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ON-SITE ENERGY PRODUCTION FROM AGRICULTURAL RESIDUES

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for

THE TEXAS A&M UNIVERSITY SYSTEM

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DISCLAIMER

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EXECUTIVE SUMMARY

The objectives of this project are to design, develop, and demonstrate a working system using agricultural residues to produce power for agricultural operations such as irrigation pumping and cotton ginning. This research has the potential of reducing significantly the dependence of agriculture on fossil fuels since the largest single usage of fossil fuel in agricultural production is the pumping of irrigation water.

With the support of TENRAC and several agencies of the Texas A&M University System, a three-phase program was undertaken by an interdisciplinary team composed of agricultural, chemical, and mechanical engineers as well as agricultural economists and forest-science researchers. Faculty members with expertise in material science and combustion emissions sampling also became involved as the investigation progressed. The three phases of the program were (1) develop design criteria for a small-scale biomass power producing system, (2) design and test system components, and (3) demonstrate a power producing system.

Fluidized-bed energy technology was selected for studying thermal biomass conversion because of its unique operating characteristics. The studies initially emphasized direct combustion though some work was done on gasification. The work focused on the evaluation of direct combustion and gasification of organic residues in a fluidized bed, design of cleanup equipment for the removal of particulates from exit gases, and coupling a steam boiler to a fluidized-bed reactor.

Direct combustion experiments were made in a 61 cm diameter fluidized bed with a heat release capacity of 1 GJ per hour. Cotton gin trash was the primary test material although some research was done using sorghum

stalks. Results from direct combustion tests were:

--Direct combustion caused the deleterious formation of coatings on bed particles; fouling of stacks, tubes and cyclones; and hot metal corrosion of coupons exposed to exhaust gases.

--The problems of direct combustion were attributed to the formation of complex chemical compounds and eutectics in the oxidizing environment of the reactor.

--The comparison of the combustion efficiency of different air distributor plates resulted in the choosing of a distributor providing a net upward flow of bed particles near the center of the fluidized bed and a net downward flow at the walls.

Gasification experiments were carried out in a 51 mm diameter fluidized bed using cotton gin trash, sorghum stalks, corn cobs and rice hulls as feedstocks. Differences exist in the gas composition and heating value produced by these feedstocks, but each can be used satisfactorily in a fluidized-bed gasifier. The predominant products of gasification suitable for combustion are carbon monoxide, hydrogen and methane. Preferred operating conditions are 760°C at atmospheric pressure. The quality of gas produced at these conditions is primarily a function of the fuel-to-air ratio. Typical heating values of gases produced by gasification are: cotton gin trash--6.26 MJ/m^3, sorghum stalks--7.74 MJ/m^3, rice hulls--9.71 MJ/m^3, and corn cobs--8.22 MJ/m^3.

Particulate removal from the low energy gas produced by a 30 cm diameter fluidized bed was evaluated using a two-stage cyclone. Results show that about 99 percent of the particulates are removed by this system. Depending on the end use, different techniques will be required to remove the remainder of the particles. A cyclone design model is being tested to verify its usefulness in designing efficient particulate-removal systems for various sizes of fluidized beds.

A fire-tube boiler was coupled to the 61 cm diameter fluidized-bed unit and provisions were made to operate the resulting system as a close-coupled gasifier-combustor to produce steam. This system is currently being evaluated and shows promise of eliminating the problems experienced with direct combustion alone. Preliminary tests show that almost 60 percent of inputted energy is converted to steam. In terms of feed, 1.00 kg of cotton gin trash produced 3.65 kg of steam (100°C, 1 atm).

Significant conclusions from this report may be summarized as follows:

--Coating of bed particles, fouling of equipment and hot metal corrosion are serious problems to overcome in the direct combustion mode of operation.

--The problems with direct combustion of biomass apparently involve complex chemical reactions of the elements comprising the biomass materials being tested.

--Operating a fluidized-bed unit in the gasification mode reduces or eliminates the bed-particle coating and fouling problems experienced with combustion.

--Low-energy gas can be produced successfully from cotton gin trash, rice hulls, sorghum stalks, and corn cobs in a fluidized-bed system.

Based on these results, gasification appears to be a more practical method of converting certain fuels to energy forms useful in agriculture than does direct combustion. Fluidized-bed gasification has been demonstrated to be a partical method for gasifying organic residues where other methods of gasification have not.

Continuation of research using the laboratory-sized fluidized-bed gasifier-boiler system will provide assurances of a technically sound large-scale system. It is recommended that the gasification mode of operation receive the major emphasis in future research because of its apparent advantages over direct combustion.

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INTRODUCTION

A viable Texas agricultural industry is important to the state and nation but increasing energy costs and the threat of shortages have raised questions about the future of this important industry. These factors have created the need for research to determine alternate energy sources for agriculture. Agricultural crop residues have been identified which could supply the Texas agricultural industry with a significant quantity of energy. Unfortunately, small-scale techniques to convert these materials to usable forms of energy were not readily available at that time.

A review of conversion technologies was made in 1977 with the conclusion that thermal conversion to produce usable energy could be implemented through either direct combustion or gasification techniques in the shortest period of time. It was further concluded that fluidized-bed energy technology was the most feasible technique for converting a wide range of biomass materials into high-grade energy.

Project Goals

The goal of the project discussed in this report is to reduce dependence of agriculture on fossil fuels by demonstrating technology for converting agricultural biomass to usable forms of energy. In Texas, the energy required in agriculture is classified as high-grade forms and is needed in operations such as pumping irrigation water, powering field machines, and processing crops. Techniques to convert agricultural organic residues and processing by-products to high-grade energy forms in small-scale, on-site applications are not available. This project evaluates fluidized-bed energy technology for converting biomass to usable energy forms.

In the initial phases of the project, a review was made of thermal and biological energy conversion techniques. It was concluded that the thermal techniques of direct combustion and gasification were the most adaptable technologies and the most rapid method of demonstrating techniques to obtain usable quantities of energy from biomass. A comparison of combustion and gasification conversion techniques is shown in Figure 1. Primary emphasis was initially placed on direct combustion because it was believed that more off-the-shelf equipment was available for this mode of operation than others. However, this report details some problems with direct combustion and recommends a shift of emphasis.

Fluidized-bed energy technology was selected for thermal conversion studies using biomass because of its unique characteristics and versatility. The ability to accept a wide variety of feedstocks with little preprocessing and accurate temperature control were two primary characteristics of fluidized-bed energy techniques which appeared to provide a method uniquely adaptable to small-scale biomass conversion.

A contract was initiated between the Texas Energy and Natural Resources Advisory Council and several agencies of The Texas A&M University System in 1978 to evaluate fluidized-bed energy technology for biomass conversion. The initial contract enabled the evaluation of direct combustion of cotton gin trash in a 61 cm diameter fluidized-bed combustor, and evaluation of gasification of cotton gin trash in 51 mm and 30 cm diameter fluidized bed reactors.

Previous Results and Recommendations

Results of the initial contract are detailed in Energy Development Fund Project 78-B-1-5 Report (Hiler, 1980). Significant results in the initial work included:

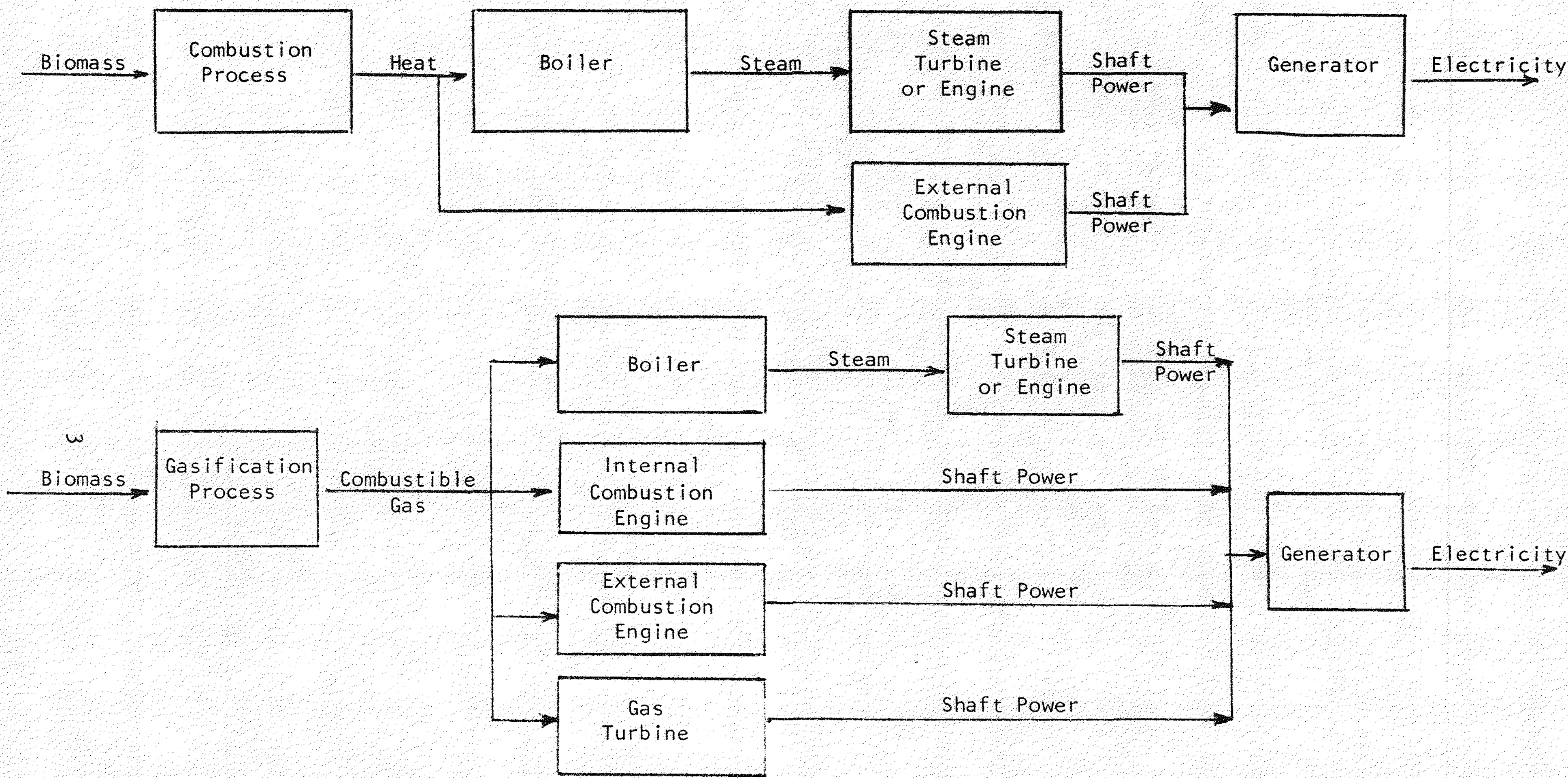


Figure 1. Comparison of processes for converting biomass to electricity by combustion and gasification.

1. Development of a fuel feed system to inject raw gin trash into the lower regions of fluidized beds.

2. Sustained periods of direct combustion using raw gin trash in a 61 cm fluidized bed at 760°C formed low melting point eutectic compounds in the system resulting in fouling of the system and erosion/corrosion of metal coupons exposed to stack gases.

3. Using a 30 cm fluidized bed in a gasification mode of operation enabled raw gin trash to be converted to a combustible gas having a heat value ranging from 3.65 to 5.29 MJ/m^3 depending on operating conditions. Problems caused by low melting point eutectic compounds were not observed in the gasifier.

4. Economic analyses for a 40,000 bales per year gin showed that a system to generate electricity and dry seed cotton approaches the economic break-even point. While neglecting gas cleanup costs, production of low energy gas was shown to be less than the current natural gas prices.

The initial tests demonstrated that fluidized-bed technology has the potential of converting raw agricultural biomass into usable energy forms. For example, cotton gin trash was used successfully in a gasifier whereas other studies have shown that other types of gasifiers have slagging problems when using gin trash. However, the direct combustion tests revealed significant problems which should be investigated further. Methods to control the formation of eutectic compounds were suggested and eutectic formation was not seen to be an insurmountable problem. Also, in view of the versatile end uses and favorable economics of gasification, the recommendation was made that gasification be evaluated more thoroughly. The fluidized-bed systems used in this work can be operated easily in either the combustion or gasification mode by controlling the fuel-to-air ratio.

Objectives

This contract was for experiments on direct combustion and gasification of biomass in fluidized beds. Specific services to be performed were:

1. Further test fluidized bed in direct combustion mode.

   - Analyze fluidized-bed combustion test results and develop boiler specifications.

   - Procure and couple compatible boiler with fluidized-bed combustion unit.

   - Test combustion unit/boiler system and analyze results.

   - Develop specifications for steam prime mover (power generation system).

2. Test fluidized bed in gasification mode.

   - Experimentally determine optimum operating conditions for low-Btu gas production from gasification of corn and sorghum residues.

   - Establish low-Btu gas cleanup requirements from analysis of measured data.

   - Design, construct and test gas cleanup equipment.

   - Investigate operating combustion unit in gasification and pyrolysis modes.

EQUIPMENT AND PROCEDURES

Three fluidized-bed units have been used in these studies and have fluidizing chamber diameters of 51 mm, 30 cm, and 61 cm. All units are based on the same design principles and use an auger which feeds fuel into the lower region of the fluidizing chamber. A schematic representing these units is shown in Figure 2.

The 61 cm unit was used for combustion studies while the two smaller units were used for gasification studies. However, all units can be operated in either mode by controlling the fuel-to-air ratio. Air in greater than stoichiometric quantities or air which supplies more than enough oxygen to react with the carbon in the fuel provides combustion. Air quantities less than stoichiometric provide only partial combustion and yield a combustible gas.

Direct Combustion Experiments

Previous combustion work identified problems with coating of bed material, fouling of system, and erosion/corrosion of metal coupons located in exhaust gases. These experiments emphasized tests to determine the mechanism causing these problems. Design and operating changes were made in the 61 cm diameter unit attempting to reduce or eliminate these problems.

Distributor Design. The air distributor system of the 61 cm diameter unit was redesigned to provide different bed circulation and mixing patterns. The original design provided a net upward movement of bed material in the central regions and a net downward movement along the walls of the unit, as shown in Figure 3a. This provided a circulating pattern of bed material movement but resulted in a large dead zone or nonfluidizing region at the base of the bed.

