up of the project.

Engine Controls and Adjustments

It took a couple of months for all of the problems with the controls of the engines to be worked out. One of the major problems was the requirement for the engines to be started and disconnected automatically. In addition, there were several adjustments to the carburetor system, the ignition system, and the gas switchover systems. But all were eventually made to operate as originally designed and specified.

Cooling Water System

When the cooling water pumps were turned on, it became obvious that they could not properly track the required set point temperature. The PID controller could not adjust the speed of the pumps without overshooting and undershooting the set point temperature of 165 deg. F. A closer analysis revealed that the pumps were operating at a very low pressure and the slightest increase in pump speed made a significant increase in flow. This problem was solved by installing a flow control valve just down-stream of the cooling water heat exchangers and to install a PID controller for that valve and to control off of temperature. The cooling water pumps were then set up to be controlled off of pressure with the pumps always maintaining at least 5 p.s.i. in the system. After installing the control valve and new controller, that part of the system worked well.

Expansion Tank

Just as soon as the system was started up again, there cropped up another problem of not being able to maintain a constant temperature in the engine-jacket cooling water system. After completely checking all of the circulating systems, and after getting the engine manufacturer involved, it was found that the expansion tank on the engine was not operating correctly. A closer inspection found that there was a baffle inside of the expansion tank that was not allowing the circulating water of the engine to flow properly. This was changed and again the engines were started up again.

Intercooler Plugging

With the use of a turbocharger on the engines, it became necessary to supply cooling water to the intercooler of the turbocharger. Again, plant effluent was used for this function. But within a few hours of operation, it became apparent that the strainer at the front of the cooling system was getting plugged and required constant flushing. The District then designed a screen at the influent to the cooling water system that greatly reduced the problem.

Power Factor

After all of the mechanical and control problems were taken care of, the District was finally ready to run the engines for a solid month. After two months of operations with no down time, the utility bill had not gone down, but in fact had gone up! After a close examination, it was found that the power factor was below 0.30 as measured by the utility. Anything below 0.90 receives a penalty from the utility. Power factor is the ratio of working power to apparent power. It measures how effectively electrical power is being used. A high power factor signals efficient utilization of electrical power while a low power factor indicates poor utilizations of electrical power. To determine power factor, one simply divides the working power (kw) by apparent power (kva).

Most loads in modern electrical distribution systems are inductive, or in other words, they need an electromagnetic field to operate. Motors, transformers, gaseous tube lighting ballasts, and induction furnaces are all examples of inductive loads. Working power consumes watts and can be read on a wattmeter. It is measured in kilowatts (kw). Reactive power doesn't do useful "work", but circulates between the generator and the load. It places a heavier drain on the power source, as well as on the power sources's distribution system. Reactive power is measured in kilovolt-amperes-reactive (kvar).

Utility companies today are becoming more and more concerned with power factor as their systems reach their design capacity. A more efficient use of the power means that the available power is used more efficiently which in turn reduces air pollution, eliminates needless expansion of power generation systems, and reduces the load on a distribution system.

The District has specified that the generators produce a power factor of at least 0.80. The power factor measured at the generators produced a value of 0.85. But when measuring the power factor where the utility power tied into the system, it was 0.30. When two engines were running it was about 0.15. However, when the engine was turned off, the power factor of the plant increased to 0.80. It was obvious that the engines were the culprits, but only when their power was combined with that of the rest of the plant at the utility feed. This problem baffled the utility company and several outside consultants.

While some time was spent in trying to understand why the power factor was varying, the solution to the power factor problem was fairly obvious, and that was to install power capacitors to generate excess reactive current. The problem was how to determine how much capacitance was needed and where to install them. The District performed an in-depth study on the nature of the power factor problem and also contacted the generator manufacturer to receive their input. The manufacturer would not allow more than 44 KVAR capacitors on the generators. The investigation done by a power specialist determined that another 100 KVAR unit was needed to bring the power factor to above 95%. Two 44 KVAR units were installed on the generators and another 100 KVAR unit was installed at the main feed of the utility power to the bus. A power meter was installed that had the capability to measure KVAR and the value was recorded on a circular chart. Since installing the capacitors, the power factor has always been above 0.98. In addition, capacitors were installed on all of the motors that were larger than 30 hp, of which there were ten.

Summary of Cost and Benefits

The District prepurchased the enginator sets in order to save sales tax, contractor mark-up, and to obtain the desired package. In addition, the District prepurchased the majority of the other major equipment items such as pumps, air handler, heat exchangers, and control instruments. The construction of the building was issued as a change-order to the Contractor that was constructing the North Plant Expansion. The installation of the equipment and the mechanical work was bid out and the Contractor on-site was the low bidder. Table 3 summarizes the costs associated with the project.

Table 3
Summary of Costs

ITEM	COST
1. Two Engine Generator Sets	$210,000
2. Mechanical Bid	150,000
3. Electrical Change-Order	50,000
4. Building Change-Order	50,000
5. Misc. Owner Furnished Equipment	35,000
6. Engineering, Design, Const. Mgmt.	45,000
TOTAL	$520,000

Currently, the District has reduced its electrical bills from an average of around $7000 per month to around $2000 per month. With further improvements to the peak shaving capabilities, the savings could go up. At this time, it is very difficult to estimate the cost of O&M since neither a major or minor overhaul has been done yet. However, it is estimated that the cost is about one cent per kilowatt hour as based on industry experience. After making debt payments and paying for O&M, there is a net of about $16,000 per year. After ten years, this amount will go up to $28,500, and after twenty years, $47,500.

Based on a total capital cost of $520,000, a discount rate of 6%, and a net benefit of $47,500 after O&M, the pay-back period is 8.6 years.

Operational "Tidbits"

The District has made several observations that it feels that have helped make this project successful.

Digester Operation

Never before has the operation of the primary and secondary digester been so important for the District. Any upset in the digester literally costs the District money since natural gas has to be used to run the generator. The District has found several items that have greatly helped in the production of digester gas.

Industrial Pretreatment Program

With the large industrial base that the District has, the possibility of an upset to the anearobic digesters was possible due to a toxic discharge. The District monitors all of its industries very closely to make sure that they do not discharge a toxic substance that would upset any of the wastewater plant's biological functions.

Constant Sludge Feed.

The District has found that by feeding a small amount of sludge every 30 minutes has optimized the gas production. There have been several instances where too much sludge was fed all at once and the digester would foam.

Gravity Thickener

The District has found the gravity thickener to be a great asset in controlling the sludge solids concentration to the digester. A blanket of about 7 feet has been found to be the optimum level in the operations of the digester and is checked daily. Sludge is thickened to around 5% from the 1-2% influent concentration. This thickening reduces the amount of feed to the digesters which then lowers the heating requirements.

Engine Maintenance

Oil is changed in the engines every 500 hours and a sample is sent in to see if the oil is breaking down. It is felt that the frequent oil changes are extending the life of the engines considerably. From the oil samples it can be determined if the rings or valves are deteriorating, if hydrogen sulfide is breaking the oil down, and if the filter on the digester gas needs to be changed. The filter removes silicon from the gas which deposits in the oil and hurts its viscosity. In addition, spark plugs are checked regularly, and the oil and water temperatures are checked every morning and afternoon.

Operator Input

From the beginning, the operators played a big part in how the facility was designed and how the problems have been solved. In fact, most of the problems in the start-up, were handled totally by the operators. This has given them the insight to know exactly how the system should operate and most importantly <u>why</u>. Their attitude toward the system is what makes it work and is probably the most important factor in making this a successful project. Designs can always look good on paper, but it is the guy in the field that ultimately makes it work.

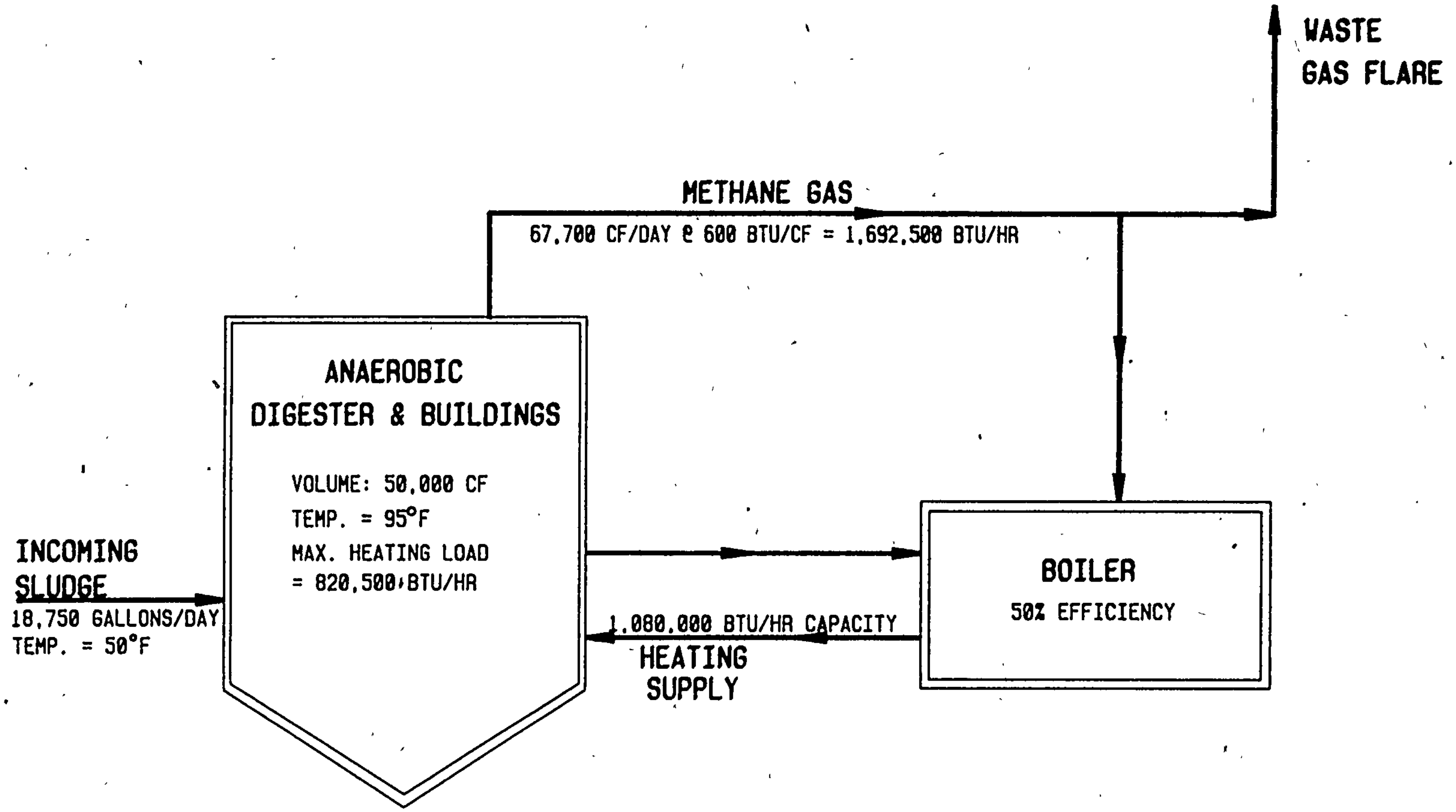
Conclusions

With the experience gained from the North Plant Cogeneration Project, the District decided to go ahead and do a cogeneration project at its South Plant. This facility with have two 85 kw engine generator sets and will produce about half of the power needed at the plant. While the District did not receive a grant for this project, it was able to reduce the cost of the project by optimizing both the building space and the electrical system. Based on good operations and a frugal design, the District has been able to make cogeneration a successful and profitable concept for the smaller waste water facility.

More importantly, the District is utilizing a renewable energy source. Over 1.25 million Kilowatt-hours are being conserved annually by better utilizing the digester gas. In addition, the energy is being utilized at a rate of 85% efficiency during the winter months when both the heat is being consumed along with the power. Finally, there is a benefit to the environment. By burning the digester gas at a much higher temperature in the engines, emissions are reduced considerably than if the gas was burned in either a boiler or a waste gas burner, which is typical of a waste water facility.