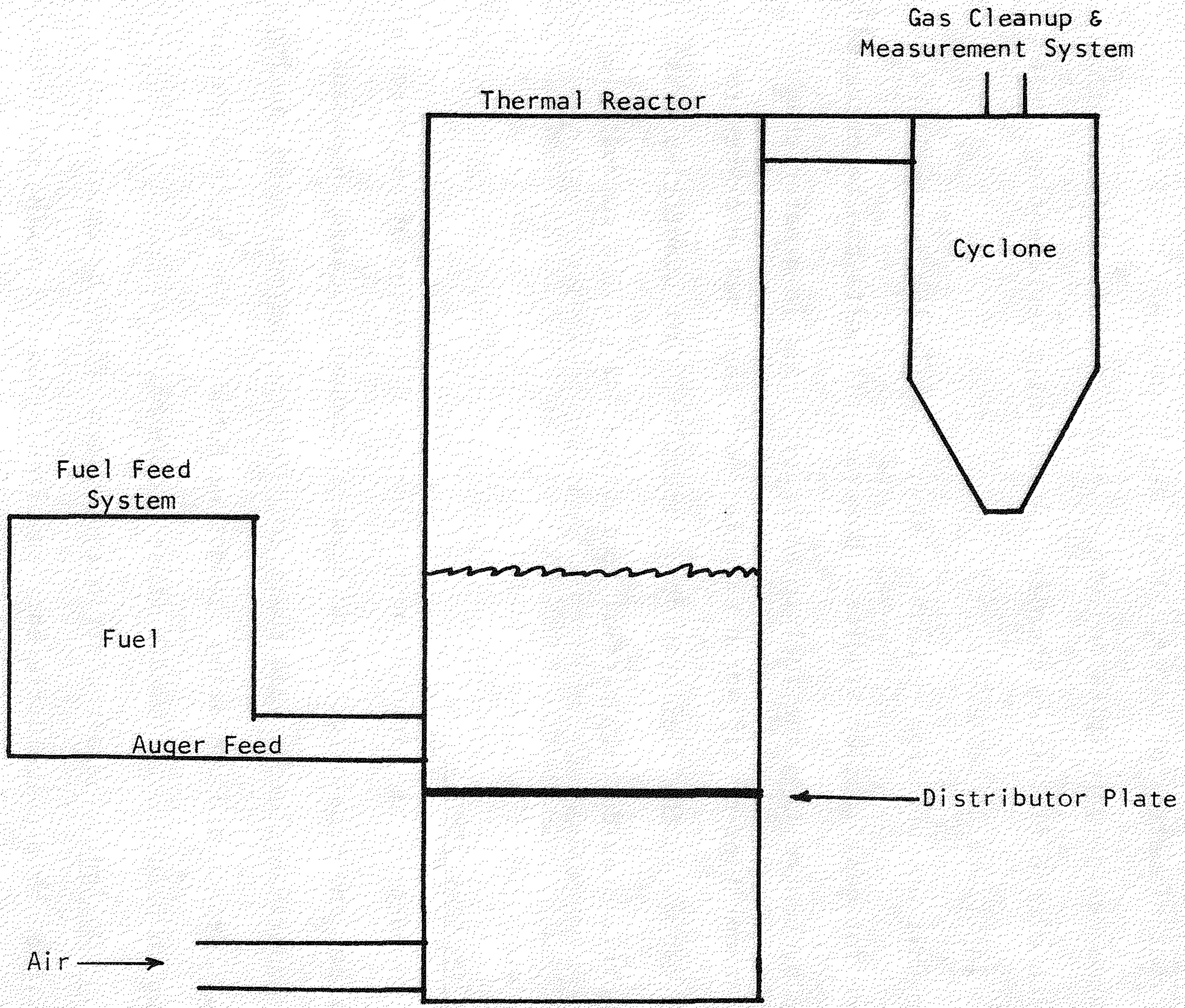


Figure 2. Schematic of fluidized bed units for biomass energy conversion systems.

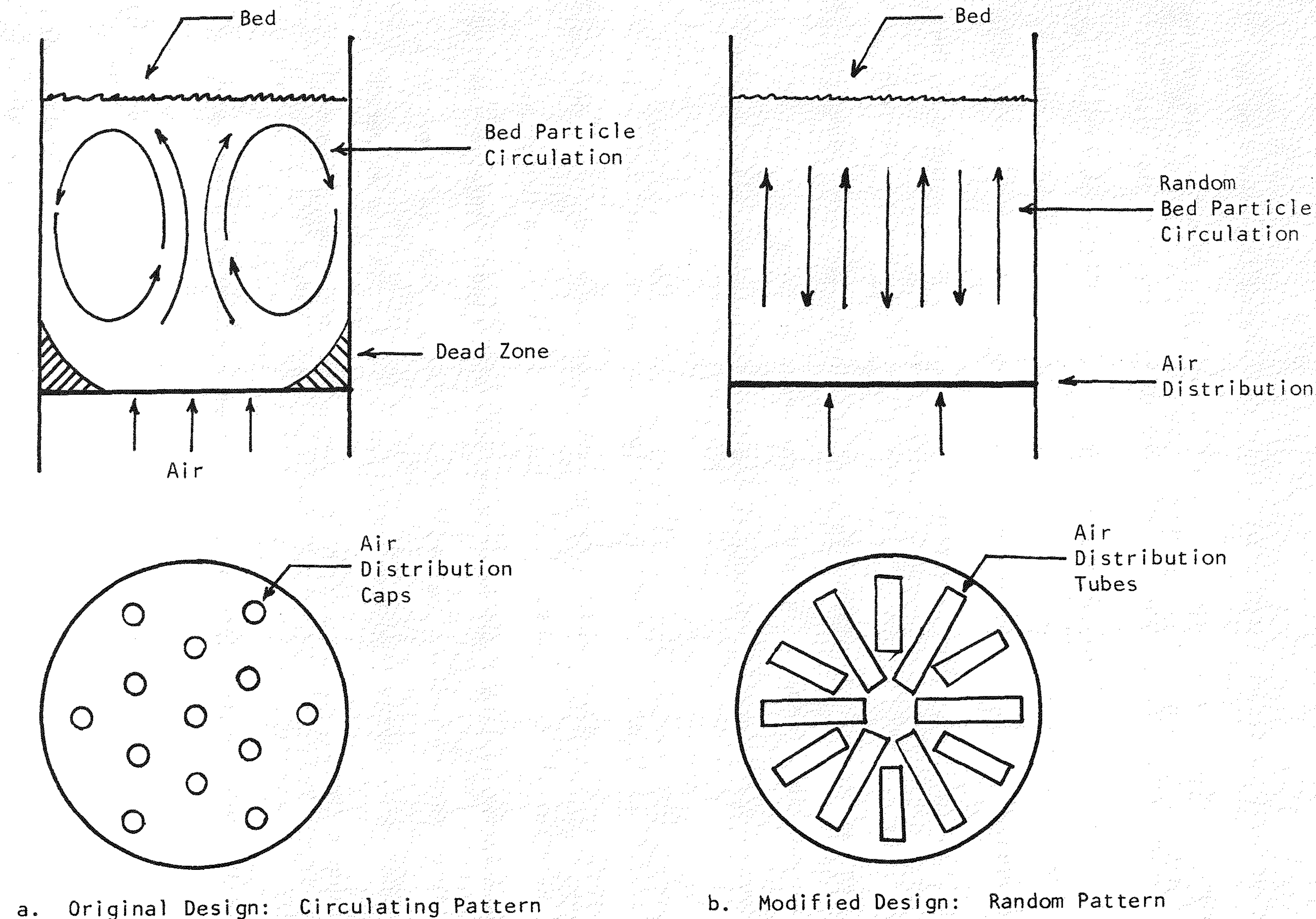


Figure 3. Schematic of original and modified designs for fluidized bed circulation and mixing.

The modified design (Figure 3b) almost eliminated the dead zone and provided uniform fluidization throughout the bed. The resulting bed mixing is a random pattern rather than a net circulating pattern of the original design. This mixing pattern was needed to test the possibility that the dead zones were causing localized characteristics which resulted in the bed coating.

Ash Sticky Point. Laboratory analyses were made to test the reaction of the ash to the bed materials being used. The sticky point of cotton trash ash was determined in a muffler oven and in the combustor mixed with bed material. Samples in ceramic containers were held at various temperatures for 15 and 30 minutes, cooled, and evaluated to determine if particles were sticking together.

Fluidized-Bed Tests. Direct combustion experiments were made in the 61 cm diameter fluidized-bed unit using procedures described in the previous report by Hiler (1978) (EDF-78-B-7-5). Cotton gin trash was the primary fuel used in the tests but sorghum stalks were also used. Operating bed temperatures were maintained near 760°C for all tests, and bed temperature was maintained by controlling fuel feed rate. Average feed rates were established by measuring the length of time needed to consume a known quantity of feed material.

Airflow was maintained between the minimum and terminal fluidization velocities of the bed particles. Airflow was measured using a laminar flow element, but unknown amounts leaked through the fuel feed system creating errors in measurements.

Temperatures and pressures were monitored at various points within the system to evaluate system performance. Particulates in the exhaust stack from the cyclone were monitored using EPA method 5 sampling techniques modified for the small stack diameter. Ash samples from the cyclone were also analyzed.

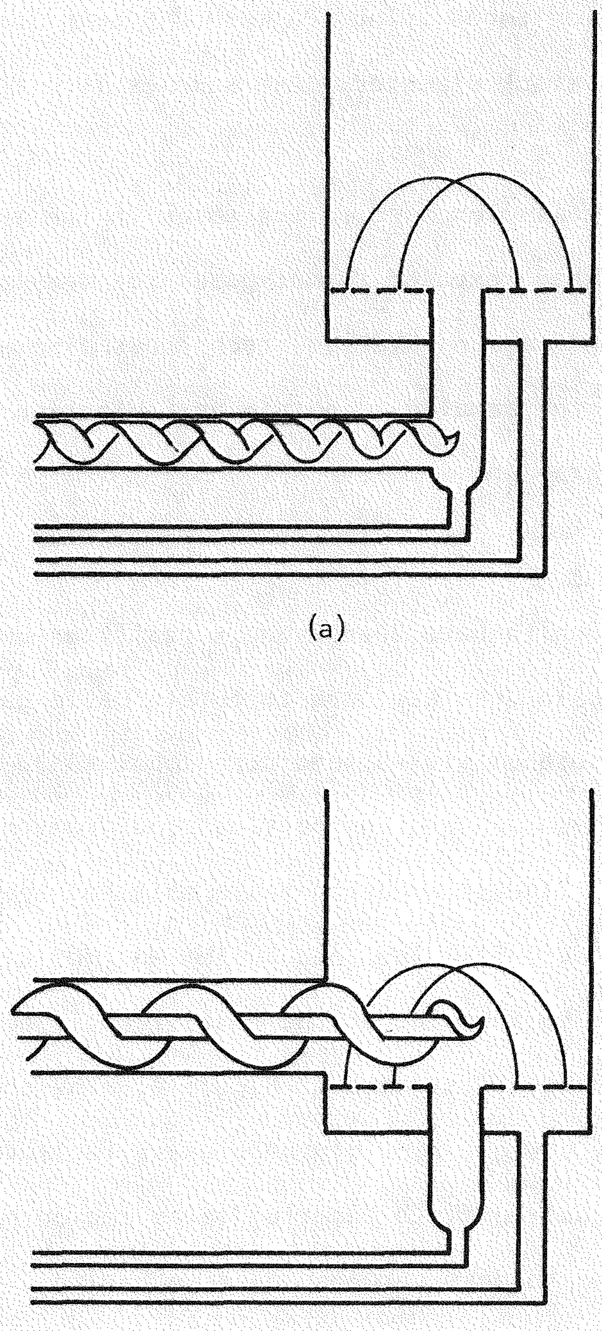
Metal coupons were also exposed to the gases in the exhaust stack. These coupons were weighed, exposed to hot gases for varying periods of time, cleaned, and then weighed again. Various techniques also were used to analyze the surface of the samples to obtain an indication of the mechanism causing corrosion and erosion.

Gasification Experiments

Two fluidized-bed units have been used in gasification experiments. A 51 mm diameter bench-scale unit was used to obtain basic gasification characteristics of rice hulls, sorghum stalks, and corn cobs. A 30 cm diameter unit was used to evaluate cyclones for removing particulates from the low-energy gas.

Bench-Scale Tests. The 51 mm bench-scale unit has been described previously by Hiler (1978) (EDF 78-B-7-5). The feed system was modified slightly to move the auger entrance to the side of the unit slightly above the air distributor. This modification is illustrated in Figure 4. The change was required because in the original design, some of the biomass fuels tended to lodge in the system before introduction into the fluidizing region and plugging the system. Fuel was ground to pass through a screen having 2.36 mm openings.

Operating bed temperatures were selected to range from 796 K to 1180 K. Fuel-to-air ratios ranged from .7 kg/kg to 1.8 kg/kg. The lower fuel-to-air ratio is similar to that which can be achieved without supplemental heat in larger units but, because of the high surface area to volume in the small unit, supplemental heat was used in all tests.



(a)

(b)

Figure 4. Redesign of fuel feed for 51 mm fluidized bed.
(a) Original bottom of reactor.
(b) Redesigned bottom of reactor.

Gas production rate was measured using a wet test meter. Samples of the gas were analyzed using a Carle gas chromatograph which was connected to a microprocessor for automatically evaluating mole percentage of the following constituents: hydrogen, carbon monoxide, carbon dioxide, nitrogen, methane, ethylene, ethane, propylene, propane, and butane. Heating value of the gas was calculated using the gas composition determined by the gas chromatograph and standard heat of combustion of the gas components.

Gas Cleaning. The 30 cm diameter fluidized-bed unit was used to study a two-stage cyclone particulate removal system. Low energy gas produced in a fluidized bed contains ash and unburned carbon particles which must be removed before the bed can be used efficiently in most applications. Cyclones have been used as cleanup devices by industry and agriculture for many years and are relatively simple and inexpensive to construct. A cyclone has no moving parts and consists of: a cylindrical shell fitted with a tangential inlet through which particulates suspended in a gas enter; an axial exit pipe for discharging the cleaned gas; and a conical base with dust discharge (Stairmand, 1951). Rietema (1961) states that the principle of separation in a cyclone is governed by the following four factors: 1) centrifugal field established; 2) radial velocity pattern; 3) residence time of the particles to be separated; and 4) turbulence which develops.

A computer model for cyclone design based on these governing principles has been developed at Texas A&M University by Dr. Calvin B. Parnell, Jr., and associates (Parnell, 1981). This model is based primarily on theory described by Muschelknautz (1970). The computer model uses airflow, air psychrometric properties, dust loading, dust density, and dust particle size to obtain a cyclone design which meets desired efficiency and pressure drop criteria (Avant, 1976). From these parameters, the efficiency pressure drop, particle size distribution (PSD), mass mean diameter (MMD), and exit loading of dust can be determined.