Acknowledgments

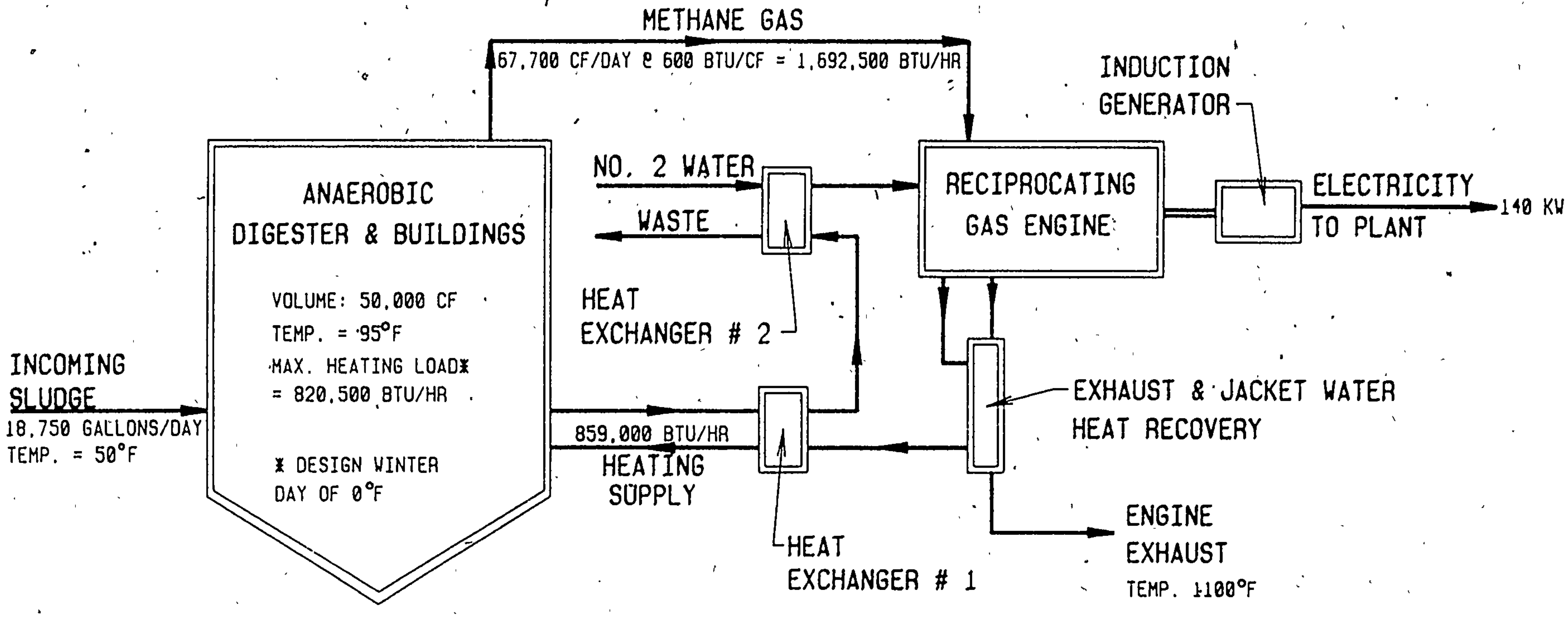
I would like to acknowledge the South Davis County Sewer Improvment District for their co-operation in the preparation of this technical paper.



EXISTING FACILITIES

FIGURE NO. 1

ENERGY INPUT		
TOTAL REQUIRED	1,645,000 BTU/HR	100%
DIGESTER GAS	1,692,500 BTU/HR	103%
ENERGY OUTPUT		
POWER GENERATION	478,000 BTU/HR	29%
EXHAUST HEAT RECOVERY	573,000 BTU/HR	35%
JACKET WATER COOLING	286,000 BTU/HR	17%
WASTE	308,000 BTU/HR	19%



PROPOSED COGENERATION FACILITY

FIGURE NO. 2

THE ACIMET® PROCESS: AN INNOVATIVE APPROACH TO BIOGASIFICATION OF MUNICIPAL SLUDGE

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Abstract

This paper reports the results of successful completion of an advanced anaerobic-digestion-process commercialization program supported by the County of DuPage, IL and the State of Illinois Department of Energy and Natural Resources, Springfield, IL. The project entailed anaerobic digestion of municipal sludge by pilot- and full-scale Acimet Process, which replaced an existing high-rate digestion system. The project was conducted at the Woodridge-Greenevalley wastewater treatment plant of DuPage County, IL. The Acimet Process relies on the application of two-phase anaerobic digestion for enhanced methane production and stabilization of municipal sludges, the disposal of which poses intractable problems in many municipal wastewater treatment plants. Unlike conventional anaerobic digestion processes, the Acimet System optimizes the liquefaction- acidification and acetogenic-methanogenic fermentations in separate acid- and methane-phase digesters operated at different hydraulic residence times (HRTs) to maximize feed hydrolysis and acidification, as well as biomethanation of the acidic intermediates. The Acimet System installed at the Woodridge Plant utilizes two mesophilic upflow digesters of novel design exhibiting unusually high product-formation efficiencies achieved without any mechanical mixing of the reactor

contents. The acid-phase digester (APD) operated at an HRT of about 1.8 days generated effluents containing 9000 mg/l - 12,000 mg/l of volatile fatty acids indicating efficient hydrolytic degradation and acidification of the complex process feed. The APD effluent was gasified in the methane-phase digester (a separate biogasifier) generating 97.5% of the system methane production. Methane content of the methane digester gas was about 65% compared with a methane content of 32% for the acid-digester gas. The Acimet Process exhibited a high methane yield of up to 8.6 SCF/lb VS added which was more than double that of the old high-rate digester. Other advantages of the Acimet Process include a capability of system operation at higher loading rates and lower HRTs, a doubling of the VS reduction, and a reduction in digested solids dewatering cost relative to those of conventional high-rate digestion; elimination of digester foaming, high pathogen kill rates, and enhanced process resilience and stability, all of which are important in relation to U. S. EPA's new 503 Regulations for ultimate disposal of digested residue.

Introduction

Disposal of municipal sludges and other organic solid and liquid wastes is a growing problem. Sludge disposal practices in the United States may be significantly impacted by the promulgation of 40 CFR Part 503 Sludge Regulations effective February 1993. The 503 regulations impose new and stringent standards on ultimate disposal of raw and processed municipal sludges by land application (including beneficial use), surface disposal in landfills and other piles, and incineration. Anaerobic digestion seems to be better than aerobic digestion, composting, and incineration in terms of its capability to process biosolids to produce an acceptable residue that meets the volatile-solids-reduction and pathogen/vector-attraction requirements of the 503 Regulations. Unlike aerobic digestion and composting, anaerobic digestion offers an opportunity to recover the energy value of biosolids in the form of methane -- a clean fuel -- and generate a residue for agronomic use.

Anaerobic digestion refers to a complex biological process consisting of several fermentation steps involving hydrolysis of polymeric feeds to produce sugars, peptides, amino acids, CO_2 and H_2; acidogenesis of the hydrolysates to produce acetate and higher volatile fatty acids (VFA); reduction of sulfur compounds to produce inorganic and organic sulfides; acetogenesis of the higher VFAs to produce acetate; and methanogenesis of acetate, and CO_2 and H_2 to produce methane. The acidogenic, acetogenic, sulfate-reducing, and methanogenic organisms that mediate these reactions have significantly different generation times and environmental optima; consequently, the efficacies of these different bioconversion processes cannot be maximized in the environment of a single bioreactor. Ideally, the overall process of anaerobic digestion should be conducted in a staged system consisting of two or more bioreactors; separate bioreactors should be provided to harbor enrichment cultures of acidogens, acetogens, and methanogens in environments that maximize the activities of the respective microbial consortiums.

Conventional Digestion Process Configurations

Several process configurations are available for commercial application of anaerobic digestion. In commercial process designs, the various fermentation steps of anaerobic digestion are conducted in a single bioreactor that caters to the requirement of the most sensitive, slow-growing acetoclastic methane formers. The most common anaerobic digestion system is the so-called "high-rate" process that utilizes a "completely mixed" primary digester operated in tandem with a secondary digester to facilitate solid-liquid separation by simple gravity sedimentation. Rational design of high-rate digesters involves the selection of an HRT at which the rate of acid production by the fermentative acidogens is balanced by the rate of acid utilization by the methanogens. The HRT needed to balance acid and methane fermentations in a single-reactor system is high because it is dictated by the kinetic limitations of acetoclastic methane fermentation. Any operating condition that enhances the

proliferation of acidogens and/or retards the growth of methanogens will increase the acid production rate requiring an increased HRT for *balanced digestion. Unbalanced anaerobic digestion* may occur under this condition unless the HRT is appropriately increased.
Operating conditions that may lead to unbalanced digestion include, but are not limited to, inadvertant increases in hydraulic and/or solids loading rate, reactor temperature excursions, lack of pH control, lack of mixing, introduction of methanogenic inhibitors, and the charging of more biodegradable feeds. Unbalanced digestion favoring enhanced acid formation and/or decreased methanogenic activity could lead to increasing VFA accumulation and concomitant pH depression, and ultimately to unstable bioreactor operation and *sour digestion.* As has been reported by numerous investigators, the occurrence of unbalanced and sour digestion is a serious shortcoming of "high-rate" digestion. This potential problem is usually overcome by digester operation at high HRTs up to 40 days depending on the feed, and low organic loading rates. High liquid retention times require the use of large and expensive digestion tanks that experience large heat losses through the tank surface area which in turn could lead to negative *net energy production.*

In completely mixed reactors, the organism specific growth rate is approximately equal to the reciprocal of the HRT. Therefore, the prevalent specific growth rate of acidogens in a high-rate digester would be between 0.06/day and 0.025/day; the rates hydrolysis of organic matter and acid formation at these growth rates would be quite low, which is still another shortcoming of the conventional high-rate digestion process. Depressed hydrolytic activity at high HRTs means that certain complex feed components would not be degraded in a single-stage anaerobic digester. The inability to biodegrade such complex feed components as oil and grease, proteins, lipids, natural and synthetic surfactants, vegetable gums, biopolymers, and certain cell fractions could cause serious foaming problems in digesters that receive primary and biological sludges.

A number of microorganisms including *Pseudomonas. aeruginosa, Acinebacter calcoaceticus, Bacillus licheniformis, B. subtilis, Rhodococcus erythropolis,* and others, which may thrive in activated-sludge or nitrification processes, are known to produce various types of complex biosurfactants (Van Dyke *et al.* 1993). These biosurfactants could be introduced into an anaerobic digester with the waste activated sludge (WAS) to cause severe foaming if they remain undegraded. It is known that such filamentous organisms as *Nocardia , Microthrix paricavella, Rhodococcus rhodochrous, Thiothrix,* and other species cause foaming in the activated sludge process. WAS that contains these organisms also causes foaming in high-rate digesters (Pitt and Jenkins 1988) probably because the foaming agents synthesized by these cells are not hydrolyzed significantly in conventional high-rate digesters. There is thus a need to develop innovative anaerobic digestion process configurations that overcome the above limitations of traditional high-rate digestion process and at the same time enhance renewable energy production from waste organics. Development of the Acimet Process was undertaken to meet this need. The process concept was originally patented by Ghosh and Klass (1977)

An Innovative Approach to Anaerobic Digestion: The Acimet Process

The Acimet Process entails biphasic anaerobic digestion of municipal sludges in a two-stage system in which a first-stage, *acid-phase* digester maximizes hydrolytic breakdown and acidogenesis of the raw feed; methanogenic gasification of the acidogenic end-products is maximized in a second-stage, *methane-phase* digester. Separate optimization of the hydrolysis-acidification and coupled acetogenic-methanogenic fermentations in two separate bioreactors results in higher organics stabilization and gasification rates and efficiencies, higher process stability and resilience, higher net energy production efficiencies, and greater pathogen kill rates than those of the conventional single-stage, high-rate digestion process (Ghosh 1987; Ghosh 1991; Lee *et al.* 1989).

The Acimet Process was tested successfully in pilot scale at the Woodridge-Greenevalley wastewater treatment plant (WWTP) of DuPage County, IL to overcome high-rate digester- foaming and overloading problems (Ghosh 1991, Ghosh *et al.* 1991; Ghosh and Buoy 1989). The pilot-plant experience formed the basis for conversion of the existing high-rate digestion facility to the full-scale two-phase Acimet Process. The full-scale Acimet Process has been operating successfully at the Woodridge-Greenevalley WWTP, DuPage County, IL for more than one year. This paper presents the results of full-scale operation of the Acimet Process at DuPage County, IL.

The Woodridge-Greenevalley WWTP

The municipal wastewater treatment plant at Woodridge, IL provides grit removal, conventional activated-sludge treatment, nitrification *via* trickling filtration, and tertiary treatment by sand filtration. The plant design does not provide for conventional primary sedimentation. Final treatment includes chlorination and postaeration of the tertiary effluent.

Sludge Disposal before Installation of the Acimet Process

At the Woodridge WWTP waste-activated sludge was concentrated by dissolved-air flotation (DAF) thickeners. The thickened sludge was digested by conventional two-stage anaerobic digestion at a mesophilic temperature. A part of the digested residue is dewatered by belt pressing and composted to produce a final product made available to the public and commercial users. The remainder of the digested residue is landfilled and land-applied for ultimate disposal. Digester gases are stored under pressure in a gas sphere. These gases are used to heat the digesters and plant buildings.

The two-stage digestion facility consisted of two 55-ft (16.6-m) diameter 28-ft (8.5-m) deep digesters operated in series. The primary high-rate digester has a floating cover; it was mixed with compressed digester gas. The high-rate digester was operated at a loading rate of 0.119 - 0.135 lb VS/ft^3/day (1.91-2.16 kg VS /m^3-day) and a nominal hydraulic residence time of 20 - 22 days.