The cyclone design model was used to design a two-stage cleaning system for the 30 cm diameter unit based on previous data obtained with cotton gin trash fuel. The cyclones were constructed using castable refractory. The first cyclone was designed to remove larger particles and reduce the particle concentration so that the second stage could remove smaller particles at higher efficiency. These cyclones were coupled to the 30 cm diameter reactor for evaluation of the cyclone design model.

For testing of cyclones, the 30 cm diameter fluidized-bed unit was operated to produce high-quality gas. This has been determined to occur when bed temperature is maintained near 760°C and fuel-to-air ratio is maintained near .65 kg/kg. During operation, high quality gas is indicated by intensity of flame as gas is flared. Rate of entering air was monitored using an orifice meter and fuel feed was monitored by calibrating feed rate to metering auger speed. Fuel feed rate was also checked during operation by recording time periods required to consume weighed quantities of fuel.

Cotton gin trash from different gins and locations has slightly different composition and texture which influenced fuel feed rate. To minimize fuel feedrate variations, the tube diameter of the auger feed system in the 30 cm diameter reactor was increased from 5 cm to 7.62 cm. The metering auger was not changed but increasing the tube size provided uniform feed rates of cotton gin trash as indicated by the calibration for one-minute and three-minute intervals shown in Figure 5.

Gas samples were taken during cyclone evaluation and analyzed using a Carle gas chromatograph. Gas composition and heating values were determined

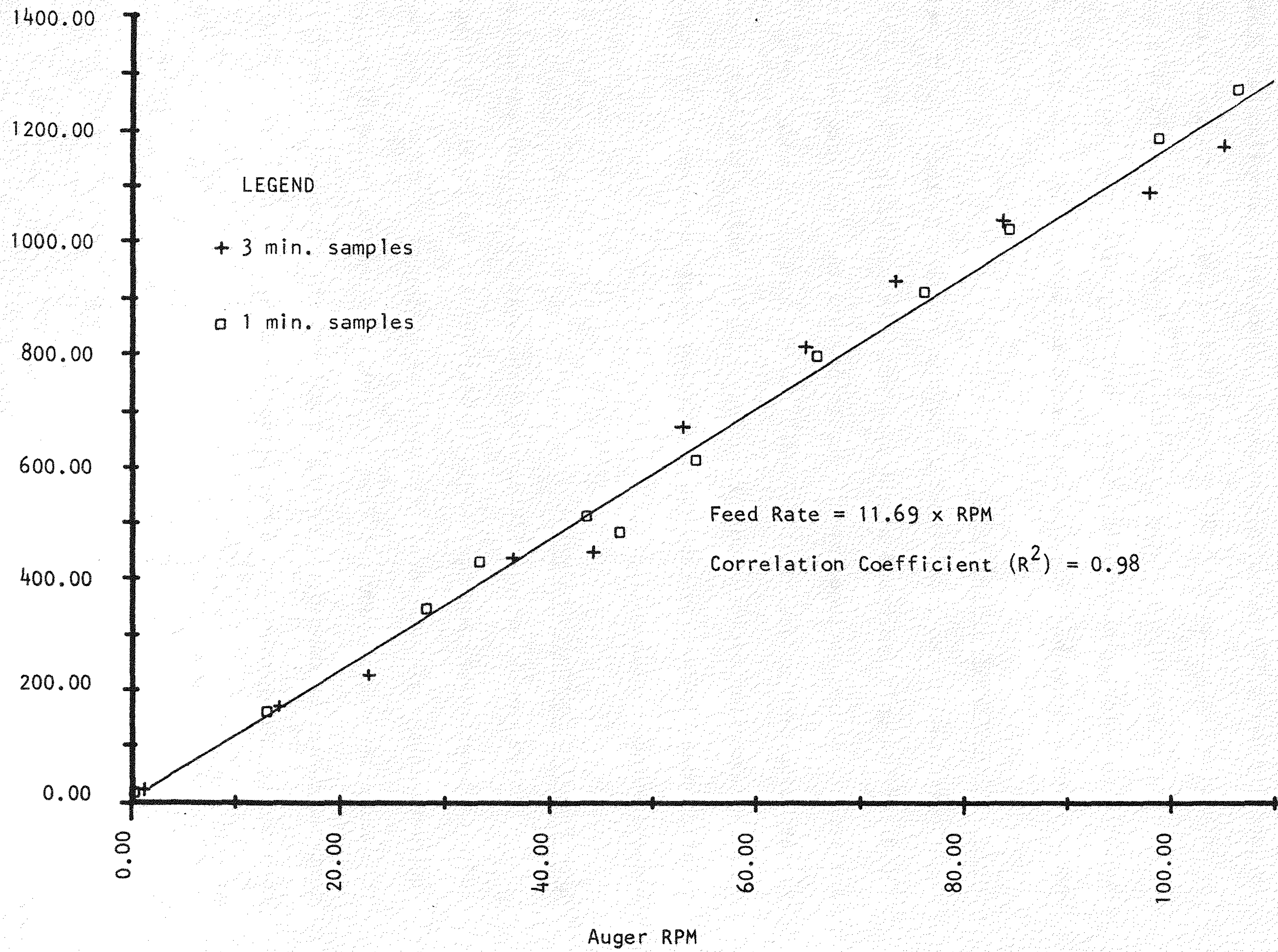


Figure 5. Calibration curve for feeding cotton gin trash with fuel feed system of 30 cm diameter reactor.

by sampling using EPA Method 5 procedures. Isokinetic sampling was achieved by adjusting the velocity of the stream entering the probe to the velocity of the gas stream in the stack. Particulates removed by each cyclone were measured by weighing quantities removed during specific time periods. Particle size distributions were analyzed using a Model TAII Coulter Counter.

Boiler Selection and Installation

Specifications were developed to couple a boiler to the 61 cm diameter fluidized-bed unit. Because of the problems encountered in direct combustion, the specifications included provisions to operate the fluidized-bed unit in either combustion or gasification mode. In the combustion mode, hot gases from the combustor cyclone would be directed to the boiler but in the gasification mode, low-energy gas from the cyclone would be mixed with additional air and burned at the boiler.

Site-Specific Economic Analysis

A preliminary site-specific economic analysis of a fluidized-bed energy conversion system was made for a gin in west Texas. All power-consuming equipment in the gin was identified and a selection of components was made to produce the energy required from gin trash. Rough estimates of equipment costs were made by contacting several suppliers which handled the desired components. Net present value techniques were used for an economic analysis of this system.

RESULTS AND DISCUSSION

Direct Combustion Experiments

Fuel Feed System. Two changes were made in the feed system for the 61 cm diameter fluidized-bed unit which improved performance over that reported in previous work (Hiler, 1980). First, the upper agitator was changed so that now there are four separate small agitators which sweep circular paths along the bottom of the hopper. The plane of rotation of each agitator is parallel to and about 4 cm above the sloping portion of the hopper bottom. These agitators are effective in preventing bridging of material, feeding it into the lower agitator, and require little power for operation. The lower agitator is formed from angle iron bolted at an angle to the center line of a rotating shaft and is the same as reported previously. The lower agitator is essential to force the biomass material into the auger conveyor; the feed system will not function without it.

The second change included placing an air lock or star feed wheel between the hopper and the fluidized-bed unit. The auger in the bottom of the hopper conveys feed material to the star feed wheel which meters it into a second auger. The second auger operates at a speed which assures only a partial fill of fuel in its auger tube. This eliminated any tendency for overfilling and clogging the auger. The star feed wheel prevents rapid escape of hot gases through the partially filled auger but some leakage occurs with each revolution. Purge air from the blower is introduced in the auger to assure that there is no backflow of hot gases and burning of fuel in the auger. This feed system has proven satisfactory for cotton gin trash from several sources and sorghum stalks which had been ground in a tub grinder.

Distributor Design. The alternate distributor design proved to be ineffective in reducing the coating on bed particles. Observations indicated that the alternate design actually decreased operational efficiency of the 61 cm diameter fluidized bed. With the random bed circulation pattern illustrated in Figure 3, burning carbon particles were observed in the ash and exiting the stack. In cold fluidization observations with the alternate design, the bed was uniformly fluidized but occasionally very large bubbles formed. At the surface, these bubbles burst and splashed bed particles high into the vapor space. These large bubbles apparently contributed to shortening the residence time of some fuel particles in the chamber. During combustion tests, high rates of bed elutriation were also measured with the alternate design.

Another factor which could cause an increase in burning particles exiting the system with the alternate design could be the method of fuel injection. Fuel is injected in the sides of the unit near the base of the reactor. The bed circulation pattern in the original design could tend to carry the material down and toward the center. The alternate design would not necessarily provide this fuel flow pattern and fuel residence time might be shortened before it reached the bed surface. From these observations, it was concluded that the original design with a net downward circulation pattern along the reactor walls resulted in superior performance. The dead zones along the side walls apparently do not contribute to the formation of coatings on bed particles.

Ash Analyses. Ultimate analyses of sorghum stalks and cotton gin trash are shown in Table 1. Other chemicals present in the feedstocks, ash, and samples collected from deposits on the exit from the cyclone stack are shown in Table 2. These analyses show that the ash is high in silica, potassium,

Table 1

TYPICAL CHARACTERISTICS OF STRIPPER HARVESTED

COTTON GIN WASTE AND SORGHUM STALKS

	Cotton Gin Waste	Sorghum Stalks
Physical Composition	Percent (Dry Basis)	
Lint	7.7	---
Burs	56.6	---
Sticks	10.7	---
Fine	24.9	---
Chemical Composition	Percent (Dry Basis)	
Carbon	42.0	40.0
Hydrogen	5.4	5.2
Nitrogen	1.4	1.4
Sulfur	< 0.5[a]	0.2
Arsenic	0.02[b]	---
Oxygen & Error	35.0	40.7
Ash	14.5	12.5
Gross Heating Value @ 11.5% Moisture	15.5 MJ/kg	15.4 MJ/kg

[a]Analysis during the study period by Schacht (1978) showed 1.7% but independent analyses have shown less than 0.5% and is considered to be a more accurate value.

[b]Present only in restricted areas where desiccants are used.

Table 2

BIOMASS FUEL AND ASH ANALYSES (PERCENT)

	Cotton Gin Waste			Sorghum Stalks		
	Feedstock	Ash[b]	Stack Deposits[c]	Feedstock	Ash[b]	Stack Deposits[b]
SiO_2	2.5	41.8	15.4	2.29	73.2	5.4
K_2O	1.2	10.5	34.3	1.17	8.4	33.3
CaO	0.9	10.8	20.2	1.27	5.0	6.5
MgO	0.4	3.3	8.6	0.31	1.5	1.5
Na_2O	0.03	0.6	1.5	0.17	0.4	0.3
P_2O_5	0.3	2.6	4.6	0.11	1.1	0.8
Fe_2O_3	NM[a]	0.7	0.6	0.26	1.0	1.9
Al_2O_3	NM	3.1	1.5	2.10	5.1	4.0
SO_3	NM	5.9	9.1	0.19	0.5	2.6

[a]NM = not measured.

[b]760°C bed temperature; average of 2 samples.

[c]Average 3 samples.

calcium, magnesium, and aluminum oxides. Ash and stack deposits from cotton gin trash fuel are also high in SO_3 and P_2O_5.

Temperatures at which ash begins to stick together was determined in a muffler oven and indicates that they are well above the 760°C operating temperatures (Table 3). However, when the ash was mixed with the mullite bed material a reduction in the sticky point temperature was observed (Table 3).

The sticky point temperatures determined in the laboratory were well above the operating temperature, but a bed material containing no silica was selected and tested in the 61 cm fluidized bed. This bed material was pure alumina but a coating still accumulated on bed particles during operation. The coating did not cause defluidization and apparently reached an equilibrium thickness in the tests. However, it was hygroscopic and would absorb moisture after cooling and stick together. The particles would stick together with enough strength to prevent fluidization when trying to restart the unit after it had remained in the cooled condition for several days.

Metal Coupon Tests. A more serious problem was fouling and corrosion of metal coupons placed in the exit hot gas stream. Metal coupons of low carbon steel, stainless steel type 304, Incoloy alloy 800, and Incoloy 825 all suffered severe corrosion damage. Average rates of weight losses per hour for sample coupons are shown in Table 4. Weight loss rate would not be expected to remain linear during long-term operation, and a rate loss relation was not established in these tests. However, relative comparisons can be made using the average weight loss per hour for these tests. The weight losses per hour were high for all materials, and would be unacceptable for heat recovery equipment.

Table 3

LABORATORY ASH AGGLOMERATION TESTS

Temperature (°C)	Time (Min.)	Ash from Cotton Gin Trash		Mullite Bed Particles	Bed Particles with Coating from Reactor	Cotton Gin Trash Ash & Mullite Bed Particles	Cotton Gin Trash Ash & Mullite with Coating
		Sample I	Sample II				
677	10	no[a]	no	-[c]	-	-	-
	30	no	no	-	-	-	-
816	10	no	no	-	-	-	-
	30	no	no	no	no	no	no
954	10	no	no	-	-	-	-
	30	no	no	no	-	yes	yes
982	10	no	no	-	-	-	-
	30	no	no	-	-	-	-
1038	10	no	yes[b]	-	-	-	-
	30	no	yes	-	-	-	-
1093	10	yes	yes	-	-	-	-
	30	yes	yes	no	no	yes	yes

[a] no: Indicates that ash particles did not stick together or agglomerate.

[b] yes: Indicates that particles adhered to one another or agglomerated; used as an indication of softening or sticky point temperature.

[c] - : Indicates no evaluation made.

Table 4

WEIGHT LOSS OF METAL COUPONS

TESTED IN 61 cm FLUIDIZED BED SYSTEM

Material	Bed Temperature °C	Average Weight Change (After Cleaning) %/hr.
Low Carbon Steel	760	-0.40
Low Carbon Steel	816	-1.20
Incoloy 800	760	-0.11
Incoloy 825	760	-0.58

The nature of the surface coatings was examined by metallographic observation of surface and transverse sections. The coating was found to be multi-layered; an illustration of a typical observed structure is given in Figure 6. Coupon surfaces were also examined in a scanning electron microscope equipped for energy dispersive x-ray spectroscopy (SEM/EDAX). The surface showed evidence of a discontinuous scale interrupted in some cases by spalled regions. The scale formed had a smooth fluid appearance, suggestive of a molten slag. It is not known whether this slag spalls due to temperature fluctuations or changes in ash composition. Certainly, a liquid slag would not spall. Some spalling seems to occur upon cooling after the experiment, but not all. Spalling was more common in specimens exposed for longer times or higher temperatures. Little spalling was noted in coupons exposed for two hours or less, but spalling was severe (i.e., the entire surface) in many specimens exposed to hot stack gases for 5 hours or more.

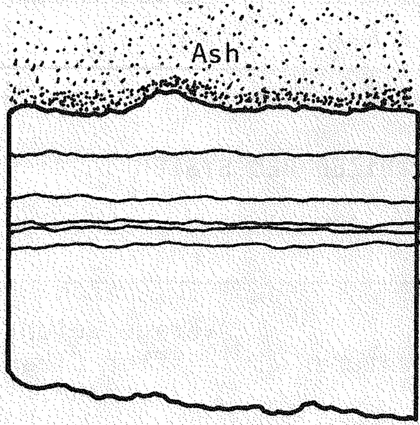


Figure 6. Profile of coatings layers; approximately 10X actual size.

The results of chemical analysis by EDAX are shown in Table 5. In each case where EDAX was used, separate spectra were recorded from prints on scaley regions(high spots) and spalled regions (valleys). In all cases, measurements taken in the valleys showed expected higher concentrations of elements composing the base material and frequently showed K and S as well. The presence of these two elements is significant in the corrosion process.

Table 5

COMPOSITION OF SURFACE LAYERS

Coupon	Exposure Time	Scale	Spalled Region
Carbon Steel #A43	6 h	K, S, Fe, Si	Fe predominant with minor K & S
Incoloy 800 #D2	25 h	Si, P, Cl, K, Ca, Cr, Mn, Fe, Ni	Cl, K, Ti, Cr, Fe, Ni
Incoloy 825 #E2	25 h	Si, V, K, Cr, Fe, Ni	S, V, K, Ti, Cr, Fe, Ni, Cu

Small specimens also were machined from coupons and examined by Auger Spectroscopy. By line scanning transverse sections, profiles of chemical composition versus depth were obtained. An example is shown in Figure 7. Of particular interest in this analysis was the distribution of S, K, and Na near the apparent interface.

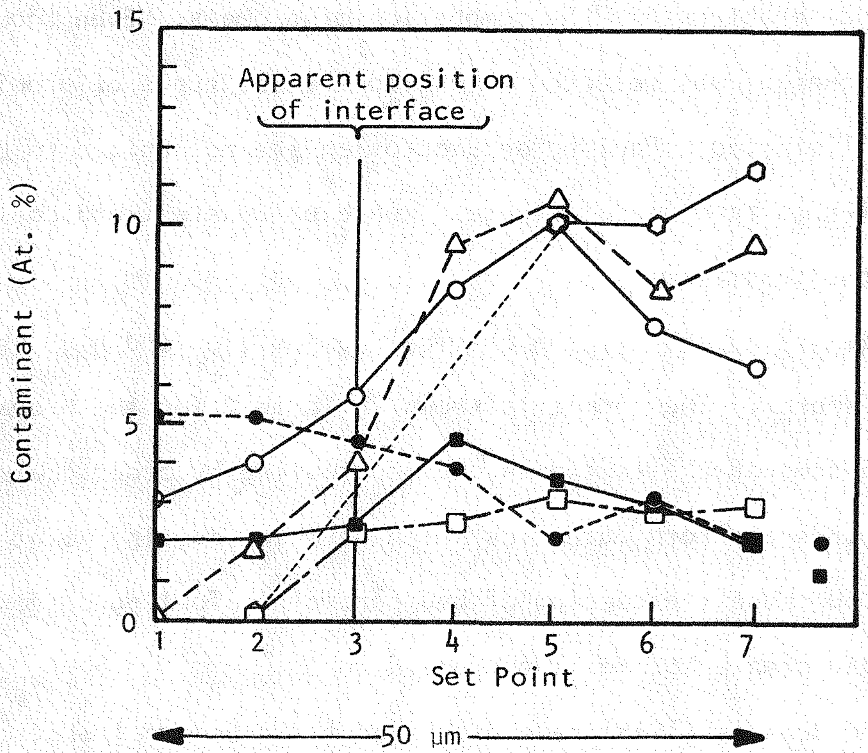


Figure 7. Partial profile of composition versus depth by Auger Spectroscopy. This figure is restricted to the region near the visible interface between coating and base metal which occurs at set point 3. Note that concentrations of S, K, and Na are maximum near the interface.

Attempts to identify the surface coatings by x-ray diffraction were not completely successful owing to the complex nature of the coatings. Diffraction patterns frequently contained so many peaks that a unique determination was unlikely. A variety of Fe, Al, and K sulfates were determined as well as Fe_2O_3 and KCl. These analyses indicate that corrosive reactions occurred between chemicals in the stack gases and elements in the metal coupons.

Mechanism of Fouling and Corrosion. Ash fouling and metal deterioration are considered serious problems for the combustion of biomass. Even though the fluidized-bed technique was selected to overcome these types of problems, they have not been eliminated. Fouling and corrosion are not unique to biomass materials and experiences from use of sludges, municipal wastes, and coals give insights into the problems.

The basic problem is apparently the chemical composition and high ash content of the fuel source. The chemicals shown in Table 2 for the biomass materials tested are some of the same ones causing fouling by other fuels. These chemical compounds can form eutectics which have low melting point temperatures and could cause the coating of bed particles, fouling of downstream components, and create hot metal corrosion.

Wall, Graves and Roberts (1975) have discussed fluid bed incineration techniques to avoid eutectic melting points when burning sludges from waste treatment processes. The sludges can contain elements of Na, K, Mg, S, P, Fe, Al, and SiO_2, which are some of the same elements found in the biomass materials used in this study. These elements can combine to form eutectic mixtures having melting points near 620°C. This temperature is below that which must be achieved to satisfactorily burn cotton gin trash.

Wall, Graves and Roberts (1975) have shown that kaolin clay essentially eliminates the buildup of molten salts and stickiness in fluidized beds burning sludges. If the sodium salts in the fuel feed can be reacted completely with the clay before they leave the reactor, the sticky compounds do not develop in the exit gas. Controlling the composition and type of chemicals in the exit gas may prevent the fouling and erosion/corrosion of metals in the exhaust of the system. Similar techniques need to be evaluated for biomass materials because heat recovery equipment cannot function satisfactorily under present conditions.

Tufte and others (1976) have discussed ash fouling potentials of subbituminous coals from the western regions of the United States. They found that the principal variables affecting fouling potential were sodium level in the ash and ash content of the coal. Comparing ash composition of the biomass materials used in this study to some of the coals characterized as high fouling coals shows some similarities in chemical composition. Sodium levels are lower than the coal ash but potassium levels are much higher.

Attig and Duzy (1969) have studied coal ash deposition in relation to boiler design. They developed a slagging index based on base/acid ratio expressed as weight percent of coal ash and the weight percent of sulfur in the coal. Similar indices are not available for characterizing slagging and fouling characteristics of biomass but are definitely needed.

Hot corrosion of iron and nickel-based alloys during service in high temperature corrosive environments is a well-documented problem of both the power industry (boiler tubes and related components) and in gas turbines. The mechanism of hot corrosion requires the melting of a slag material onto the metal surface. This slag is chemically active and combines with the metal to form a corrosion product. For example, the operating temperature of a turbine is frequently determined by the maximum blade temperature allowed by the particular alloy in use and the melting point of the ash. Typically, operating temperatures must be kept below 832°C to prevent melting of alkali sulfates, primarily Na_2SO_4 and K_2SO_4.

Ash from the fluidized-bed reactor contains chemical species frequently associated with hot corrosion, namely: K, Na and S. Sulfur and oxygen are important constituents in hot corrosion because of the formation of sulfates. Certain alkali sulfates have unusually low melting temperatures; in combination with cations from the base material, the melting point may be further lowered. Mixtures of more than one sulfate compound may yield an even lower melting eutectic. For example, K_2SO_4 melts at 1093°C; $K_3Fe(SO_4)_3$ melts at 693°C; and the eutectic of $K_3Fe(SO_4)_3$ plus K_2SO_4 melts at 627°C.

The literature contains numerous examples of this type of reaction and many are reported in Phase Diagrams for Ceramists (Levin, 1974). A short listing of some low-melting compounds found in fly ash from coal-fired boilers is shown in Table 6. Comparing this list to analysis of the ash produced by the fluidized-bed reactor, Table 2 supports the contention that the environment for hot corrosion of metal does indeed exist.

Table 6
LOW-MELTING COMPOUNDS FOUND IN COAL FLY ASH

Compound	Tm (°C)
$K_3Fe(SO_4)_3$	618
$K_3AL(SO_4)_4$	654
$KFe(SO_4)_2$	694
$Na_3Fe(SO_4)_3$	625
$Na_3Al(SO_4)_3$	646
$NaFe(SO_4)_2$	690

Gasification Experiments

Bench-scale Tests. The 51 mm bench-scale fluidized-bed gasifier was used for gasification studies of rice hulls, sorghum stalks, corn cobs, and cotton gin trash. Elemental analyses of representative samples of feed materials are shown in Table 7. The most significant differences between the materials was the low ash content of corn cobs as compared to that of other materials.

Heating value of gas produced from sorghum stalks, rice hulls, and corn cobs are shown as functions of fuel-to-air ratios and temperatures in Figures 8 through 10. The lower fuel-to-air ratios are nearer those expected to be achieved in larger diameter gasifiers using air as the fluidizing medium and where no supplemental heat is used. Over the limited temperature range evaluated, heating value of the gas was independent of temperature and primarily a function of fuel-to-air ratio. Although heating value of the gas in the temperature range tested varied primarily as a function of fuel-to-air ratio, gas composition varied slightly with temperature.

Gas composition as a function of temperature for a fuel-to-air ratio near 0.80 kg/kg is shown for the three fuels in Figures 11 through 13. This fuel-to-air ratio is near what might be achieved in larger diameter gasifiers and provides a relative comparison of gas composition from different biomass materials. Neglecting nitrogen, CO was the predominant gas followed by CO_2 where the fuel was rice hulls and corn cobs. Where sorghum stalks were the fuel, CO_2 was the predominant gas followed by CO. The other major gas components were hydrogen, methane and ethane.

Carbon and thermal conversion efficiencies are also of interest in evaluating the gasification result. These efficiencies are shown for sorghum

Table 7

ELEMENTAL ANALYSIS OF FEED MATERIALS

Elements (1)	Corn Cob	Sorghum	Rice Hulls	Cotton Gin
Carbon	46.24	44.44	41.31	41.56
Hydrogen	7.57	5.57	8.38	5.71
Oxygen	42.31	36.07	32.96	35.29
Sulfur	0.30	0.31	0.02	0.37
Nitrogen	1.16	1.07	1.03	1.00
Arsenic	0	0	0	0
Ash	2.42	12.54	18.32	16.07
Moisture Content	11.75	8.47	7.89	7.85
Heating Value (MJ/kg)	20.3	17.4	16.5	17.2

	Formula	Formula Weight
Corn Cob	$C_7H_{13.75}O_{4.80}N_{0.15}$	176.71
Sorghum	$C_7H_{10.53}O_{4.19}N_{0.14}$	164.65
Rice Hulls	$C_7H_{12.77}O_{4.19}N_{0.15}$	165.91
Cotton Gin	$C_7H_{11.54}O_{4.46}N_{0.14}$	168.89

(1) Elemental analyses given in weight percent at dry basis.

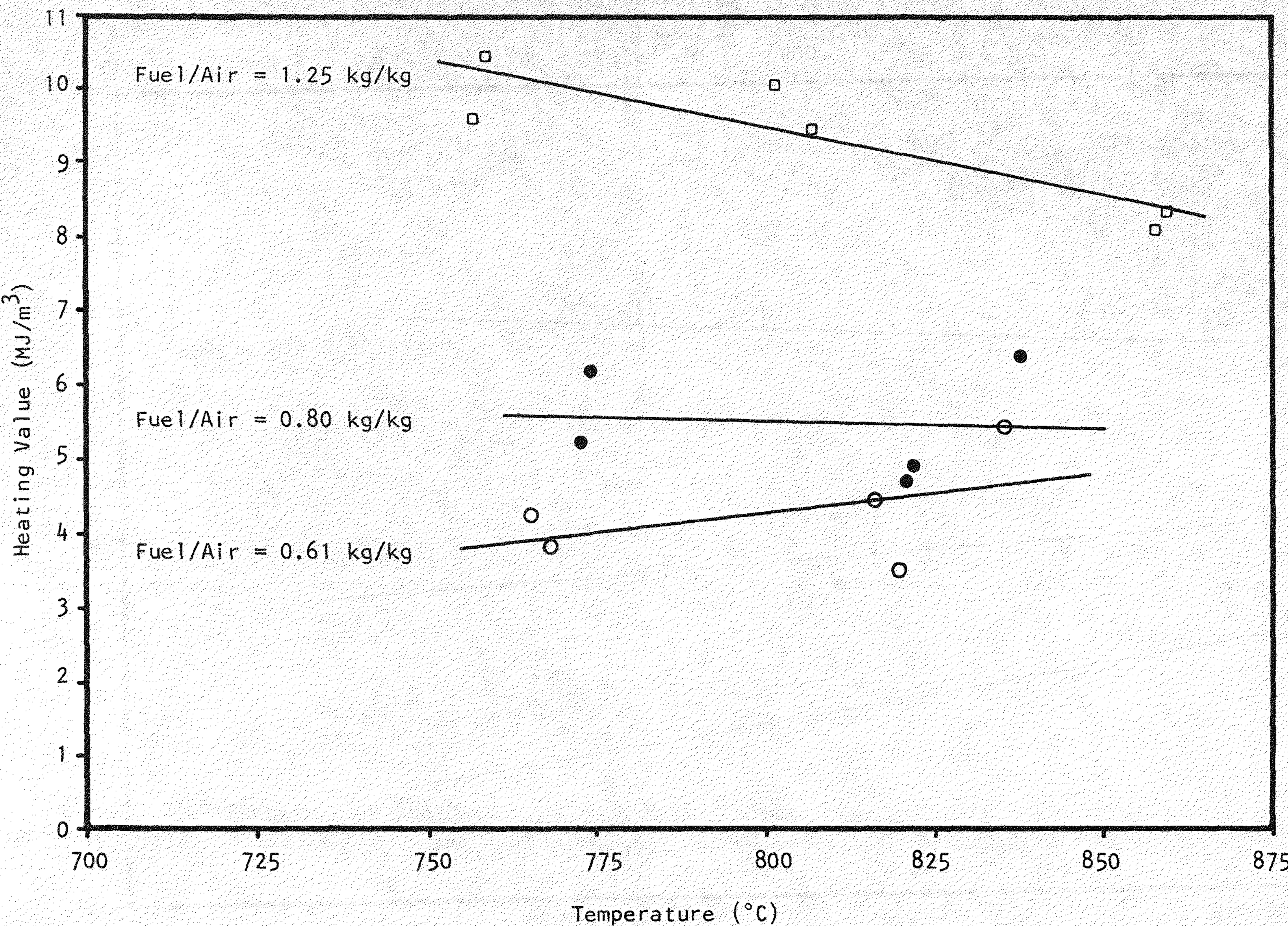


Figure 8. Effect of temperature and fuel to air ratio on heating value of gas produced from sorghum stalks.