Sludge Disposal by the Acimet Process

The full-scale Acimet System was designed to digest DAF-thickened WAS. The DAF unit was replaced by a novel rotating-drum thickener in 1993. The full-scale Acimet System utilizes a new 21-ft diameter and 34-ft deep cone-bottomed upflow acid-phase digester operated *without any mechanical mixing* at a mesophilic temperature. This digester has a fixed cover. It can be operated at three side-water depths corresponding to culture volumes of 76,000, 65,500, and 47,700 gallons. The acid digester can be operated at HRT's between 1.5 and 4.0 days. It is fed with concentrated sludge for periods of 22 to 23 hours per day, which is equivalent to continuous feeding for all practical purposes.

The existing high-rate digester is utilized as an *oversized* methane digester of the Acimet System. Although results of the pilot plant studies showed that an HRT of 9 days was adequate for methane-phase digestion, it was not possible to obtain a methane-digester HRT of less than about 18 days with the existing 55-ft diameter high-rate tank. The methane digester was capable of compressed-gas mixing which is not required for the two-phase mode of operation. The methane digester is operated now in an upflow feeding mode without compressed-gas mixing.

Discussion of Acimet-Process Performance Data

Proper monitoring of the performance of a digestion process requires the measurement of a number of parameters. A number of analyses and measurements are conducted daily to monitor the performance of the full-scale Acimet Process operating at the Woodridge WWTP. Twenty five essential measurements and analyses are performed on the aqueous and gaseous influents and effluents. Influent and effluent sludge flow rates are measured for each of the two Acimet digesters. The process feed, acid- and methane-digester effluents, and a methane-digester recirculation stream were analyzed for total solids (TS), volatile solids (VS), and pH. Acid and methane digester temperatures are measured at several levels within each tank. Gases emanating from each digester were measured by separate gas meters. These gases were also analyzed for contents of CH_4 and CO_2. The acid digester effluent was analyzed by gas chromatography to determine the concentrations of C_2 through C_6 VFA's.

Table 1 presents recent operating and performance data for the full-scale Acimet Process at the

Woodridge WWTP at DuPage County, IL. This table shows monthly averages of several operating and performance parameters for the first four months of 1993. Variabilities of these parameters are presented for April 1993 data. The feed sludge flow rate varied the most (19%); acid- and methane-digester HRTs, organic loading rates, and gas production rates, which are directly related to

Table 1. Operating and Performance Data for Full-Scale Acimet Process: Monthly Averages

	Jan 1993	Feb 1993	Mar 1993	Apr 1993
Feed sludge				
Flow rate, gal/day	23,312	26,670	27,611	27,698.0 (19)*
TS, wt%	6.8	5.9	6.6	7.1 (11)
VS, wt%	83.0	84.2	79.1	77.1 (3)
pH	6.2	6.2	6.3	6.3 (2)
Acid digester effluent				
Temp, ^{0}F	95.1	94.7	94.5	94.9 (2)
HRT, days	1.7	1.8	1.8	1.7 (15)
VS, wt%	79.0	81.9	78.9	73.0 (4)
Loading rate, #VS/ft^3-day	1.77	1.81	1.85	1.80 (17)
pH	5.6	5.7	5.7	5.6 (2)
Gas prod, SCF/day	5621.0	6246.0	6577.0	7049.0 (14)
Gas composition				
CH_4, mol %	21.1	25.4	31.6	31.7 (5)
CO_2, mol%	77.8	73.4	67.3	67.3 (3)
(N_2 + other), mol%	1.1	1.2	1.1	1.0
VFA (total), mg/l	10,235.0	9985.0	9860.0	10,155.0 (10)
Methane digester effluent				
Temp, ^{0}F	100.2	99.9	100.0	99.7 (0)
HRT, days	19.1	18.9	18.9	18.3 (22)
VS, wt%	62.7	64.6	63.7	57.3 (2)
Loading rate, #VS/ft^3-day	0.16	0.17	0.17	0.17(18)
pH	7.6	7.7	7.7	7.6 (0)
Gas prod, SCF/day	113,268.0	130,370.0	131,432.0	149,145.0 (17)
Gas composition				
CH_4, mol %	64.6	65.5	65.2	64.6 (2)
CO_2, mol%	35.3	34.4	34.8	35.4 (3)
Acimet System				
HRT, days	20.8	20.7	20.7	20.0
Loading rate, #VS/ft$_3$-day	0.15	0.15	0.16	0.15

* Numbers in parentheses are coefficients of variation in percent

the feed-sludge flow rate, had similar variabilities of 15%-18%. The *intensive* operating and performance parameters of temperature, VS content, pH, and gas composition had very low variabilities ranging between 0-3%.

The Acimet acid-phase digester was operated at HRTs of 1.7- 1.8 days and loading rates of 1.77-1.85 lb VS/ft^3-day. The methane-phase digester had HRTs between 18 and 19 days. The overall Acimet System had an HRT between 20 and 21 days, which was not required, but could not be avoided since the existing, oversized high-rate digestion tank was used as the methane digester. Results of the pilot plant studies showed that the Acimet Process could be operated to exhibit satisfactory performance at an HRT of 11 days or lower (Ghosh and Buoy 1989; Ghosh 1991). The large size of the methane digester also resulted in a low system loading rate of about 0.16 #VS/ft^3-day which was about one-half of that applied to the pilot two-phase system (Ghosh and Buoy 1989; Ghosh 1991). The acid digester effluent had a low pH (5.6-5.7) and high VFA concentrations between 9800 mg/l and 10,200 mg/l. Acetic acid was found in highest concentration followed by propionic, butyric, valeric, and caproic acids. About 85% by weight of the measured volatile acids was accounted for by acetic, propionic, and butyric acids (Table 2).

Table 2. Volatile Acids Analyses of Acid Digester Effluents: Monthly Averages (All analyses are in mg/l)

	Jan 1993	Feb 1993	Mar 1993	Apr 1993
Acetic	3320	3365	3795	3575
Propionic	2880	2440	1865	1855
Butyric	2615	2565	2675	2795
Valeric	1115	1370	1200	1390
Caproic	305	245	325	540
Total	10,235	9985	9860	10,155

Gas Production

Gas production rates and efficiencies, as well as feed conversion efficiencies (as measured by VS reduction) exhibited by the acid and methane digesters and by the overall two-phase process are shown in Table 3. The data showed that gas yield, methane yield, and gas production rate increased steadily through the months of January, February, March, and April 1993. Acid-digester gases accounted for only 4.5% of the total system gas production. Liquefaction and acid production were the major reactions in this bioreactor.The methane digester performed as a biomethanation reactor as 98% of the system methane gas production was derived from this digester. Both Acimet digesters exhibited specific gas production rates that were equal to or higher than those of conventional high-rate digesters. The acid digester produced about one volume of gas per day per volume of culture which was adequate for mixing and effecting the needed mass transport in an anaerobic system. Gas production rate in the methane digester was about double that of the acid digester, which was enough to provide the required mixing of the digester contents.

Volatile Solids Reduction

Volatile solids reduction was calculated by the following conventional formula (Eq 1):

$$VS_R = [VS_i - VS_o] / [VS_i - (VS_i)(VS_o)] \qquad (1)$$

where: VS_R is volatile solids reduction efficiency, decimal percent; VS_i is influent volatile solids concentration, decimal percent; and VS_o is effluent volatile solids concentration, decimal percent. The overall VS reduction was also estimated from the measured influent and effluent flow rates, and influent and effluent TS and VS concentrations, as given by Eq 2.

$$VS_R = Q.[(TS_i)(VS_i) - (TS_o)(VS_o)] \quad (2)$$

where: Q is the feed sludge flow-through rate, lbs/day; and TS_i and TS_o are influent and effluent total solids concentrations, decimal percent. The VS reduction data calculated by the above two equations were, at a maximum, within 18% of each other (Table 3). The reason for this compatibility between the two methods of calculation is that both equations rely on influent and effluent VS data.

The acid-phase digester converted the complex feed VS to lower-molecular-weight organic compounds which are also measured as volatile solids. Consequently, VS reduction effected by the acid digester was low (17-23 wt%). The VS reduction in the methane digester was high since the volatile organics fed to this fermenter were converted to and recovered as CH_4 and CO_2. The Acimet Process VS reduction of 60% - 66% calculated by the traditional formula (Eq 1) was 150% - 300% higher than VS reductions of 20%-40% reported for conventional high-rate anaerobic digestion of WAS.

Table 3. Gasification and Organic Solids Reduction Efficiencies: Monthly Averages

	Jan 1993	Feb 1993	Mar 1993	Apr 1993
Gas yield, SCF/lb VS added				
Acid digester	0.50	0.54	0.58	0.61
Methane digester	10.10	11.28	11.67	13.00
Acimet system	10.60	11.82	12.25	13.61
Methane yield, SCF/lb VS added				
Acid digester	0.11	0.14	0.18	0.19
Methane digester	6.50	7.39	7.61	8.40
Acimet system	6.61	7.53	7.79	8.59
Sp. Gas production rate, vol/vol-day				
Acid digester	0.88	0.98	1.03	1.11
Methane digester	1.66	1.91	1.92	2.18
Acimet system	1.60	1.83	1.85	2.09
Volatile solids reduction[1], %				
Acid digester	22.9	19.5	17.2	19.7
Methane digester	55.6	57.5	44.0	50.4
Acimet system	65.6	65.8	53.6	60.1
	[54.1][2]	[62.5]	[63.1]	[62.6]
	(62.4)[3]	(69.5)	(72.1)	(80.0)
	69.0[4]	77.3[4]	77.3[4]	77.2[4]

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[1] Calculated by using Eq 1 unless otherwise stated.

[2] VS reductions within square brackets were calculated by using Eq 2.

[3] VS reductions within parentheses were calculated by using Eq 3.

[4] These VS reductions were calculated by using Eq 4.

It has been shown that VS reductions calculated by Eq 1 do not agree with those obtained from mass balances of organic components of digester feeds and effluents(Ghosh and Buoy 1989). For example, Eq 1 yielded a VS reduction of 55.7% for mesophilic two-phase digestion of DuPage sludge at a system HRT of 12 days compared with a VS reduction of 71.3% computed from mass balances of the major feed and effluent components of carbohydrate, protein, and lipids. By this rationale, the real VS reduction achieved by the full-scale Acimet Process could be about 78%.

Eq 1 perhaps yields erroneous results because it is based on the assumption that the mass of fixed solids in the feed sludge is equal to the mass of fixed solids in the digested sludge, which was not borne out by actual data (Ghosh and Buoy 1989). Furthermore, VS measurements performed by the APHA Standard Methods procedure are usually in error for several reasons, the discussion of which is beyond the scope of this paper.

Elemental analysis of the DuPage sludge indicated that it had a theoretical gas yield of 13.6 SCF/lb VS added assuming that 80% of the VS is gasified. VS reductions achieved with the DuPage sludge can be estimated by comparing the observed gas yield with the theoretical yield mentioned above as shown by the following equation:

$$VS_R = [G_y/13.6]\ 80 \tag{3}$$

According to Eq 3, the Acimet Process could have achieved VS reductions up to 80% (Table 3).

VS reductions can also be estimated by assuming that reduction in the VS mass must be *at least* equal to the mass of gas produced, in which case Eq 4 can be used. VS reductions calculated from Eq 4

$$VS_R = \text{Mass of system gas/Mass of feed VS} \tag{4}$$

should be less than the actual reduction, and are conservative estimates of this important parameter. Examination of the results of VS-reduction computations presented in Table 3 suggests that VS reductions calculated by Eqs 3 and 4 seem to be more reliable, and those calculated by Eq 1 are unrealistically low.

Estimation of Volatile Solids Reduction from Mass-Balance Calculations

Simple mass balances were performed around the overall Acimet System utilizing measured masses of VS charged to and discharged from the system, and calculted masses of acid and methane digester gases. The results of mass-balance calculations presented in Table 4 show that the total mass of digester gases was greater than the mass of VS conversion for all 4 months. Since digester gases were measured directly by well-calibrated gas meters, the calculated mass of the total system gas was more reliable than the calculated mass of VS conversion, which was based on data from three separate measurements (flow rate, and TS and VS concentrations), one of which (the VS concentration) is of questionable accuracy as discussed above. In addition, errors in measuring these three parameters are expected to introduce a larger error in the calculated VS conversion than that incorporated into the gas mass computed from single direct measurements. It is for these reasons that we believe that VS conversions reported on Line 3 of Table 4 were lower than what they should have been in the absence of errors and measurement problems discussed above. This is to say that VS reductions calculated by Eq 2 were also lower than the actual reductions. Since the VS data are questionable, any VS-reduction-calculation model that is based on VS concentrations alone, such as Eq 1, is also questionable. It may be argued, therefore, that volatile solids reductions calculated by Eqs 3 and 4 are more realistic. On this basis, it is reasonable to state that VS reduction achieved by the Acimet System increased from about 65% in January 1993 to 73% in February to 76% in March to 78% in April 1993. These conversion efficiencies are double or more than double of those reported in the literature for biomethanation of complex organic substrates (Ghosh 1991).

Table 4. Mass Balance Around the Acimet System
(Based on monthly averages)

	Jan 1993	Feb 1993	Mar 1993	Apr 1993
VS fed to system, #/day	13,330	12,456	12,501	13,017
VS out of system, #/day	4372	4171	4150	4136
VS converted, #/day	8958	8285	8351	8881
Acid-phase gas, #/day				
CH_4	50	68	93	93
CO_2	510	534	543	549
Methane-phase gas, #/day				
CH_4	3453	3693	3657	3750
CO_2	5189	5334	5375	5651
Mass of system gas, #/day	9202	9629	9668	10,043
Difference,* %	2.7	14.0	13.6	11.6

* Calculated as a percentage of the gas weight

Comparison of Acimet Process and Conventional High-Rate Digestion

The Woodridge-Greenevalley WWTP utilized a gas-mixed high-rate reactor (which was part of a "two-stage" digestion system) before converting the existing digestion system to the Acimet Process. The full-scale Acimet Process design was based on information compiled from operation of a pilot-scale two-phase system. Comparison of the performances of the conventional high-rate digester with those of the Acimet pilot and the Acimet full-scale systems shows that two-phase operation afforded substantially higher VS reduction, and gas and energy production rates and efficiencies than those exhibited by high-rate digestion (Table 5).

It should be noted that the old high-rate digester was plagued by severe foaming episodes As discussed in previous reports, application of the Acimet Process eliminated the foaming problem (Ghosh and Buoy 1989; Ghosh *et al.* 1991). Table 4 also shows that methane energy production by the full-scale Acimet System was 124% higher than that of the old high-rate digester. The Woodridge plant has more than doubled its previous gas production. The surplus methane gas will be used to operate a new cogeneration system being planned by the County. Overall, Table 5 shows that the full-scale Acimet Process outperformed the pilot process in terms of the liquefaction capability of the acid-phase digester and the methane-generation ability of the methane digester.

As reported in previous papers, several other benefits may be derived by conducting two-phase anaerobic digestion of municipal sludges by the Acimet process. These benefits include a capability of system operation at higher loading rates and lower HRTs, a doubling of the VS-reduction efficiency, and a reduction in digested solids dewatering cost relative to those of conventional high-rate digestion; elimination of digester foaming, high pathogen kill rates, and enhanced process resilience and stability, all of which are important in relation to U. S. EPA's new 503 Regulations for ultimate disposal of digested residue (Ghosh 1987; Ghosh and Buoy 1989; Ghosh 1991).

Conclusions

This paper reports the results of operation of a full-scale two-phase anaerobic digestion system known as the Acimet Process. Design of this innovative sludge digestion process was based on the results of operation of a pilot plant installed at the Woodridge-Greenevalley WWTP, DuPage

Table 5. Comparison of Performances of Conventional High-Rate Digestion and Two-Phase Digestion by the Acimet Process

Parameter	High-rate	Acimet System	
		Pilot*	Full-Scale
Feed TS, wt%	6.0	7.5	6.8
Feed VS, wt%	74.0	77.4	80.0
HRT, days	20	12	20
Loading rate, #VS/ft^3-day	0.14	0.29	0.16
VS feed, #/day	9500		12,000
VS out, #/day	6000		4500
VS reduction, %[1]	37	56.4	62.5
Gas production, SCF/day	68,000		138,000
Gas prod rate, vol/vol-day	1.00	2.21	1.85
Gas yield, SCF/# VS added	7.16	7.37	11.5
Methane content, mol %	59.0	67.6	65.0
Methane yield	4.22	4.98	7.48
Effl VA in acid-phase effl, mg/l	—	9445	10,059
Acid-phase pH	—	5.6	5.7
Methane-phase pH	—	7.7	7.7
Energy value of gas, 10^6 Btu/day	—	40.1	89.7

* Pilot plant data shown here were reported earlier by Ghosh *et al.* (1991)

County, IL to eliminate severe foaming episodes, and to alleviate digester overloading problems. The Acimet Process provides for the optimization of hydrolysis-acidification and coupled acetogenic-methanogenic fermentations in separate acid- and methane-phase digesters operated at HRTs of 1.8 days and 19 days, respectively. Both digesters were operated in an upflow mode without mechanical mixing. Although an HRT of 12 days would have been adequate for methane-phase digestion, a 19-day HRT resulted because the existing high-rate digester was used as the methane digester for the Acimet Process. The Acimet acid digester produced an acidic effluent with a pH of 5.6 and a,total VFA concentration of about 10,000 mg/l. End products of acid-phase fermentation were gasified in the methane digester to produce a 650-Btu fuel gas. A highly buffered alkaline environment reflected by a pH of 7.7 prevailed in the methane digester. The overall Acimet Process exhibited a biogas yield of up to 13.6 SCF/lb VS added and a methane yield of up to 8.6 SCF/lb VS added corresponding to a unusually high VS reduction of about 78%. The Acimet digesters never experienced any foaming, which was a chronic problem with the old high-rate digester. Methane production by the full-scale Acimet Process was 124% higher than that of the old two-stage digestion process. DuPage County is planning to utilize this large surplus of methane production to operate a new cogeneration system to generate electric power for internal use. The full-scale Acimet System outperformed the pilot process in terms of the bioliquefaction capability of the acid-phase digester and the gasification efficiency of the methane-phase digester. The Acimet Process has several other advantages that were reported in previous papers.

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BIOMASS POWER PRODUCTION IN AMAZONIA: ENVIRONMENTALLY SOUND, ECONOMICALLY PRODUCTIVE

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Abstract

With the support of the US Agency for International Development, the National Rural Electric Cooperative Association (NRECA) is assisting their utility counterparts in Bolivia to improve electric service in the country's rural population. In remote areas, the cost of extending transmission lines to small communities is prohibitive, and diesel generators represent an expensive alternative, especially for baseload power. This has led to serious consideration of electric generating systems using locally available renewable resources, including biomass, hydro, wind, and solar energy.

A project has recently been initiated in Riberalta, in the Amazonian region of Bolivia, to convert waste Brazil nut shells and sawmill residues to electricity. Working in tandem with diesel generators, the biomass-fired plant will produce base-load power in an integrated system that will be able to provide reliable and affordable electricity to the city. The project will allow the local rural electric cooperative to lower the price of electricity by nearly forty percent, enable the local Brazil nut industry to increase its level of mechanization, and reduce the environmental impacts of dumping waste shells around the city and in an adjacent river. The project is representative of others that will be funded in the future by NRECA/AID.

Introduction

The National Rural Electric Cooperative Association (NRECA) signed a cooperative agreement with the Agency for International Development (AID) in 1991 to develop and implement the Electrification for Alternative Development Project (ADEP). The purpose of ADEP is to provide increased access to electric service in rural areas of Bolivia, thereby increasing employment and income generating opportunities in the formal, licit economy. While ADEP has a focus in the non-coca producing and so-called "expulsion zones"[1] of Bolivia, the project is nation-wide in scope.

In the pursuit of viable biomass options under ADEP, NRECA retained the Winrock International Institute for Agricultural Development to investigate fuel supply availability. Winrock is a non-profit rural development organization with expertise in forestry and power generation from wood and agricultural residues.

Bolivia is a geographically diverse country characterized by dramatic changes in landscape and climate, ranging from the Altiplano, a plateau at an elevation of 13,000 feet stretching from the border of Peru to the southern border with Argentina, to the llanos (flatlands) in the Santa Cruz region, to the tropical rain forest to the north in the departments of Pando and Beni. These flatlands form the beginnings of the Amazon Basin, with abundant resources but difficult access caused by the high seasonal rains.

Bolivia is approximately 1,098,581 square kilometers in land area with a population in 1992 of 6,344,396. The result, 5.8 people per square kilometer, is one of the lowest population densities in Latin America (INE, 1992).

The combination of geographic diversity, low population density, and low economic productivity have led to very low electrification coverage in rural areas (30%). The national grid covers a very small portion of total area, interconnecting the major cities of La Paz, Cochabamba, Santa Cruz, Oruro, and Sucre, but providing little coverage beyond these major metropolitan areas. To address the needs of areas not served by the grid, generation from diesel power plants has to date served the majority of non-grid connected areas, mostly via a system of rural electric cooperatives. However, the experience has been almost universally discouraging with this technology; problems have ranged from very costly and problematic transportation of diesel fuel, to extremely poor maintenance records of the diesel engines. It was therefore concluded early in the ADEP project to strongly consider the use of renewable energy technologies as an alternative to diesel power for use in these isolated areas.

Riberalta is a community of some 46,000 people approximately 75 miles south of the Bolivia border with Brazil (see Figure 1). The community derives its livelihood largely from the Brazil nut industry, composed of growers and processors. The area produces over 8,000 Tonnes of processed Brazil nuts per year, making it one of the largest producers in the world of this product.

For many years, the electric cooperative in Riberalta (Cooperativa Eléctrica de Riberalta, CER) has generated electric energy from a bank of medium speed diesel engines. While the service has been relatively reliable, the cost of generation has been expensive ($0.22/kWh) and the cooperative has only been able to provide sufficient capacity for domestic loads.

Recent changes in international standards have forced the Brazil nut industry to make a shift from manual labor and very low energy use to become much more mechanized and hence, more energy intensive. The principle

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[1] Expulsion zones are areas from which people migrate to work in coca producing regions on a seasonal or permanent basis. These include areas in the Valles Altos, Chuquisaca, Potosi, and others.

changes will force processing plants to begin using controlled product drying, cooling, and packaging techniques in an effort to decrease aflatoxin levels in the packed product ready for shipment. This change will require much higher consumption of electric energy to drive chillers and material handling equipment.

For these reasons, and due to ever increasing costs of diesel, CER requested ADEP assistance to design, finance, and construct a biomass generation plant to off-set diesel generating costs. It is believed that this project can provide dramatic economic benefits to the community of Riberalta without producing harmful effects on the natural environment. While the project will utilize primarily a refuse fuel from a food processing industry, it will also use wood off-cuts from local sawmills. Both the impact of the use of the biomass fuel and the economic benefits of the project to the community of Riberalta will be examined in depth in later sections of this paper.

Current Power Generation in Riberalta

For the past forty years, the CER has operated with an isolated diesel power plant providing power to over 3,200 cooperative members. However, industrial customers have been forced to self-generate due to insufficient installed capacity provided by CER. Self generation in most cases is a very costly enterprise and one that requires a high degree of logistical coordination. Moreover, with the changes noted above in the Brazil nut processing plants, industrial energy requirements in Riberalta will increase dramatically. To become and remain competitive, the local Brazil nut processing industry must secure stable and affordable sources of electric energy.

Figure 2 provides a graphical depiction of the present and projected energy and power demand for CER. There exists a substantial unmet demand within CER's system, principally resulting from the Brazil nut processing plants, saw mills, and a section of the city that has not yet been electrified. This unsatisfied demand has been estimated as high as 2,500 kW, and although this is a very rough estimate, a significant increase in demand is expected as soon as the biomass plant is commissioned and energy prices are reduced.

At present, CER operates a power plant composed of 2 medium speed (1000 rpm) and 1 high speed (1500 rpm) diesel engines. Table 1 provides a list of the engines in use at this time. As this table indicates, two of the engines have already reached the limit of their useful lives, while the third engine (Caterpillar 1500 rpm) has relatively few operating hours. The Sulzer engines, in contrast, are over thirty years old, but were totally rehabilitated upon purchase and installation in Riberalta. These engines will be used to provide base-load power until the biomass plant is brought on-line in 1994.

Table 1. Description of current CER generating plant.

Model	Speed (RPM)	Hours of Operation	Capacity
Lanmar	1000	30,000	720 kW
Caterpillar	1000	60,000	625 kW
Caterpillar	1500	10,000	600 kW
Sulzer (3 units)	428	Overhauled	456 kW/unit

Source: NRECA, 1993.

To meet the increases in demand, CER has undertaken a two-fold strategy. Firstly, the cooperative purchased the three Sulzer generator sets mentioned above and will place these units in service in 1993 (see Table 1 above). These units have a combined name plate capacity of 1,368 kW and will be used to provide base load power for the next year of service.

Secondly, the cooperative in collaboration with ADEP will construct a 1,500 kW biomass power plant. The biomass plant will be used in combination with the slow speed Sulzer units to provide energy for the next five years, with supplementary power being provided by the existing medium speed diesel units. This will allow the cooperative to meet a much larger portion of the presently unsatisfied industrial demand while decreasing the cost of energy supplied (the financial analysis will be presented in a later section of this report). Perhaps most importantly for the cooperative, the addition of industrial loads will increase the long-term viability of the cooperative by introducing a more stable and reliable source of income and demand.

Characteristics of the Biomass Power System

While the final design of the power plant will be completed after a supplier has been selected, general design characteristics of the fuel delivery system, boiler, turbo-generator, and station switch gear have been determined. A brief description of these system components follows in this section.