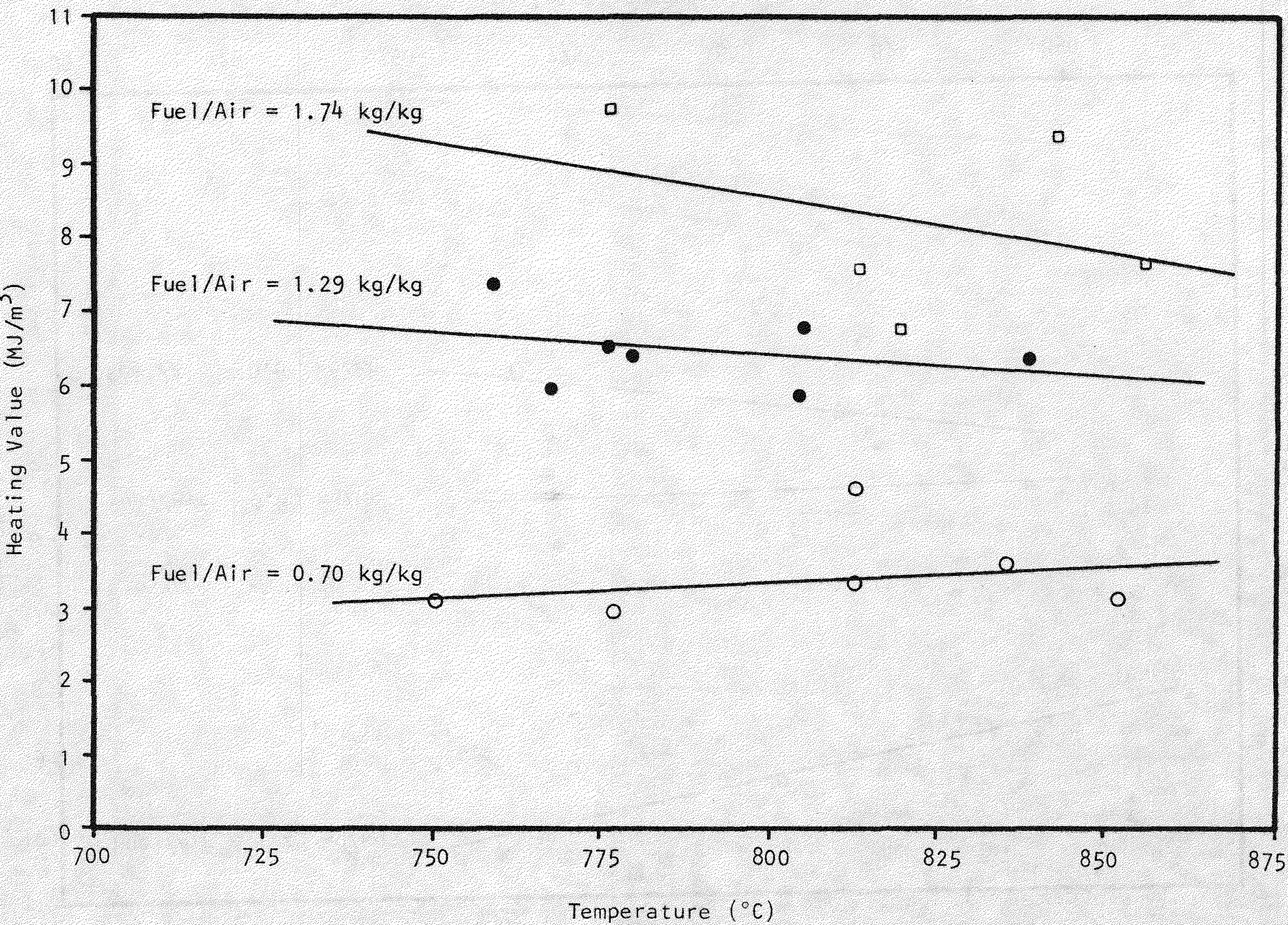


Figure 9. Effect of temperature and fuel to air ratio on heating value of gas produced from rice hulls.

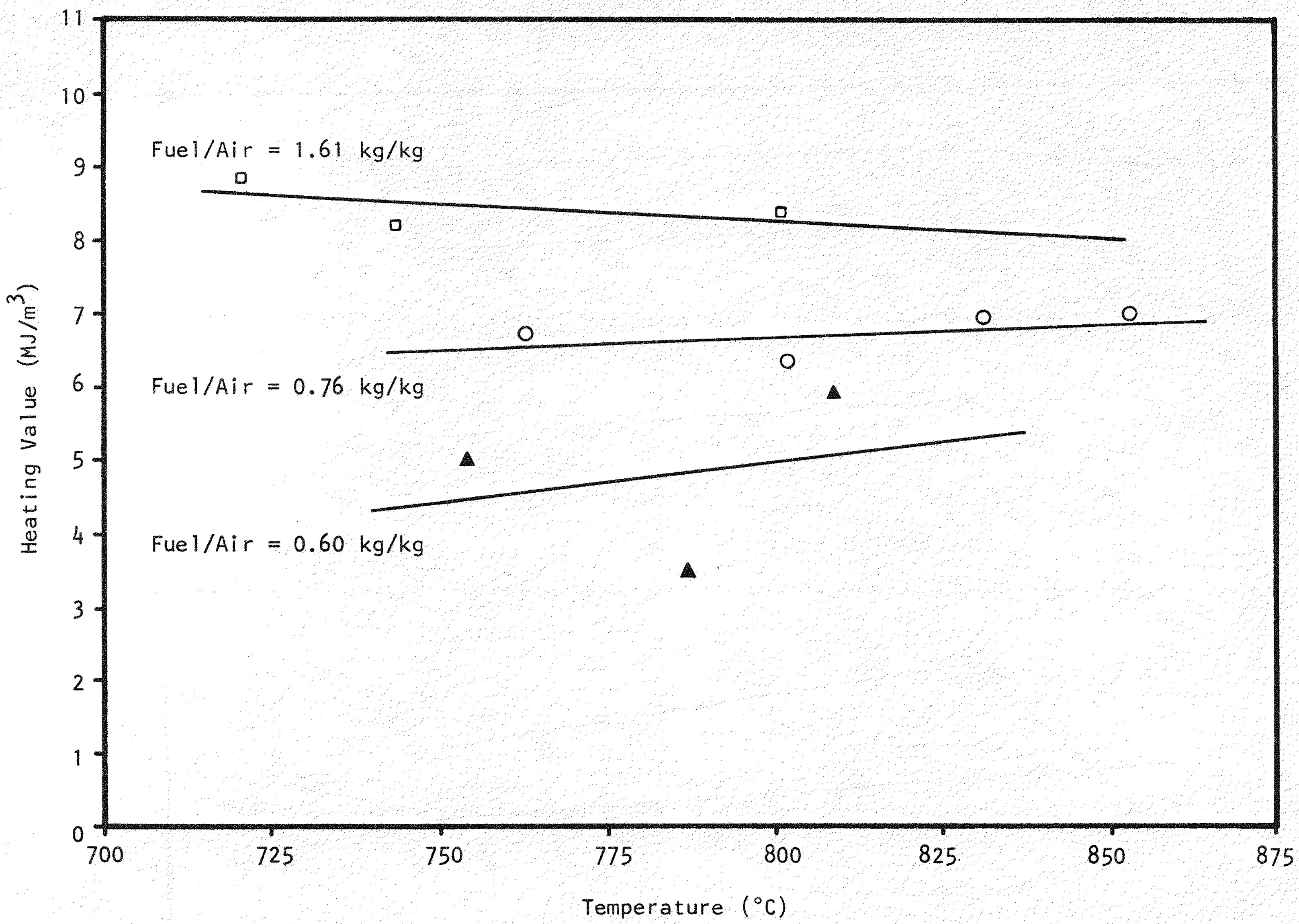


Figure 10. Effect of temperature and fuel to air ratio on heating value of gas produced from corn cobs.

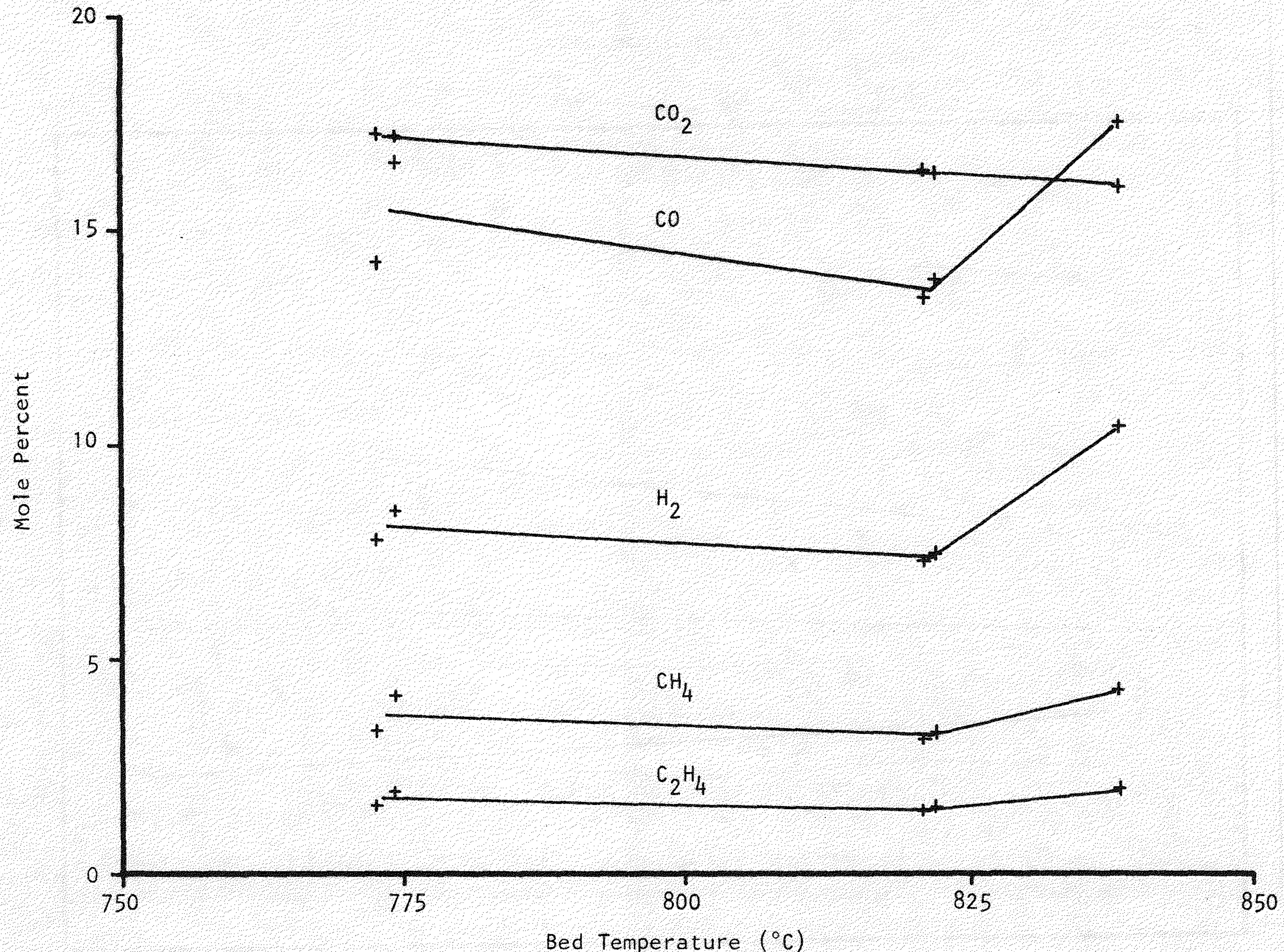


Figure 11. Composition of gas (excluding nitrogen) produced from sorghum stalks at a fuel to air ratio of 0.8 kg/kg.

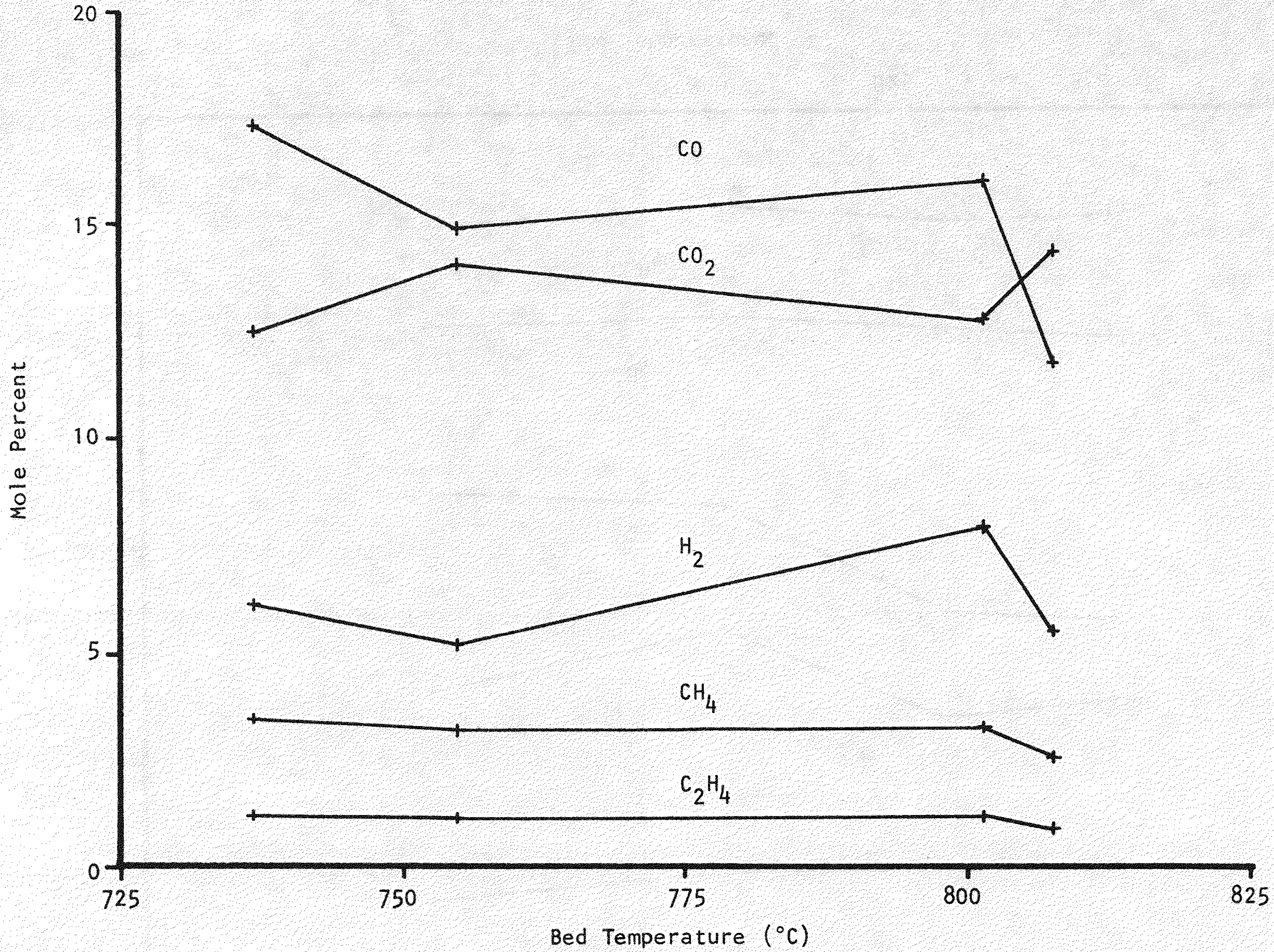


Figure 12. Composition of gas (excluding nitrogen) produced from rice hulls at a fuel to air ratio of 0.862 kg/kg.