The fuel will be collected from the processing plants and sawmills in Riberalta by truck and transported to the powerhouse site. The fuel will be placed in a temporary on-site storage area, from which it will be transported to the fuel processing zone by front-end loader. The fuel will be reduced in size and dried if in excess of 30% moisture content. (in the case of wood fuel) before being placed in the loading chamber of the boiler.

The boiler will be a fixed-grate, fire-tube design with a steam pressure of 250 to 400 psig. The boiler may include a superheater section to increase overall combustion efficiency. The boiler will provide superheated steam to a multi-stage condensing steam turbine generator with a capacity of 1,875 kVA operating at 50 Hz.

The biomass system will have the capability to supply full load on either Brazil nut shells or wood waste, and will be capable of operation at a turn-down capacity of 25% while maintaining stable boiler conditions. The station switch gear will provide control for both manual and automatic synchronization of the biomass generation and diesel engines in the powerhouse.

During periods of routine maintenance, the diesel plant will be used for prime power purposes. However, during all other periods, it will be used for peaking purposes only. With the addition of the biomass system, there should be sufficient capacity to satisfy all system loads for the next 10 years.

Fuel Resources

A thermal power plant in Riberalta could count on sawmill waste and Brazil nut shells sufficient for at least 1.5 megawatts of power, at a cost corresponding to transportation alone. While limited in volume, these wastes are much cheaper, probably by more than a factor of two, than any readily available alternative. More expensive, but probably more abundant, sources of fuel include agricultural land clearing, future forest management operations, and energy plantations.

Brazil Nut Shell Availability

Riberalta's ten Brazil nut processing plants prepare annually 800,000 "boxes" of clean nuts weighing 20 kg each, mostly by a process of autoclaving, quenching and hand shelling. While some waste shells are used in small steam boilers and furnaces to heat air for drying, an analysis performed for CER indicates an annual net availability of approximately 8,000 Tonnes of dry shells from the immediate vicinity of the town. (Hasse 1988). With a heating value of approximately 3.7 kCal per kilogram, the shells are enough fuel for just under one MW of power at 5 kCal per kWh, assuming a capacity factor of 80 percent.

Although most of the whole nuts are brought in by river boats from greater distances, a substantial number are collected near the city. The supply of the latter is diminishing as badly managed fires for agricultural land clearing kill more than half of the mature Brazil nut trees and all of the young ones.

The Brazil nut shelling operations are under market pressure to automate their processes to improve quality control and labor working conditions, as mentioned above. At least one plant has installed a more energy intensive automated process that involves freezing the nuts for 24 hours at -40C in a refrigerator cooled by an ammonia chiller with a 100 horsepower compressor, followed by mechanically fracturing the shells and removing them in an air separator. This plant uses all of its residues to fuel a power plant constructed around an inefficient reciprocating steam engine. Access to reliable electric power from the cooperative will serve to improve the economic attractiveness of the new technology and thus to enhance the ability of this industry to compete effectively in the future,

Sawmill Wastes

The community has seven sawmills, of which one is under construction and not yet in operation. These mills are all located in a row along the river, which provides convenient and economical means of transport, downstream from the town. Table 2 below indicates the monthly volume of residues generated at each of the operating mills. Of the approximately 1240 cubic meters of residues produced in a typical month, between 200 and 300 cubic meters will be in the form of sawdust. which is now dumped in the river. The solid wood slabs, trimmings and edgings are given away free at the sawmill site for domestic use, and some mills will also deliver the wood to private homes for Bs. 15 ($4) per "carrada," a wagon measuring approximately 3M x 1.7M x 0.7M. However at all mills, some unused solid residues remain and are burned.

Table 2. Sawmill Wastes and Power Requirements in Riberalta

Monthly Volume	Sawmill							
(Cubic Meters)	Bolital	Destre	Mavari	Mamoré	Madecom	Ipacaraí	Cabrera	Total
Logs Received	767	486	450	550	630	275	0	3157
Lumber Produced	460	340	270	330	378	138	0	1916
Residues (%)	40%	30%	40%	40%	40%	50%		39%
Residues (Volume)	307	146	180	220	252	138	0	1242
Primary Species	Mahogany	Cedar	Mahogany	Mahogany	Mahogany	Mahogany	(Not in Operation)	
Power Supply	GRID	GRID	GRID	GEN. SET	GEN. SET	GEN. SET	GEN. SET	
Generator KW		90		166.5	130	80	230	696.5

Source: Winrock International, 1993.

Production levels tend to be lower in December and January than during the remainder of the year, and the degree of reduction during these months fluctuates from year to year depending on weather-related difficulty in obtaining logs. The sawmill sites are accessible by narrow dirt roads, which will accommodate only small trucks transporting wood. (The same roadway limitation applies at the new generating station under construction by the cooperative.)

At a dry density of 0.5 Tonnes per cubic meter, the 1000 cubic meters of residues (excluding sawdust) amounts to 500 Tonnes per month, or about 17 equivalent dry Tonnes per day. This quantity would provide fuel for 0.6 MW of continuous power at 100 percent capacity factor for at least ten months of the year, or the same output all year at a capacity factor of 80 percent, assuming a heat rate of 5 kCal per kWh. The amount should increase as the new Cabrera sawmill comes on line. This fuel will require comminution at the power plant site and sufficient storage capacity to accommodate reductions in supply in December and January.

Fuel Wood Production

Land Clearing

Slash and burn agriculture is typical of the surrounding area. Forest land, in parcels of one or two hectares, is cut over and the residues burned to make room for small scale agriculture, and then a variety of crops are grown for the remainder of a three-year cycle. After that time, the land, no longer able to support viable agriculture, is abandoned to recover through natural succession, and the cycle is repeated. This practice creates large but not easily quantifiable amounts of waste wood, some of which is prepared and sold locally for fuel. From the air, the surrounding area appears heavily forested, with occasional parcels cleared for farming. Abandoned parcels seem to be regenerating readily with new trees.

Agricultural land clearing in the vicinity of Riberalta has the short-term potential to supply substantial additional amounts of fuelwood at a delivered price of approximately Bs. 40 to Bs. 50 ($10 to $12) per green Tonne, and alternative uses of sawmill wastes by the power plant may force present users to purchase firewood for domestic cooking from the countryside. To the extent that wood from land clearing becomes the marginal source of supply, its cost will determine the market price of firewood from all sources. For this reason, and because of uncertain future supplies of free biomass residues, a project developer at these sites may be wise to secure firm contracts in advance for lower cost wastes or assume a fuel cost equivalent to the land-clearing residue price of about Bs. 25 per kCal ($1.50 per million Btu).

Forest Management

Riberalta's location at the junction of the Beni and Madre de Dios Rivers offers access to timber from large areas of forest land. Forest management designed to maximize the sustainable productivity of the forest land might provide a source of fuel, depending on location and conditions, in the form of cull logs and thinnings, and it will help to assure the future of the timber industry. To the extent that power plants represent a profitable market for wastes generated by forest management, they provide an added incentive for adopting its practice. On the other hand, fuelwood markets are not likely to be a sufficient inducement to bring forest management into being, absent a regulatory and land ownership structure that internalizes the benefits of future high-valued (non-fuel) products.

Government planners in Bolivia tend to foresee a decline in timber production due to restrictions in logging and inadequate forest management caused by weak regulation and an uncertain stake on the part of individual developers in the husbanded resource. Such pessimism is certainly warranted near cities and major towns; forests are either severely degraded or gone, as they are in virtually all countries worldwide. In the case of the Riberalta mills, however, raw material is coming down-river from areas in which there are no large towns, much of it subject to annual or periodic inundation during the rainy season. Perpetually-sustainable forest management, including mahogany, is still a possibility, and Riberalta is ideally located to depend on it. USAID is preparing a proposal to promote sustainable forestry, and other donors are also concerned. The Riberalta timbershed seems an ideal location for such a project, and a dendrothermal cogeneration plant would be a useful part of it.

Energy Plantations

Intensive silvaculture energy plantations have emerged as a possible way of assuring future fuel supplies and protecting natural forests. Researchers at the Bolivian Amazonia Forest Research Institute in Riberalta, for example, advocate eucalyptus plantations to insure long term supplies of fuelwood. Although fuel from this source would be more costly, some of the cooperative directors and other members of the community have advanced the notion that the cooperative should be willing to incur some limited additional expense if necessary to assure that the biomass power plant operates on a long-term sustainable basis.

Compared to the existing sources, tree plantations established for the sole purpose of supplying fuel are costly. Figures in the vicinity of Bs. 150 ($45) per green Tonne have been reported, but commercial experience is not widespread. Few if any plantations have been economically successful supplying fuel, in contrast to higher-valued materials like paper pulp, lumber or metallurgical charcoal. In locations where energy plantations represent only an insurance policy and may never be harvested, the cost of establishing and managing them is even more likely to be prohibitive.

Other Sources

Riberalta lies just below the confluence of two large rivers, the Beni and Madre de Dios, and a substantial volume of logs and trees float by the city every day. Some of the abundant material is collected by boat if it has commercial value as saw timber, however it is unclear whether a suitable means of collecting large volumes of fuelwood from the river could be devised, and if so, whether the cost would be competitive with other sources.

Competing Uses

Using the sawmill wastes for power generation will reduce its availability to the population for cooking and is thus likely to result in increased consumption of firewood derived from land clearing. In addition two ceramic tile factories are major consumers of fuelwood for firing kilns. One of these factories purchases monthly between 200 and 300 "square meters" of firewood, equivalent to approximately 0.5 cubic meters, or 0.25 dry Tonnes. Sawmill wastes are not used because of their rapid combustion and inconvenient, non-uniform shape. A square meter of firewood delivered to the factory costs between Bs. 10 and Bs. 15 ($2.50 to $3.75), depending on quality, which would amount to about Bs. 50 ($12) per air dry Tonne. Because removal of the wood facilitates farming operations, the wood in place has little or no cost, and the delivered price reflects primarily the cost of cutting to size, loading and transportation. Both the military and private truck operators represent an established fuelwood delivery industry.

Financial Impact of the Project

As mentioned earlier, the current price of electricity in Riberalta is $0.22/kWh, and the cooperative has losses registered as high as 17% of energy generated. These losses result from an antiquated distribution system, very old and faulty service entrances, and high transformer losses. A decision was made during the pre-feasibility phase of the project appraisal process to include a complete rehabilitation of the grid as a part of the project financing.

The total estimated project cost is $1,700,000 to $2,000,000. This is composed of $1,200,000 for the generation system, and an additional $500,000 for the rehabilitation of the distribution system. The cost of the biomass system was estimated based upon price quotations from two US and one Brazilian supplier, with total installed costs ranging from $850 to $1200 per installed kW.

CER spends approximately $450,000 per year in fuel cost at present (see Table 3 below). The calculated overall efficiency of generation (less system losses) is 18%. This figure is low even taking into account the poor condition of the current power plant. Upon inspection of the engines, it was found that the turbo-charger cooling circuit was not separated from the water-jacket circuit, effectively de-rating the engines and lowering the capacity and fuel efficiency. With the addition of the rehabilitated Sulzer engines, the efficiency of generation should increase from 28% to 33% at a minimum, lowering fuel cost by over $200,000 per year.

Table 3. Annual fuel cost and consumption rates for CER.

System	Capacity	Efficiency	Consumption	Fuel Cost
Actual	1760	18%	.51 l/kWh	$450,000/yr
Sulzer	2500	28%	.33 l/kWh	$288,000/yr
Sulzer	2500	33%	.28 l/kWh	$245,000/yr
Biomass	4000	12%	2.2 kg/kWh	$50,000/yr

Note: Capacities reflect total CER plant capacity, including present diesel engines.
Source: NRECA, 1993.

As Table 3 illustrates, the addition of the biomass plant will dramatically reduce the annual fuel costs. The total estimated annual fuel cost including cost of biomass an supplemental diesel is $150,000, assuming a the biomass plant will provide 3,500,000 kWh per year to the CER grid.

It is estimated that due to the additional installed capacity, energy sales will increase in the first year by 20 to 25 percent from 4,160,000 kWh to over 5,000,000 kWh per year. In addition, with the rehabilitation of the distribution grid, losses should be reduced from an average of over 17% at present to less than 9%. Both of these factors should play a very strong role towards increasing the viability of the biomass project and the financial position of the cooperative in general. The loss reduction alone will decrease annual fuel payments by over $50,000 per year.

The financing for the project will be shared by three parties. NRECA, through ADEP, will finance up to $1,000,000 in equipment and services costs. CER, with a grant from the Beni Regional Development Corporation (CORDEBENI) will provide $320,000 in project financing. The National Fund for Regional Development will provide up to $600,000 in project financing for the cost of the rehabilitation of the distribution system. The total amounts financed will be determined once contracts are ready to be awarded to suppliers of the biomass system and distribution system components; the total price tag of $1,700,000 will rise if NRECA decides to increase capacity from 1,000 to 1,500 kW..

The funds invested by NRECA/ADEP for all projects have relatively attractive terms, with an interest rate of 6 percent and an amortization period of 10 to 15 years. The CORDEBENI funds provided to CER are grant funds and will represent CER's equity investment in the project. The funds provided by the National Fund for Regional Development will be mixed grant and loan funds, with 40 percent provided without a repayment condition, and 60 percent in the form of a 15 year, 13 percent interest loan.

Given these terms, a project cash flow analysis was performed, taking into account all project costs and income streams to determine the net present value of the project. Table 4 provides a summary of CER costs, including fuel, administrative, O&M, interest charges, taxes, and other expenses. It also provides a summary of income for three tariff rates. Calculations to determine the project net present value were performed assuming a 12 percent discount rate using the loan/grant structures as stated above. NPV's of $5,365,000, $2,547,000, and $668,000 were calculated for average tariffs of $0.22/kWh, $0.16/kWh, and $0.12/kWh, respectively. In all cases, the project yielded quite attractive returns. An initial investment of $1,920,000 was assumed as the highest capital cost scenario.

Table 4. CER operation costs and projected income.

Category	Present	With Project
Salaries	$117,140	$117,140
Fuel & Lubricants	$450,000	$150,000
Operation/Maint	$21,000	$21,000
Administration	$42,350	$42,350
Amort. Payments	$24,050	$125,700
Taxes	$86,550	$96,370
Others	$17,050	$17,050
Income @ $.22/kWh	$965,000	$1,100,000
Income @ $.16/kWh	n/a	$800,000
Income @ $.12/kWh	n/a	$600,000

Source: NRECA, 1993

The above analysis attributes all income to the project, but also assesses all costs to the project. In reality, the income stream that should be attributed to the project would be that generated by the biomass power system alone, i.e., seventy percent of the total annual income. However, the cost attributed to the project would be only forty percent of the total costs listed above, including most of the amortization expense, $50,000 of the fuel expense, and approximately $70,000 of the tax expense. Therefore, if the project were analyzed independently of the rest of the power station, the results would be even more attractive. All costs and income streams were included in the above analysis due to the fact that the Codigo Nacional de Electricidad (National Electric Code) prescribes that project analyses be done in this way.

One can also see the benefits the project will yield the community from the three tariffs used above. At present, CER consumers pay $0.22/kWh. When the project is fully operational, CER will petition a rate decrease between $0.12 and $0.16 per kilowatt-hour to pass the benefits of the project on to the members of the cooperative. In all likelihood, a lower industrial tariff will be offered than residential to encourage increased use of electricity in the Brazil nut processing plants and sawmills. In turn, the processing plants and sawmills will provide fuel at a discounted price to the electric cooperative. This will allow both industries to expand and become more competitive with their Brazilian counterparts while supporting the electric industry and the community as a whole to provide more reliable and affordable electric energy.

Future Use of Biomass Power in Bolivia

At present, NRECA is performing pre-investment analyses on four additional sites. In two of these sites, biomass fuel will be purchased from sawmills and/or a combination of managed forestry projects. In the other two projects, the principle fuel will be bagasse generated as a by-product from sugar mills.

Cobija

Cobija, located on the Brazilian border in the department of Pando, is a smaller community than Riberalta, but one with a similar economic structure. While Cobija produces markedly fewer Brazil nuts, the principle industry is Brazil nut production, combined with production of sawn lumber. The community is provided power by the Empresa Nacional de Electricidad (ENDE) *via* isolated diesel generation. The price of power here is lower than in Riberalta, but still high ($0.15 per kWh). As in Riberalta, the cost of energy and the problems involved with fuel delivery and maintenance of the engines is forcing ENDE to seek alternatives to diesel generation. ENDE had proposed that NRECA consider financing a small hydroelectric site, but it was decided to consider both a biomass and hydro option for future power production. The technical and financial analyses should be complete by August, 1993.

Biomass fuel resources are probably more limited here. The community has two large and two small sawmills; one large, one medium-sized and three small Brazil nut shelling operations, and the area around Cobija has been cleared, to a large extent, and converted to pastures and cropland. Compared to Riberalta, little potential fuelwood remains in the agricultural areas, and the great majority of the remnant forests are on slopes and gullies, where disturbance is undesirable and wood harvest expensive. The waterways serving Cobija drain a much smaller land area, than do either the Beni or Madre de Dios rivers, both of which serve Riberalta. The Brazilian part of the watershed is, further, essentially deforested, and according to the Bolivian power company's local manager, the Brazilians have restricted fuelwood harvesting in the area.

San Ignacio de Velasco

San Ignacio is a community in Chiquitania, a region of ancient Jesuit missions in Santa Cruz Department. San Ignacio has a population of approximately 11,000 and is served by a cooperative slightly smaller than CER. The cooperative has a peak demand of 1,250 kW, served by four high speed diesel engines, but the substantial, centrally located sawmill industry does not use significant amounts of power from the local grid. The same series of problems encountered in Riberalta is present in San Ignacio, including a retail power price of $0.15 per kWh.

Six sawmills are located within a few hundred meters of each other in an industrial park on the outskirts of the town. These mills, which now dispose of wastes by open burning, could provide an average of 1370 cubic meters per month, or approximately 20 equivalent dry Tonnes of fuel per day, to a power plant which could be located adjacent to the mills to minimize the cost of fuel collection. The fuel supply at this site alone would provide for approximately one megawatt of power, probably for ten years or more. Continued availability depends on overall future development patterns and not on present conditions. Logging by itself is unlikely to remove the great areas of forest which remain, partly due to lack of mechanization and adequate roads. However, pressure is growing for cleared land for future cultivation of peanuts, coffee, corn and soybeans as part of intensive agricultural schemes promoted by the World Bank and the German Gesellschaft für Technische Zusammenarbeit (GTZ). If and when local forests are commercially depleted, river transportation will not be available to serve the town, as in the case of Riberalta, and all-weather roads are scarce.

A wood-fired power plant had been proposed for San Ignacio as long as seven years ago by a study performed by the Organization of American States (Park, 1987). However, financing was never secured, and the silvaculture studies needed to determine the proper species for fuel wood production were never performed. The Winrock team that performed the resource assessment for Riberalta also performed a preliminary analysis on both the Cobija and San Ignacio sites. While it appears relatively certain that sufficient biomass could be produced, an institutional structure has not been identified that could manage the fuel wood production and delivery as required to make the project feasible. Further analyses will be performed in the near future, but the fuel management portion appears to be the most problematic feature of this project at present.

Santa Cruz

Other opportunities to generate and sell energy to the grid appear feasible in two locations, one in Santa Cruz, where there is a group of four sugar mills, each with sufficient excess steam capacity to generate up to 5,000 kW to the grid. Most attractively, the harvest season coincides with the electric cooperative's (CRE) period of maximum demand. CRE purchases power from the national generation company, ENDE, for a price of $6.20 per kW on a ratchet clause contract; they pay demand charges based upon the maximum demand for the highest month over the preceding 12 month period. Maximum demand is currently at 120,000 kW, so purchasing power from a group of sugar mills during the peak demand period could be a very attractive proposition. Unfortunately, the mills are still under government ownership, and studies have just begun to define the real potential and a fair purchase price of power. It will in all likelihood be another twelve to twenty-four months before the feasibility, both financial and political is sufficiently defined to allow a project to be developed.

Bermejo

The last project that has as of yet been identified also involves bagasse power generation, this time in the city of Bermejo. Bermejo is a small industrial town on the border of Bolivia and Argentina. ADEP is presently co-financing the development of a small natural gas power station to provide power to the town. However, it appears that generation from biomass could compete quite readily with natural gas to in the near future. A study to determine the feasibility of this project will be performed in early 1994.

Beyond the Immediate Horizon

Over 140 small rural electric distribution systems exist throughout rural Bolivia. The great majority of these cooperatives are located in Santa Cruz and the Beni, two of the three departments that are heavily forested. NRECA/ADEP is attempting to systematically develop a program to replace or supplement isolated diesel generation with biomass generation where biomass fuels appear to be plentiful and viable institutional structures exist. From the experience in Riberalta, it appears that these projects can be developed such that very limited if any significant impact on the environment would occur. With suitable regulatory provisions and owner incentives, pro-active forest management in areas like Riberalta could yield more than sufficient fuel for power plant purposes, while increasing the yield from presently poorly managed areas. In contrast to the tales of the systematic destruction of the Amazon basin, these projects can provide needy communities with a means to increase economic output, improve the quality of life, and sustain the precious resources they depend upon for their survival both today and in the future.

Acknowledgments

The foregoing discussion reports on the efforts of a team of individuals representing several diverse institutions involved in bringing Bolivian biomass projects to fruition. Although space here is inadequate to acknowledge everyone who has made valuable contributions to the success of this work, the authors wish to express their particular indebtedness to the following people. Mr. Robert Chronowski of Alternative Energy Development, Inc. has been responsible for much of the financial and technical development of the project in Riberalta, and Dr. C. Buford Briscoe, Consultant to Winrock International, provided indispensable expertise in wood resources in the context of sound forest management practice. Mr. Danilo Carranza and Mr. Andrew McAllister, both of NRECA's La Paz-based staff, have ably coordinated the sometimes chaotic array of actors and kept the projects moving ahead. Finally, the project in Riberalta could not have advanced this far without the dedication and capability of the manager and directors of the local electric cooperative.

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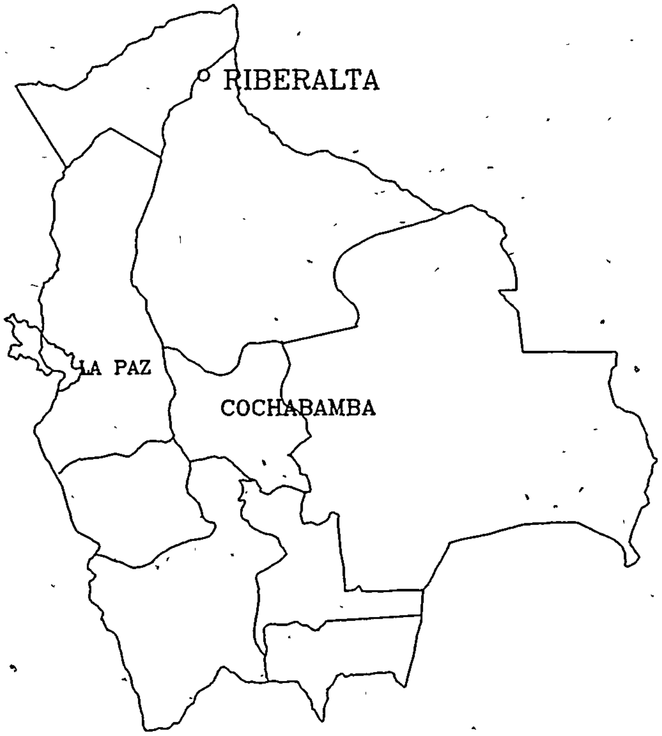

Figure 1. Map of Bolivia Showing Riberalta Project Site

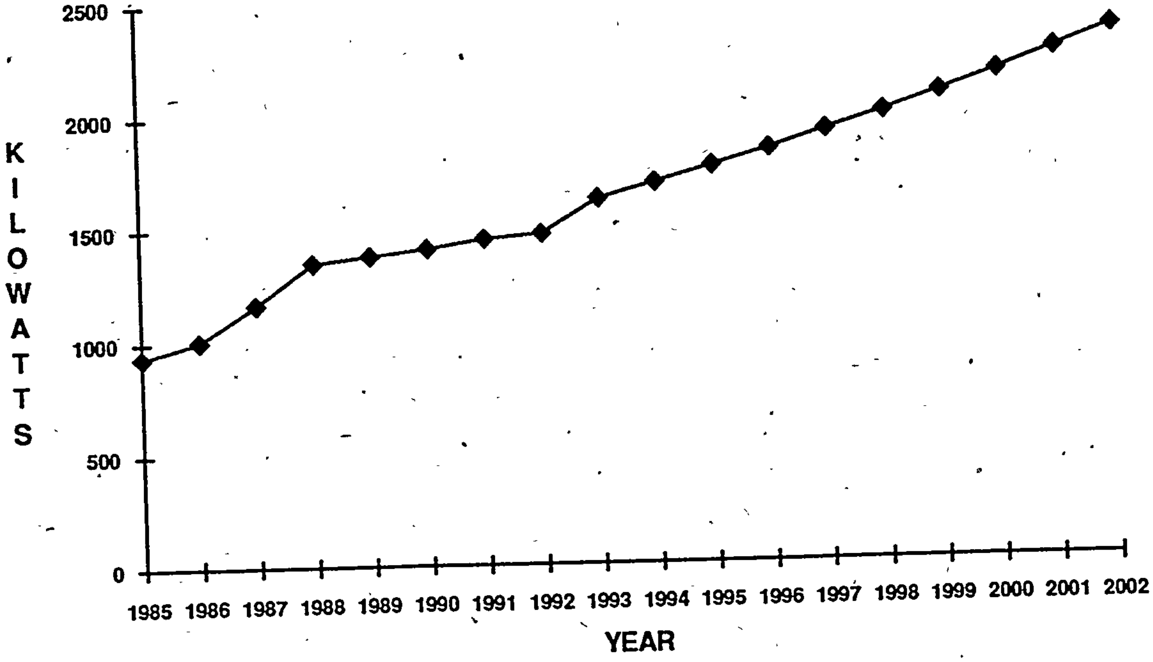

Figure 2. Demand Projection - Riberalta Electric Cooperative

A FLUIDIZED BED FURNACE FIRED WITH BIOMASS WASTE TO SUPPLY HEAT FOR A SPRAY DRYER IN A PLANT PRODUCING FLOORTILES

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Abstract

This project has been implemented at a factory producing floortiles for domestic use. The project consists of a fluidised bed combustion system burning coal or wood or a mixture of both to produce hot combustion gases to provide heat for spray drying process.