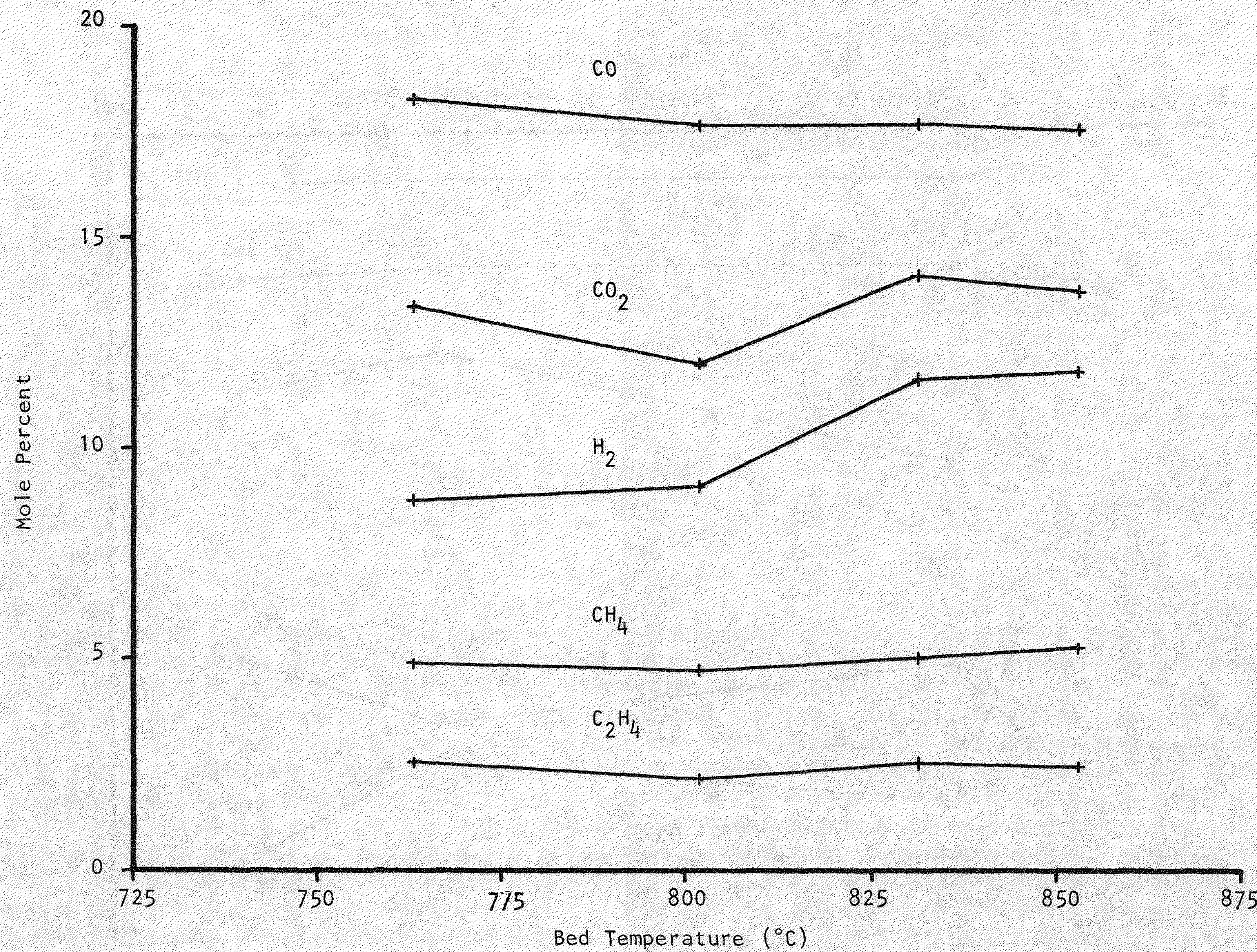


Figure 13. Composition of gas (excluding nitrogen) produced from corn cobs at a fuel to air ratio of 0.765 kg/kg.

stalks, rice hulls, and corn cobs as a function of fuel-to-air ratio in Figures 14 through 16. Carbon efficiency was given as the ratio of the amount of carbon in output gas to the amount of carbon in the fuel feed. Thermal efficiency was the ratio of the heat value of the produced gas multiplied by gas production rate to the heat value of the fuel multiplied by fuel feed rate. From 45 to 65 percent of the input heating value of the fuel is converted into gaseous products. Sensible heat is also produced and might be usable in some cases but is not included here.

Although no quantitative measurements were made on tar production, relative values were determined from observing the gas filter. More tars were produced for all fuels at low temperatures, the 1011 K to 1033 K range, but was especially evident for corn cobs. Tar formation also increased when fuel-to-air ratio was increased.

These results show that a wide range of biomass feedstocks can be converted into low energy gas by using fluidized-bed technology. Different biomass fuels produce only small differences in gas composition and heating value for similar operating conditions. Fuel-to-air ratio is the predominant parameter influencing gas quality in the temperature range of interest.

Gas Cleaning. The cyclones designed for evaluation in a gas cleanup system for the 30 cm reactor are high efficiency types. In these types of cyclones, the velocity at the entrance should be approximately 1070 meters per minute. The design of the cyclone is specified in relation to the diameter of the barrel, D_c. In Figure 17, a schematic of a cyclone is illustrated in which the total height of the cyclone is 6D, with the height of the cone being 5D, and the height of the barrel being 1D. This cyclone configuration is termed a 1D-5D cyclone. The width of the inlet is D/8; the height of the inlet is the same as barrel height, and the diameter of the outlet is D/2.

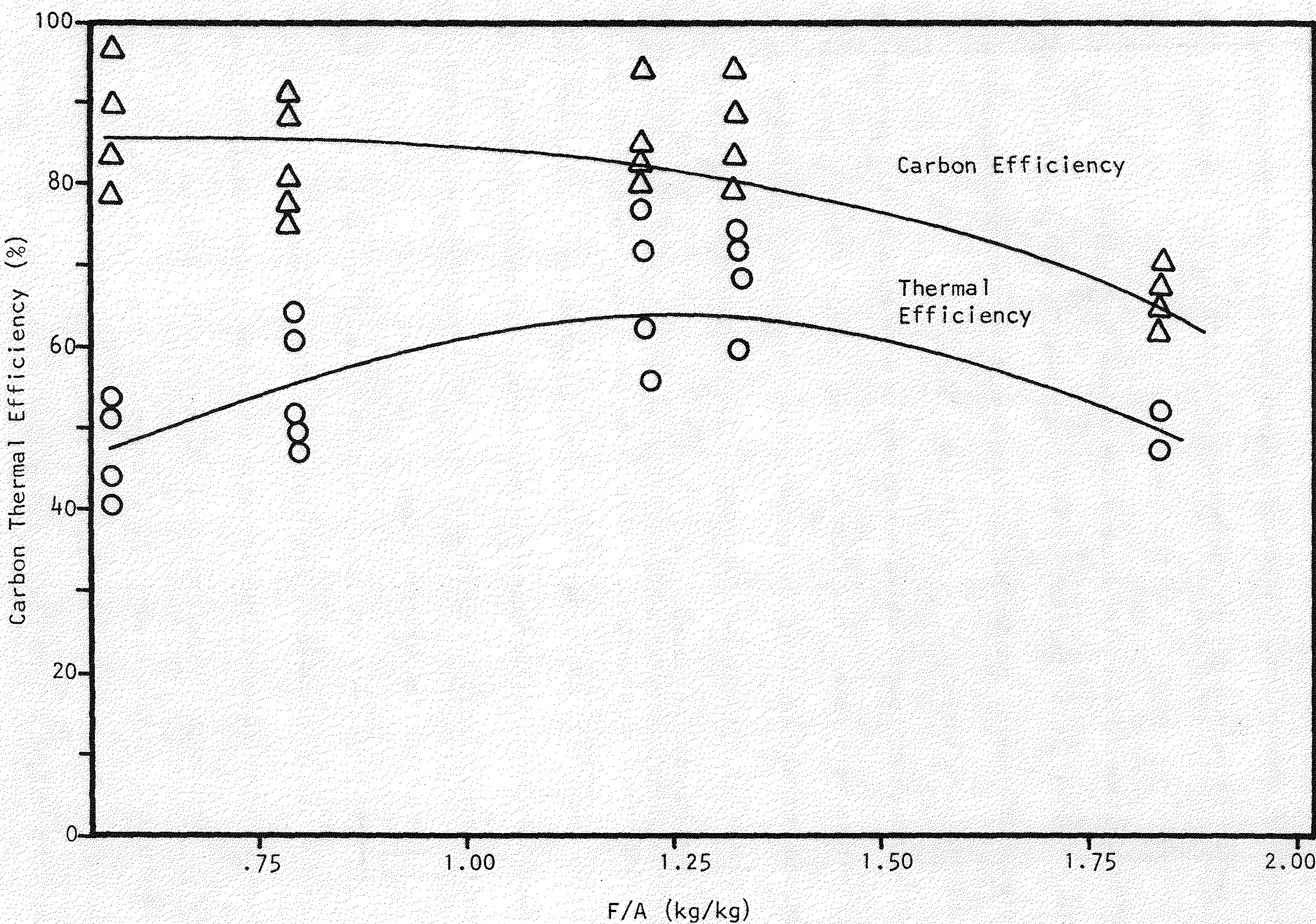


Figure 14. Thermal and carbon efficiencies of sorghum experiments.

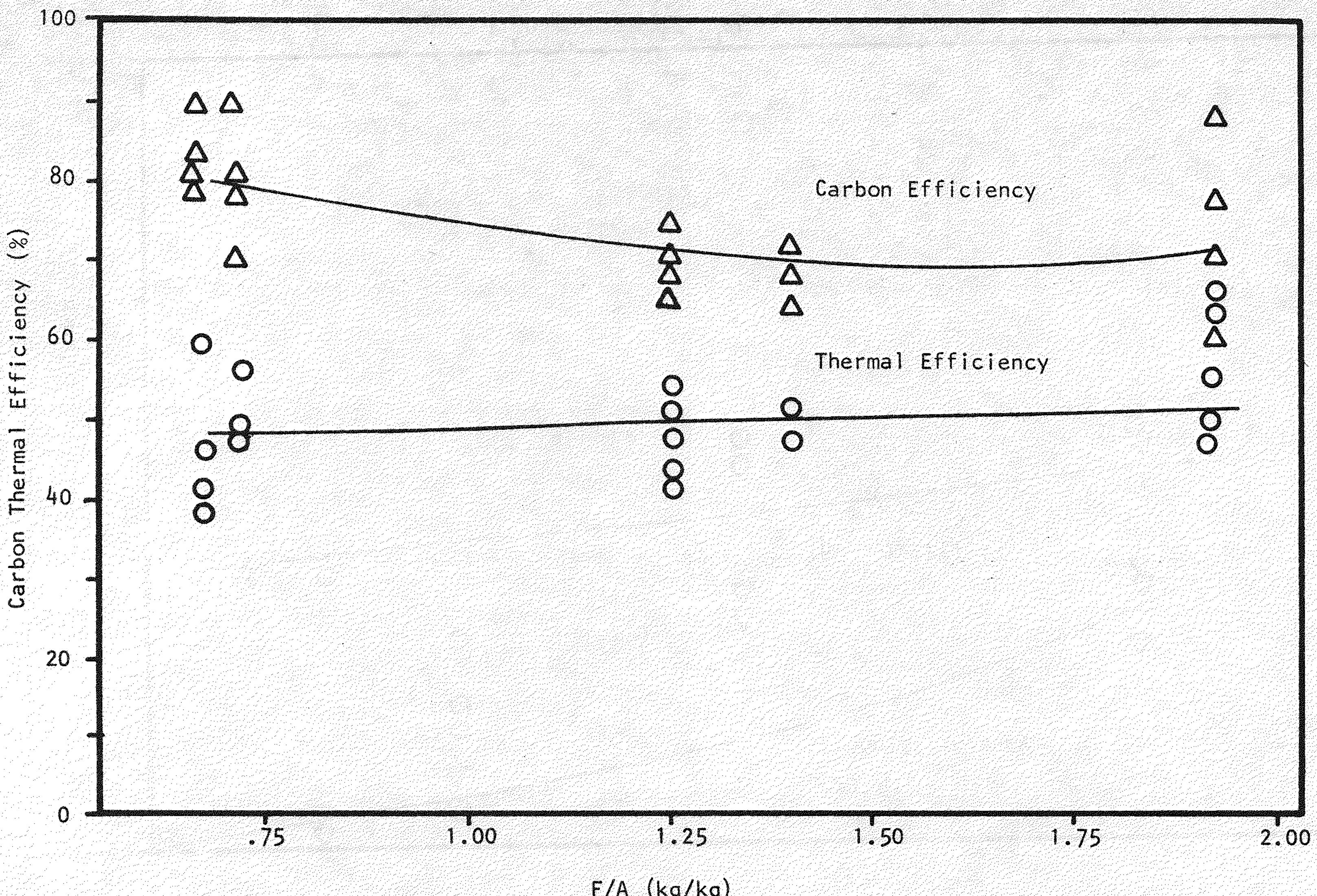


Figure 15. Thermal and carbon efficiencies of rice hull experiments.