The system was designed by INETI for a maximum output of 8 MW thermal energy and all the engineering calculations were carried out to dimension the furnace to provide this amount of heat.

Shallow bed concept was used for complete burning of the biomass particles which contained volatiles up to 75% by weight. The sand bed was used as a flame stabiliser for the combustion of volatiles. The combustion of volatiles in the freeboard was mainly controlled by mixing them with air. The bed temperatures had to be kept below 800 °C due to sintering behaviour ashes and other impurities. The combustion temperature had to be maintained in the range 700 - 800 °C to achieve combustion efficiencies of 85% or more. The combustion efficiency i) did not increase substantially above 90% of excess air although levels of up to 120% were used during combustion and ii) was found to increase through air staging in the order of 20 to 25%, by simply adding 45 to 55% of the air required to the freeboard zone. No SO_2 was observed in flue gases when burning only biomass but there was some NO_x formed and the level of conversion of fuel-N to NO_x was found to be about 25 - 30%.

INTRODUCTION

The advantages of fluidised bed combustion technology in dealing with low-grade fuels including various types of wastes are comprehensively documented and have previously been successfully demonstrated. Presently, the most viable scope of applications for fluidised bed technology covers those units designed for industrial end-use systems to produce energy on-site. The abundant availability of biomass encouraged many companies in Portugal for its use to substitute fuel-oil, the most common fuel utilised by industry. Production of floortiles is an important industrial sector in Portugal and employs highly energy intensive processes like spray drying for the manufacture of the end product.

Biomass particles have high content of volatile matter and burn with a yellowish flame. At about 750 °C, 70% of the input weight is released as volatiles and burn in the gas phase. There is no sulphur present in the waste particles but the fuel nitrogen content could at times be comparable to coal. Steps have to be taken to reduce the amount of oxides of nitrogen formed during combustion.

INETI undertook a research programme to burn biomass in a fluidised bed combustor with the aim of improving the combustion efficiency by controlling temperature and access of oxygen to the particles. Shallow bed with a height of 20 cm was used and most of combustion was encouraged to occur at the freeboard zone in the gas phase. The access of oxygen was controlled through staging of the air supply. The bed temperature was varied between 700 and 800 °C and the particles fed to the bed underwent a fast devolatilisation step. Most of the volatiles burned in the freeboard. Part of the air was supplied to the freeboard zone at various heights along the combustor and was introduced with increasing swirl to enhance mixing in the upper part of the freeboard so that sufficient time was given for fuel-N to convert to nitrogen rather than to NO_X.

This paper reports the experimental results obtained only with biomass burning on the unit during the initial stages of the operation. Combustion efficiencies over 96% were obtained with very low levels of NO_X and CO.

EXPERIMENTAL

The fluidised bed furnace consists of the following components:

i.) Wind box and the air fan for the combustion air;
ii.) The air distributor;
iii.) The combustion chamber;
iv.) The daily fuel storage hoppers and the fuel feeding systems;
v.) The secondary air supply;
vi.) Start-up unit for ignition;
vii.) Ash extraction system;
viii) The storage hoppers for limestone and inert bed materials and the feeding systems;
ix.) Combustion gas exit and the cyclone system for particulate removal;
x.) Control systems for automatic operation of the furnace.
xi.) The steel structure for the support of the furnace and its ancillaries:
xii.) The gas duct to transport the hot combustion gases from the fluidised bed combustor.

The combustion chamber consists of bed and freeboard zones. The bed section is divided into two parts to each of which a separate distributor plate will be attached. The separation walls between the sections of the bed are made of refractory material. Slots are used for the interchange of the bed material and the gas between the sections to achieve better solid and gas mixing. The separation wall is 1600 mm high.

Each section of the bed has its own distributor plate to which there are 210 standpipes attached to introduce the fluidising air. The standpipes are 120 mm high and with a diameter of 25 mm. On each standpipe, there are 36 nozzles situated in equal numbers at three different heights.

The walls of the combustion chamber are refractory coated and can withstand both reducing and oxidising atmospheres. The temperature on the outside is brought down to about 55 ^{o}C by additional insulation.

The base area of the combustor is 4.5 m^2 for each section of the bed, totalling an overall bed area of 9.0 m^2. The cross section of the each section is 2 250 mm by 2 000 mm. The height of the combustion chamber is 3000 mm.

Two thermocouples are placed in the combustor, one at a height of 250 mm and the other at 2 800 mm above the distributor plate. Pressure probes are placed at various points to monitor the variations in the pressure.

The location for feeding fuel, sand and limestone is the same and is at a height of 450 mm from the distributor plate. The limestone is added to the bed when coal is also used to control the emission levels of SO_2, and the sand is fed mixed with the fuel. The feeding is under gravity and the mixture will be transported using screw feeders.

The secondary air inlets are placed at two different heights to ensure complete combustion of biomass burning.These inlet points are at 700 and 900 mm above the distributor plate and the air is supplied through two ports at each height for each section.

The operating conditions of the fluidised bed furnace could be briefly summarised as follows:

Bed temperature = 850 ^{o}C
Gas velocity = 1.5 - 2.0 m/s
Gas temperature at the exit of the furnace = 700 ^{o}C
Fuel feed rate = 1 000 - 1 500 kg/h
Excess air levels = Up to 200%.

The hot gases leaving the combustor is transported in two ducts which are refractory coated. There is an external insulation to minimise the heat losses and in actuality, the temperature at the exterior is less than 40 ^{o}C.

RESULTS AND DISCUSSION

The combustion of biomass particles was observed to be associated with the luminous flame of burning volatiles that were released. The flame length almost covered the height of the freeboard when no staging of air was carried out. With proper staging, the flame length was reduced to about less than 800 mm.

Combustion temperature was kept below 800 ^{o}C to prevent ash fusion. The temperature was varied from 550 to 800 ^{o}C to determine its effect on combustion efficiency as demonstrated in Figure 1. As expected, the temperature gave rise to an increase in the overall efficency, however, what appeared to be more important parameter was the staging of the air. There was a significant increase in the level of complete combustion by introducing part of the air in stages to the freeboard. With no staging, high levels of unburned hydrocarbons and CO were observed in the combustion flue gases leaving the combustor. Table 1 briefly summarises the results obtained. The amount of hydrocarbons and CO in flue gases appeared to decrease substantially by the introduction of the combustion air in stages. However, better combustion was achieved by introducing the air to the freeboard at different points along the height. It was also necessary to increase the level of swirl in the staged air gradually along the freeboard height. This caused a reduction in flame length and decreased the amount of NO_x formed.

The effect of excess air levels on combustion efficiency is given in Figure 2. It is clear that only above 140% of excess air acceptable combustion efficiencies were achieved with staging the air and increasing the amount supplied to the freeboard. With no staging, maximum combustion efficiencies obtained were in the order of 80% which is considered too low. Even with air staging and 25% of air supplied to the freeboard the combustion efficicency obtained did not exceed 85% and for an industrial operation, this was found to be below the required levels.

Biomass particles contain varying amounts of fuel nitrogen depending on their origin. Their oxidation to NO_x occurred during the combustion. Table 2 demonstrates the effect of air staging and temperature on the amount of NO_x formed. It appears that the conversion of fuel-N to NO_x varied between 15 to 30% as commonly observed with coal combustion. Staging of the combustion air helped to reduce the levels of NO_x formed and the effect of gradual staging at several points along the freeboard height was in fact more pronounced in bringing down the NO_x amount. In the same Table, the observed values for CO were compared with those for NO_x for different excess air levels and this clearly demonstrates the influences of excess air and temperatures to increase NO_x formation even with air stagingand higher combustion efficiencies which led to significant reductions in CO amounts formed.

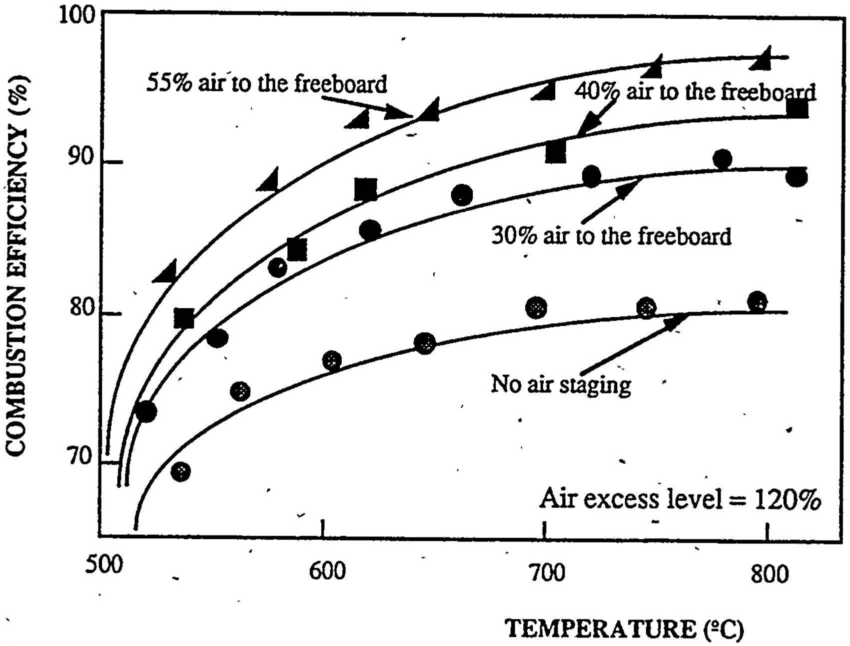

FIGURE 1 - The influence of temperature and air staging on the combustion efficiency

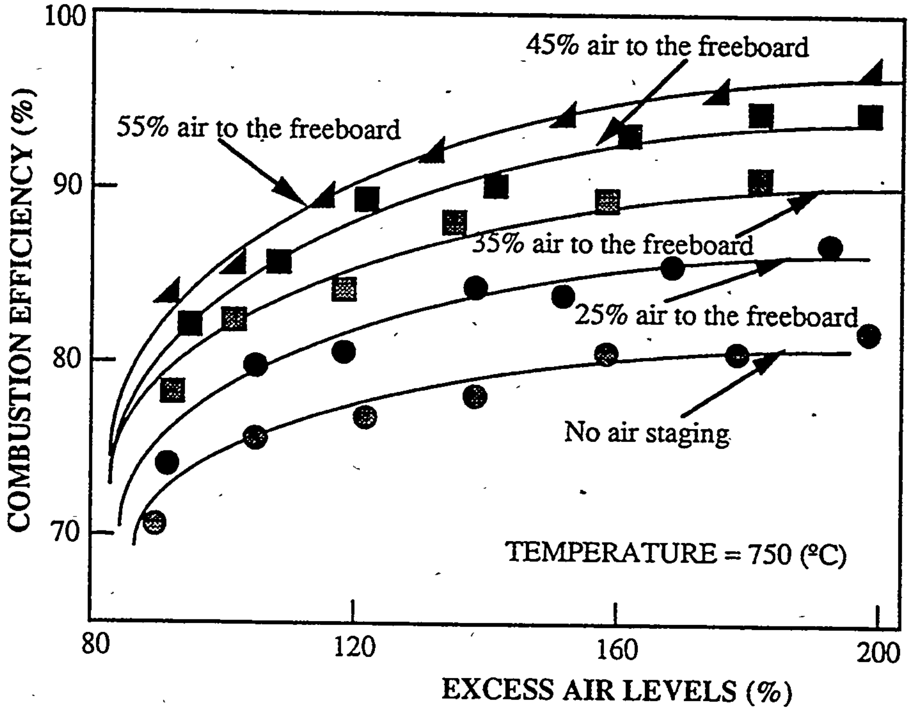

FIGURE 2 - The influence of excess air levels and air staging on combustion efficiency

TABLE 1 - The summary of the results demonstrating the effect of air staging on the amount of unburned combustibles.