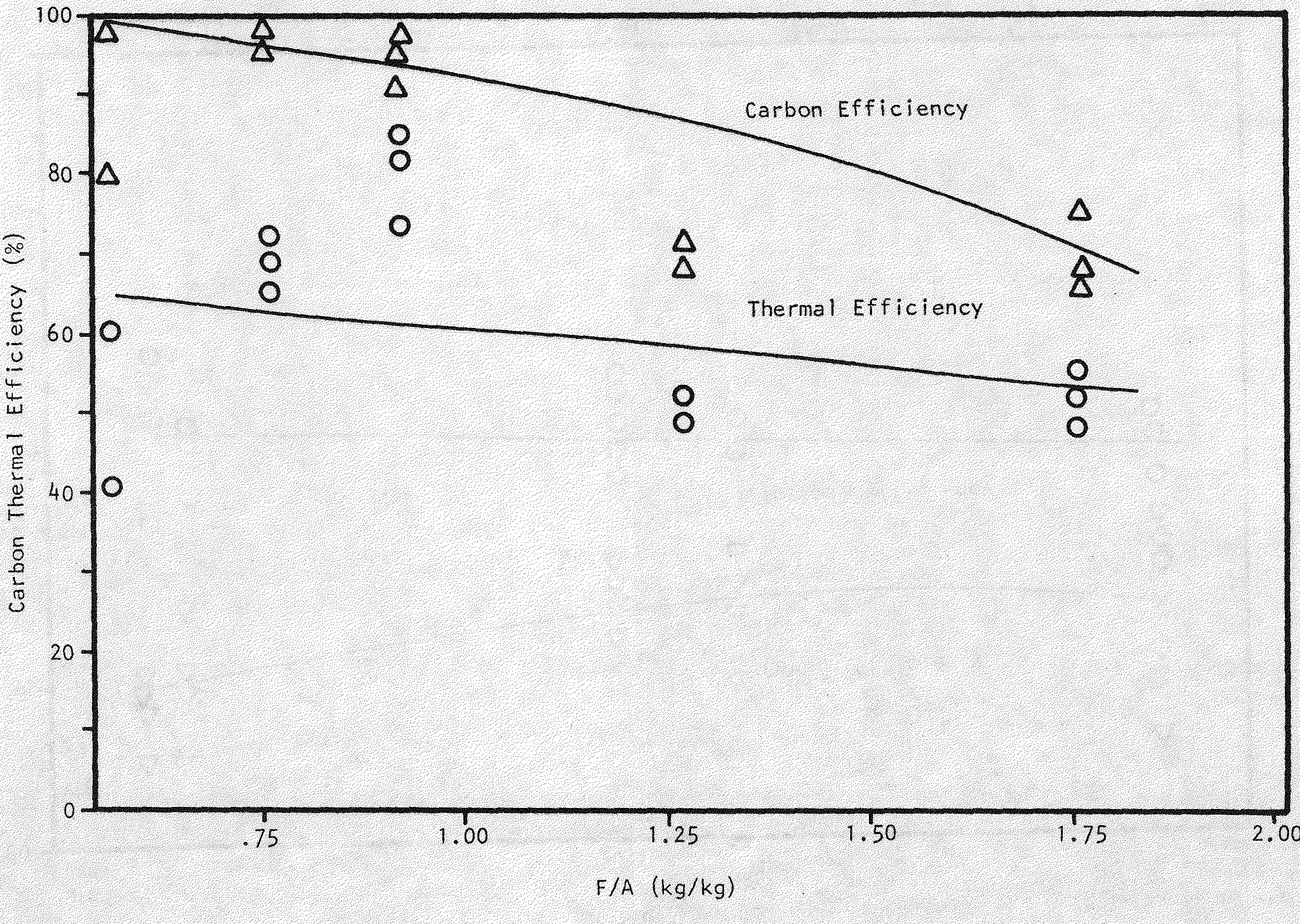
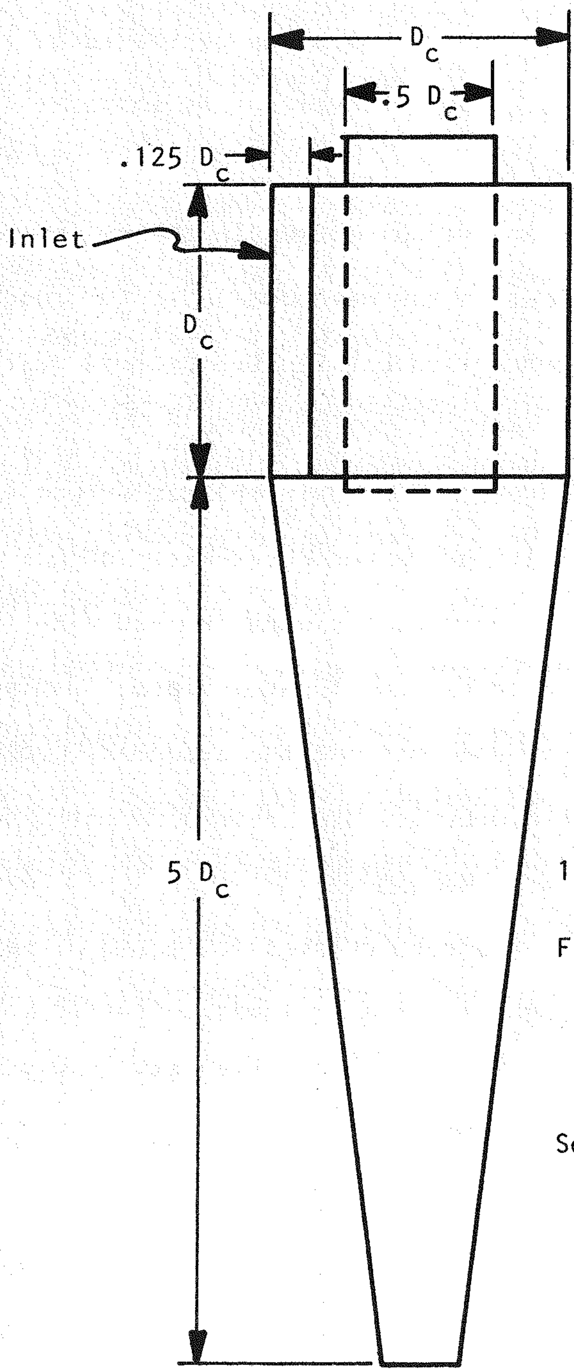


Figure 16. Thermal and carbon efficiencies for corn cob experiments.



1D-5D Cyclone Basic Dimensions

First Stage:

D_c = 5.08 cm (4 in.)
A = $D_c/8$
B = $D_c/2$

Second Stage:

D_c = 5.08 cm (4 in.)
A = $D_c/16$
B = $D_c/4$

Figure 17. Basic cyclone dimensions.

The basic dimensions of the two cyclones designed for the 30 cm reactor are given in Table 8 with the following differences on the second cyclone. The entrance width was decreased to maintain high velocity entrance velocity as gas cools. Also, the diameter of the exit pipe was decreased to increase efficiency. Input data used for design of the cyclones is shown in Table 8 with the output data on both cyclones.

The computer model provides an analytical method in the design of cyclones but very little experimental verification has been completed for conditions encountered with the gasifier. A comparison between the cyclone design model and measured data are given for one test.

The total mass concentration of particulates in the gas stream exiting the fluidized bed was found to be 163.4 grams per cubic meter of gas (g/m^3). In terms of fuel feed, 0.21 grams of particulates were removed with the gas for each gram of fuel. The mass concentration of particulates leaving the first or primary cyclone with the gas and entering the secondary cyclone was 12.42 g/m^3. The mass concentration of particulates remaining entrained in the gas leaving the secondary cyclone was 1.42 g/m^3.

Particle size distributions for the particulates collected at various points are shown in Figures 18 through 21. The cyclones collected more of the smaller particle sizes than predicted but less of the larger particle sizes. In general, the design model appears to provide a useful design aid; comparison between observed and predicted data is given in Table 9.

Penetration is also useful in evaluating cyclones (Spaite and Burckle, 1977). Penetration is defined as the ratio of pollutant escaping cyclone to the pollutant entering cyclone. Three penetration values for the different size ranges of the primary and secondary cyclones are shown in Tables 10 and 11.

Table 8

INPUT AND OUTPUT DATA

FOR CYCLONE DESIGN COMPUTER MODEL

		Cyclone Stage		
		1st	2nd	Total
Model Input				
Type		ID-5D	ID-5D	
Inlet Height	(cm)	10.16	10.16	
Inlet Width	(cm)	1.27	0.635	
Body Height	(cm)	60.96	60.96	
Outer Diameter	(cm)	10.16	10.16	
Outlet Radius	(cm)	2.625	1.332	
Cone Height	(cm)	50.8	50.8	
Outlet Area	(cm^2)	21.65	5.574	
Inlet Area	(cm^2)	12.90	6.451	
Dust Outlet Diameter	(cm)	5.08	5.08	
Air Outlet Height	(cm)	12.065	12.065	
MMD	(μm)	9.14	4.339	
Load In	(g/m^3)	56.4	16.1	56.4
MASD	(g/min)	83.05	10.48	
ACFM	(m^3/min)	1.47	0.65	
Viscosity Gas	(cp)	0.0382	0.0216	
Density Gas	(g/m^3)	318.	716.	
Temperature Gas	(°C)	748.	185.	
Density Particle	(g/ml)	2.4	2.4	
Inlet Velocity	(m)	1141.	1010.	
Exit Velocity	(m/s)	680.	1168.	
Model Output				
Efficiency	(%)	71.5	92.9	98.0
Press Drop	(cm of H_2O)	2.77	12.6	15.37
Cut Diameter	(μm)	6.211	2.37	
Load Out	(g/m^3)	16.1	1.1	1.1
Critical Load Ratio		1.462	2.733	
Air Flow/Dust Flow		0.177	0.224	

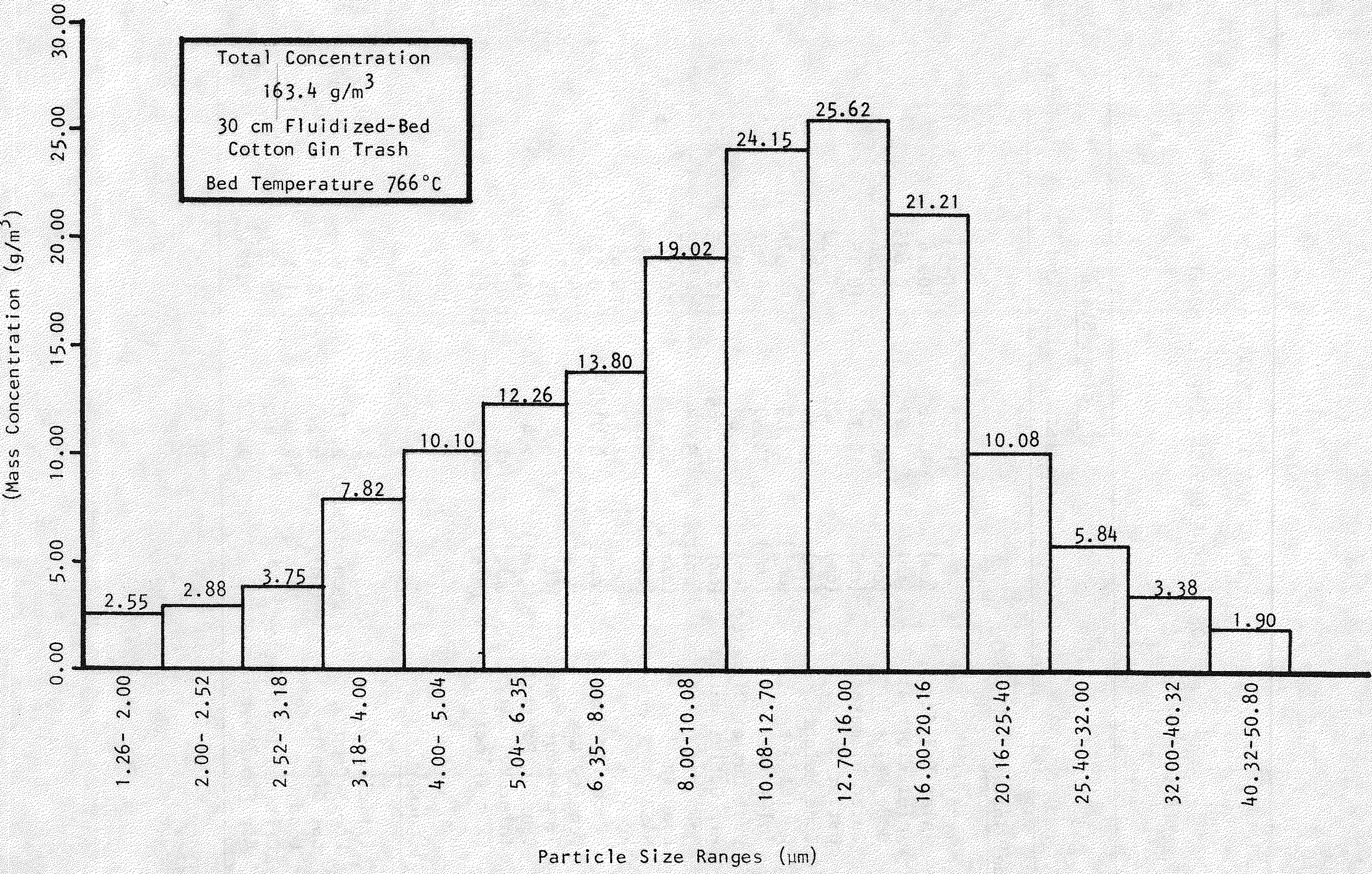


Figure 18. Total particle size distribution; 30 cm fluidized-bed gasifier, cotton gin trash fuel.