OPERATING CONDITIONS	CO (% by vol)	Hydrocarbons measured as CH4 (% by vol)	Unburned wood particles as % of the input
- No air staging, 80% excess air, temperature=750 °C	1.56	6.35	35
- No air staging, 150% excess air, temperature=750 °C	0.96	4.86	28
- Air staging with 30% of air introduced to the freeboard at one point, 80% excess air, temperature=750 °C	0.09	1.28	14
- Air staging with 50% of air introduced to the freeboard at two points, 100% excess air, temperature=750 °C	0.005	0.55	8

TABLE 2- The effect of air staging on the levels of NO and CO emitted

Bed temp. (ºC)	Air staging	Nº of staging	Excess air (%)	CO (%)	NOx ppm	NOx with no staging ppm
700	Yes	1	120	0.017	135	185
750	"	1	120	0.012	178	210
800	"	1	120	0.009	196	278
700	"	2	150	0.005	139	229
750	"	2	150	0.003	258	340
800	"	2	150	0.002	326	428
700	"	3	150	0.008	115	229
750	"	3	150	0.004	187	340
800	"	3	150	0.0005	278	428

THE EXPERIENCE OF BURNING THE HIGH-MOISTURED WASTE OF BIOMASS CONVERSION

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Abstract

Industrially developed countries have at their disposal a large stock of operating boiler plants for utiluzation of the timber industry waste materials (bagasse, bark, wood chips, hydrolytic lignine, sawdust, etc.) as well as for biogenesis of energy.

The standard combustion methods employing a bed or flare process cannot guarantee a reliable and economic boiler plant operation with abruptly changing biomass characteristic features. Thus, the moisture content in bark or lignin, supplied to the enterprises of the pulp and paper industry, can vary from 50 to 75% during an hour. The boiler operation becomes more complicated due to variation in feed composition size fraction. Particle sizes can vary from powdered to very large ones (to a fraction of a meter), and can differ from each other hundred thousand times. To adjust thermal and size fraction characteristics of fuel the use is made of a complex bulky set of preparatory equipment which operation becomes complicated by the ingress of large metal and mineral inclusions into the starting fuel.

The well-known low-temperature whirling combustion technology developed in the S.Petersburg State Technical University used on most of Russian power plants in order to burn fuel was taken as a basic. A long-term highly economical and stable operation of boilers has been echived by means of up-to-date vortex chamber aerial dynamics, the use of unique devices of fuel feed and preparation with screening the waste materials into sizes. A long-term repair-free campaign cycle is due to simplification in fuel preparation system enabling to effect this technological process. The firing chamber is equipped with a multi-chamber device where screening and fuel particles preparation with the removal of non-combustible inclusions take place.

At present the firing chamber with multi-step process of burning is in operation with 20 boilers. The firm "POLYTECHENERGO", a developer and producer of such equipment, carries out the modernization of the boiler plant without changes in the its thermal circuit. In most of cases no replacement of draught means is needed. Competitive with the proposed low-temperature wirling technological process can be only a fluidized bed process, but due to the complexity in service, low reliability, high energy expenditures, such chambers at present are very few. The capital expenses on existing boilers updating for a fluidized bed process exceed the expenses on a low-temperature wirling process by 15-20 fold.

A use of the waste of industrial conversion of biomasses as a fuel corresponds the expendituse, because the tasks of ecologie, transportation and utilization are solved simultaneously. The presence of too big concentration of waste can decrease an effectiveness of the whole industrial process. This waste can also harm the surrounding bio- and hydrospheres especially if this waste contains harmfull or stinking components.

Despite the wide potential possibilities of power employment of some organic waste that can replace partly or even completely an expensive fuel, this direction has been hampered by the absence of relyable and economical rebox devices which would correspond to up-to-date demands of the boiler design.

The purposes of this work were design and industrial assimilation of effective furnace construction intented for burning biomasses with a high level of moisture including lignine and bark. It was also necessary to create a sufficiently simple method of modernization which could be used to deal with the traditional type of device using jet burning of fuel and which would not demand huge expanditures for its realisation..

According to the European internationale classification of fuels, a low-grade fuels are those containing a ballast more than 40% and having the heat of burning less than 16 MJ/kg. The hydrolitic lignine (waste of wood hydrolysis) and bark has the heat of burning considerably less than mentioned above one (about 5...7 MJ/kg). The working dampness depends largeby on coocking technology and varies from 50% to 80%. As for the volatile components, lignine and bark can be defined as a high reactionary fuels. Fractinal containtment of lignine is determined by the metod of coocking and can include the 0,05 m pieces simultaneously with the smallest particles. The mechanical roughness of lignine depends on containtment of some mineral admixtures (clay, sand) and mainly on containtment of hard dissolved polysacharides. A special mention should be made that the caracteristics of hydrolytic lignine may widely vary during the time. It can be either free flowing on lump or semi-liqide. This influences its transportaion and the process of preparation for the burning. There are sulphur containing admixtures and also some aerosols with unpleasant odor. The containtment of sulphur per an analitical mass can exeed 2...3%.

Thus, lignine and bark can should considered as a class of hign-damp, low-calorie, high-reactional, exposive and hard-burning kinds of fuel with sharply-changing unpredictable properties.

The well-known low-temperatute whirling furnace developed in the S.Petersburg State Technical University widely used on most of Russian power plants in order to burn fuel was taken as a basic.

The scheme of the boiler E-50-24 K is shown on the figure. The modernization of boiler was to allow to provide a full utilization of lignine out of both the main manufacture zone and dust-heap. This boiler is serialy produced by the boilerbuilding plant (Belgorod, Russia) and has been installed on the biochemical plant (Kedainiaj, Lithuania). In order to prepare the fuel for burning the disconnected system of dust-preparation with two stages of dust concentrators was used. The product of the drying was dropped out of the boiler. The faults of this system that restrict its employment are difficulty, big shape, the increased employment of working force on repair and service, the increased danger of explosion and also low economy and reliability. The most essential fault is the discharge of unpleasant gases elaborated by drying agent to the athmosphere. Exploitation of this boiler using lignine became impossible.

On the way to modernization of this boiler, a method of fuel burning within the fluidized bed furnase has been considered. Now a deep interest is being expressed toward it in many countries because of the cleaning of combustion product out of sulphur oxids.

However, such method demands a huge expenditure and particularly full change of the boiler. Besides, the widely employment of fluidized bed furnase is hampered by low reliability of equipment and by considerable expenditures on its own needs.

The main idea of a new furnace device is to increase the particle time of burning by means of whirling aerodinamics with creation a repeated circulation of fuel and furnace gases.

As a result of an action of two flows an intensive whirling movement of gases with a gorizontal axis is created. The burning fuel concentration within the volum of gases increases from each other several times. This makes the process unsencitive to changes of coming lignine characteristics.

On the figure the same boiler E-50-24 K after its modernization is presented. The huge and bulky system of dust preparation was eleminated only by changing the aerodynamic process within the furnace. In order to improve thermical system of preparation of big particles and to eleminate the fuel falling, a shelf classificator is installed in the lower part of furnace. This classificator dry fuel particles by means of hot air coming to the burning and separates them to fractions.

The furnace operates according to the following rules.

1. The fuel alone the incleaned leak chanel with the determined velocity is transported stright out of the bunker into the furnace by means of a pump.

2. Having left the burner as a result of radiational heat exchange between a lignine particles and the flow of hot gases the smallest particles are warmed up and burnt up. Particles of middle size are involved into the repeated circulation where the stages of drying, warming, ignition, burning take place one by one.

3. The air flow of lower blowing is directed toward the side of main burners. Therefore, the fuel warming being handled out of burners is fulfilled considerably rapider by means of convectional heat exchange which is added to the radiational heat flow.

4. Coarse particles, being within the flow of hot air which is handled through the classificator, lose their moisture, a part of volatile components, their weight and return again to the furnase due to the thermical preparation. Such a preparatoin of coarse particles (their mass does not exeed 20% of the total fuel mass) is accompanied with the formation of small fractions by means both the destruction of particles and consequences of discharge

of small coal particles. These small particles are discharged in conjuction with the presence of flow.

The intergrated experiments of the modernizated boiler found out the following advantages:

1. The useful action coefficien has grown from 83,0% up to 86,9%.
2. The specific discharge of sulphur oxide has remained on the level of 1,7 10^{-3} kg/ m^3.
3. The specific discharge of nitrogen oxide has gon down from 0.55 to 0.3 10^{-3} kg/ m^3.
4. New constaction saves about 1 MW of electric power required for its own needs by excluding of some apparatuses.
5. The working and repair conditions have been improved and simplified.

On tne base of results of modernization, the "Belgorodsky boilerbuilding plant" began to produce such boilers serialy.

The designed whirling technology of burning improved with regard to coal on the power plant "Sekerky" (Warsaw) showed that it posessed additinal posibilities in order to use the method of dry additions for the cleaning of furnase gases out of sulphur.

The repeated circulation of fuel and furnace gases leads toward formation of considerable zone with low (lower than 1480 K) temperatures. It allowed to decrease the SO_x emission down to 50% by means of supply of sorbent within the furnace of boiler WP-120 on the 12 m level. Quantity of SO_x being descharged into the athmosphere has been decreased from 0,711 to 0,350 kg/GJ. This fact corresponds today's demands on the extremely admitted discharges for the boilers of B group.

As a result of this work we can admitt that a new type of low-temperature whirling furnace device has been designed to burn some biomasses and fuels of wide range of quality (from lignine and bark to coal). This device also posesses high technical and ecological characteristics.

This furnace device is able to occupy the intermediate position between traditional flame furnace and those using the fluidized bed furnace without loosing the advantages of each of them. In addition, this device does not demand difficult and expensive system of dust preparation.

It is obvious, that the low-temperature whirling process with multi-step burning of fuel, wastes and biomass offers ample scope for updating the existing and developing new boilers.

On the bas of three years experience of exploitation of modified boilers with the whirling low-temperature furnace, the company "POLYTECHENERGO" (Russia) can offer the recostructions of these boilers to those who will be inerested in it. The full delivery of all components is guaranted.

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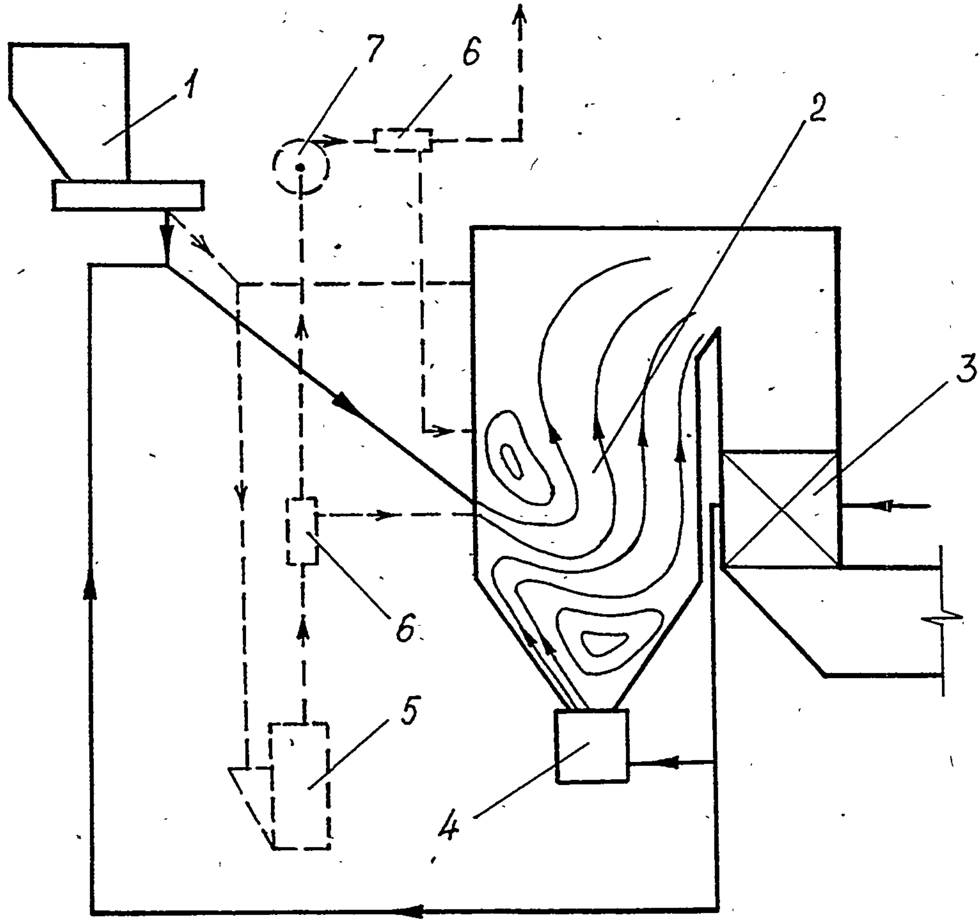

Scheme of the boiler E-50-24K after its modernization

1 - bunker of fuel;	2 - whirling furnase;	3 - preheater of air;
4 - classificator;	5 - mill-ventilator;	6 - dust concentrator;
	7 - exhauster	

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PROCEEDINGS
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