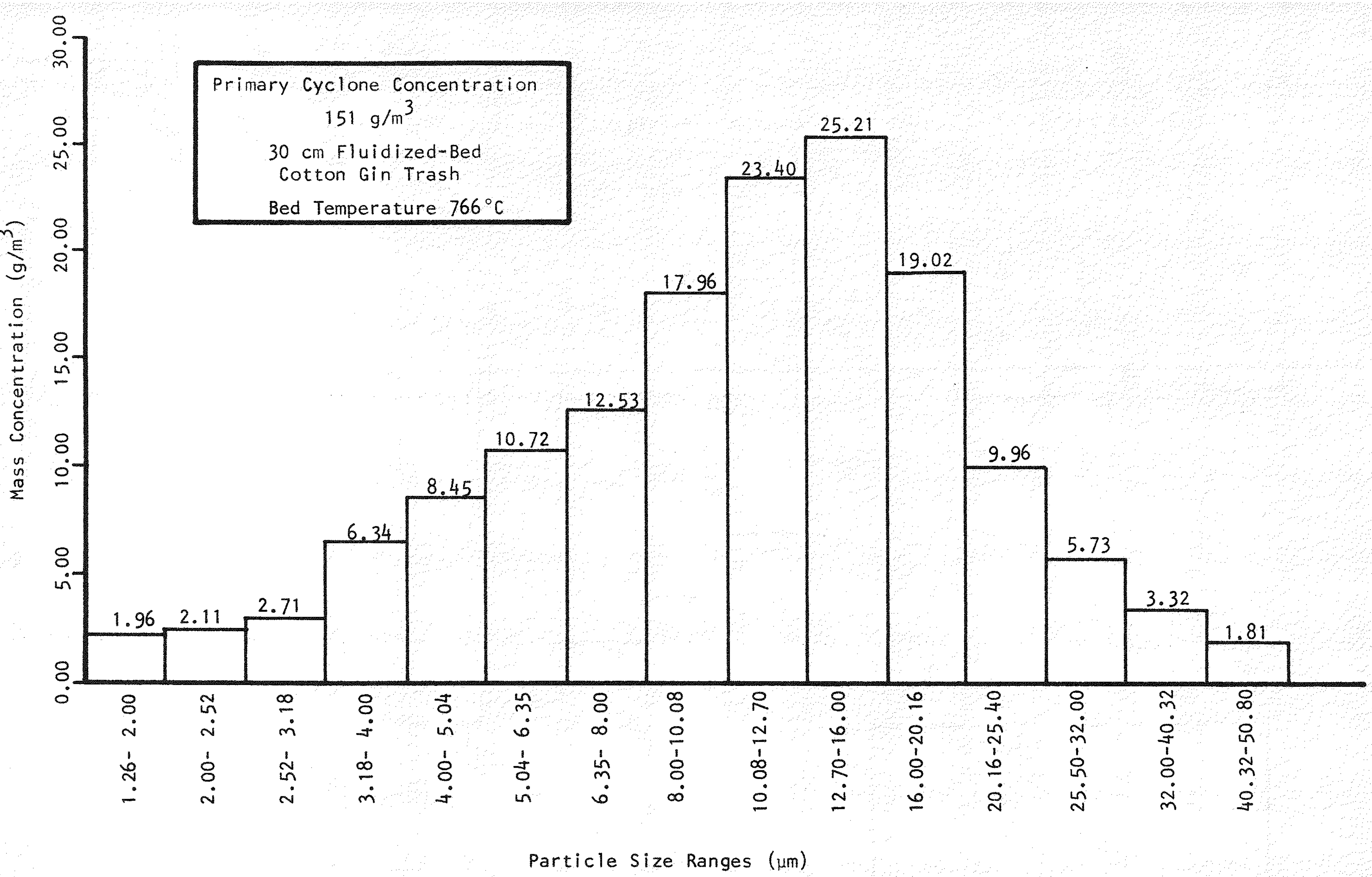


Figure 19. Particle size distribution for particles removed by Primary Cyclone; 30 cm fluidized-bed gasifier, cotton gin trash.

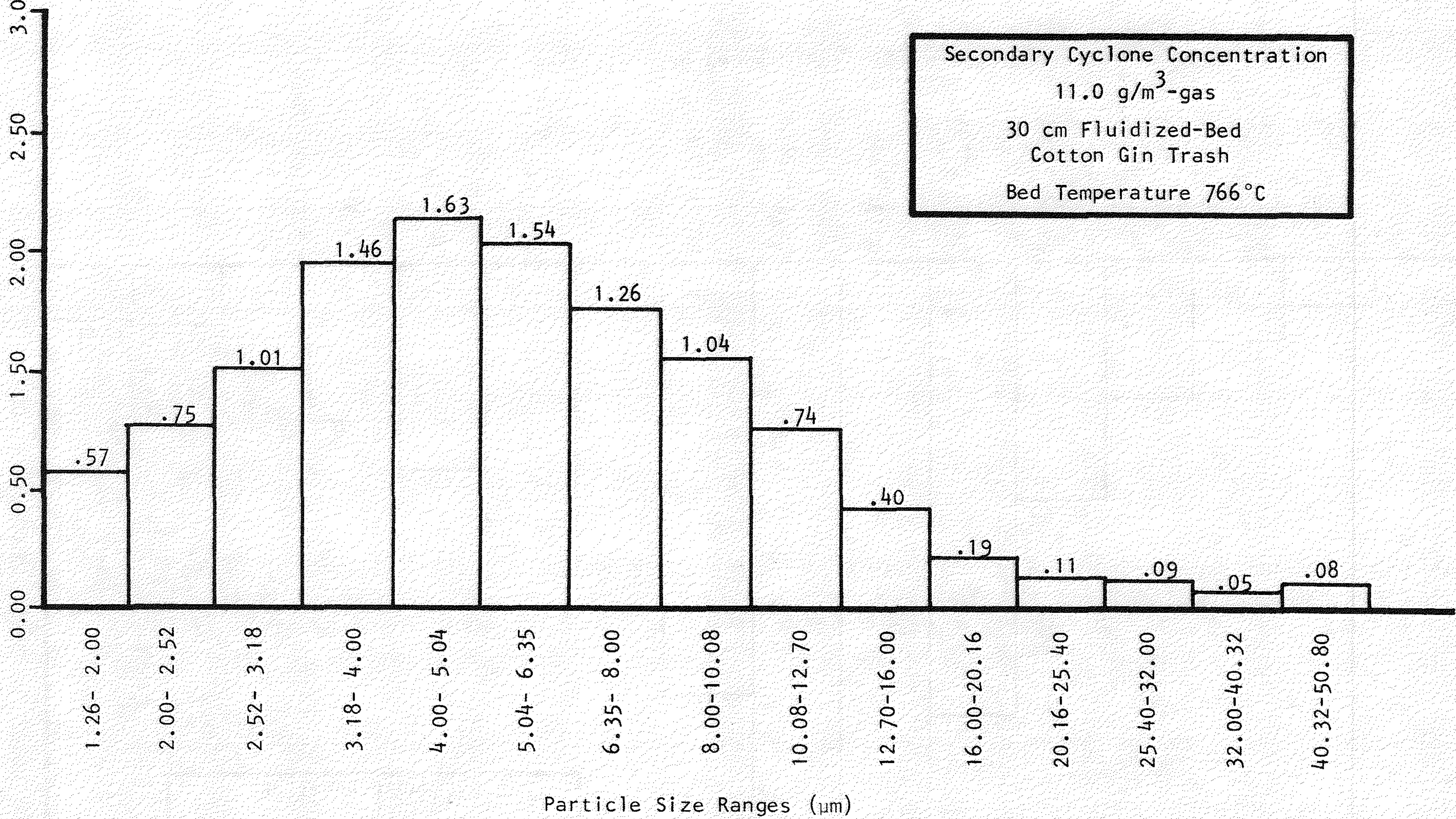


Figure 20. Particle size distribution for particles removed by secondary cyclone; 30 cm fluidized-bed gasifier, cotton gin trash.

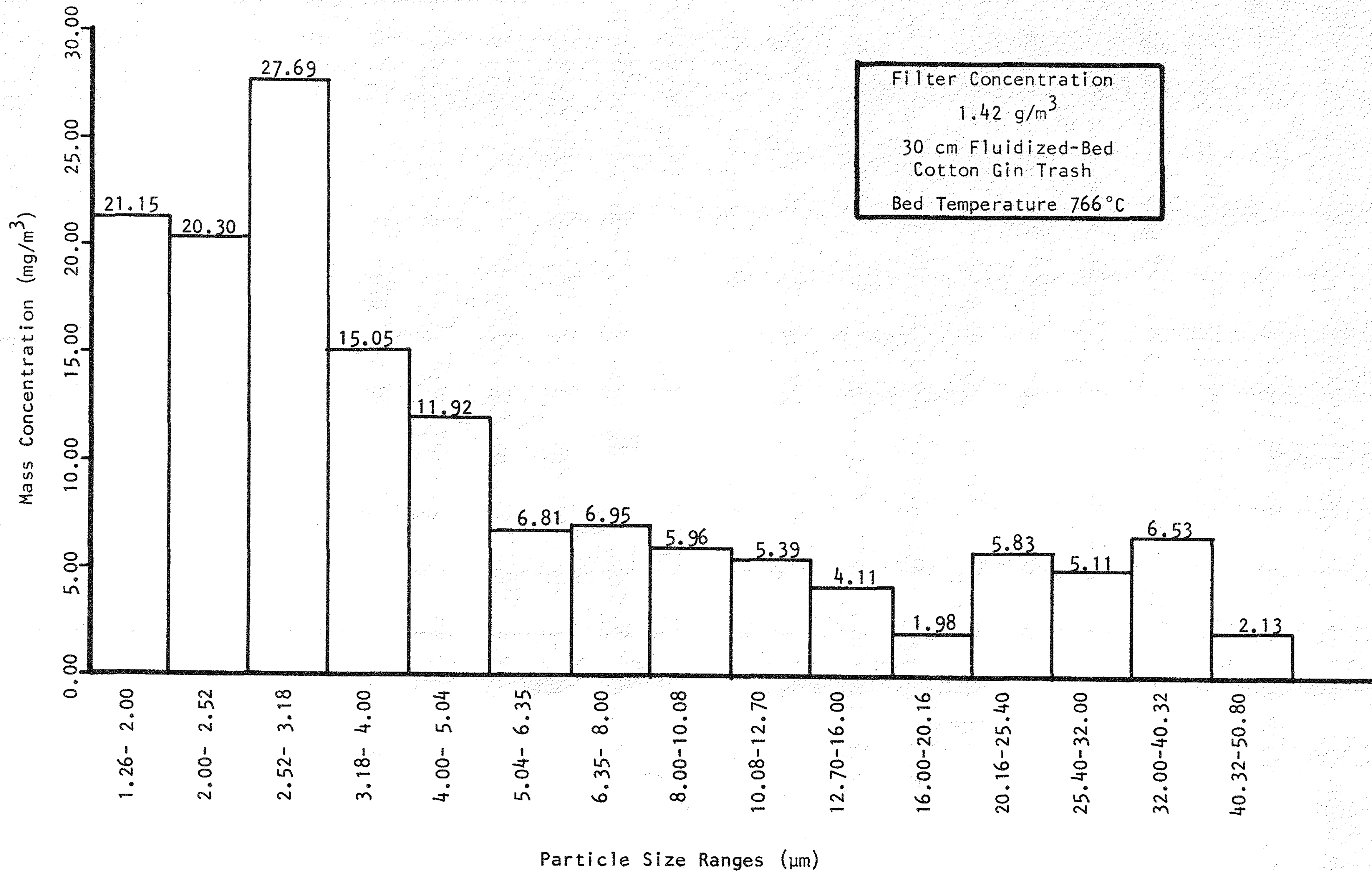


Figure 21. Particle size distribution for particles remaining in gas stream; 30 cm fluidized-bed gasifier, cotton gin trash.

Table 9

COMPARISON OF OBSERVED AND PREDICTED DATA FROM CYCLONE DESIGN MODEL

	Primary		Secondary		Total	
	Observed	Predicted	Observed	Predicted	Observed	Predicted
Efficiency (percent)	92.4	81.9	88.6	95.3	99.1	99.1
Pressure drop (mm of H_2O)	--	49	388	451	--	499
Load out (g/scm)*	12.42	29.27	1.42	1.38	1.42	1.38
Cut diameter (μm)		5.078		1.65		

*scm = standard cubic meters of gas

Table 10

PENETRATION VALUES FOR PRIMARY CYCLONE

Particle Size Range (μm)	Observed Data	Predicted from Original Design Data	Predicted from Measured Operating Conditions
2.0 - 2.52	0.252	0.970	0.933
2.52 - 3.17	0.270	0.920	0.859
3.17 - 4.0	0.189	0.848	0.751
4.0 - 5.04	0.163	0.576	0.599
5.04 - 6.35	0.126	0.388	0.413
6.35 - 8.0	0.092	0.195	0.158
8.0 - 10.08	0.055	0.050	0.064
10.08 - 12.7	0.031	0.050	0.004
12.7 - 16.0	0.016	0.004	0.0
16.0 - 20.2	0.103	0.0	0.0
20.2 - 25.4	0.012	0.0	0.0
25.4 - 32.0	0.018	0.0	0.0
32.0 - 40.3	0.029	0.0	0.0

Table 11

PENETRATION VALUES FOR SECONDARY CYCLONE

Particle Size Range (μm)	Observed Data	Predicted from Original Design Data	Predicted from Measured Operating Conditions
2.0 - 2.52	0.030	0.463	0.242
2.52 - 3.17	0.027	0.197	0.078
3.17 - 4.0	0.010	0.097	0.006
4.0 - 5.04	0.007	0.009	0.0
5.04 - 6.35	0.004	0.0	0.0
6.35 - 8.0	0.005	0.0	0.0
8.0 - 10.08	0.006	0.0	0.0
10.08 - 12.7	0.007	0.0	0.0
12.7 - 16.0	0.010	0.0	0.0
16.0 - 20.2	0.010	0.0	0.0
20.2 - 25.4	0.050	0.0	0.0
25.4 - 32.0	0.049	0.0	0.0
32.0 - 40.3	0.057	0.0	0.0

One penetration value was that experimentally observed, one was predicted from original design data and the other was predicted using measured operating parameters.

Efficiency is one minus penetration so the lower the penetration value, the higher the cyclone performance. The penetration values show that the cyclone design model has a wider deviation for small particles than for larger particles. The measured efficiencies generally were greater than the predicted which indicates the model provides a conservative method for cyclone design. A more thorough model verification is needed and is in progress.

Steam Generating Tests

Based on results of combustion and gasification experiments, specifications were developed for a boiler to be coupled to the 60 cm fluidized-bed reactor. Specifications included ability to operate the boiler with the fluidized-bed reactor in either combustion or gasification modes. However, based on current results, gasification is considered to be the more technically viable mode of operation because less fouling occurs in this mode. The steam-producing system now consists of five subsystems as shown in Figure 22. These subsystems are:

1) fuel feed,
2) fluidized-bed reactor,
3) cyclone particulate removal,
4) gas mixing chamber-burner, and
5) five tube boiler.

The first two subsystems have been described previously; the other systems are briefly described here.

Cyclone Particulate Removal. Two cyclones are used for removing particulates: a primary cyclone placed in the exit gas stream from the fluidized bed, and a secondary cyclone in the exit gas stream from the boiler. All ash is

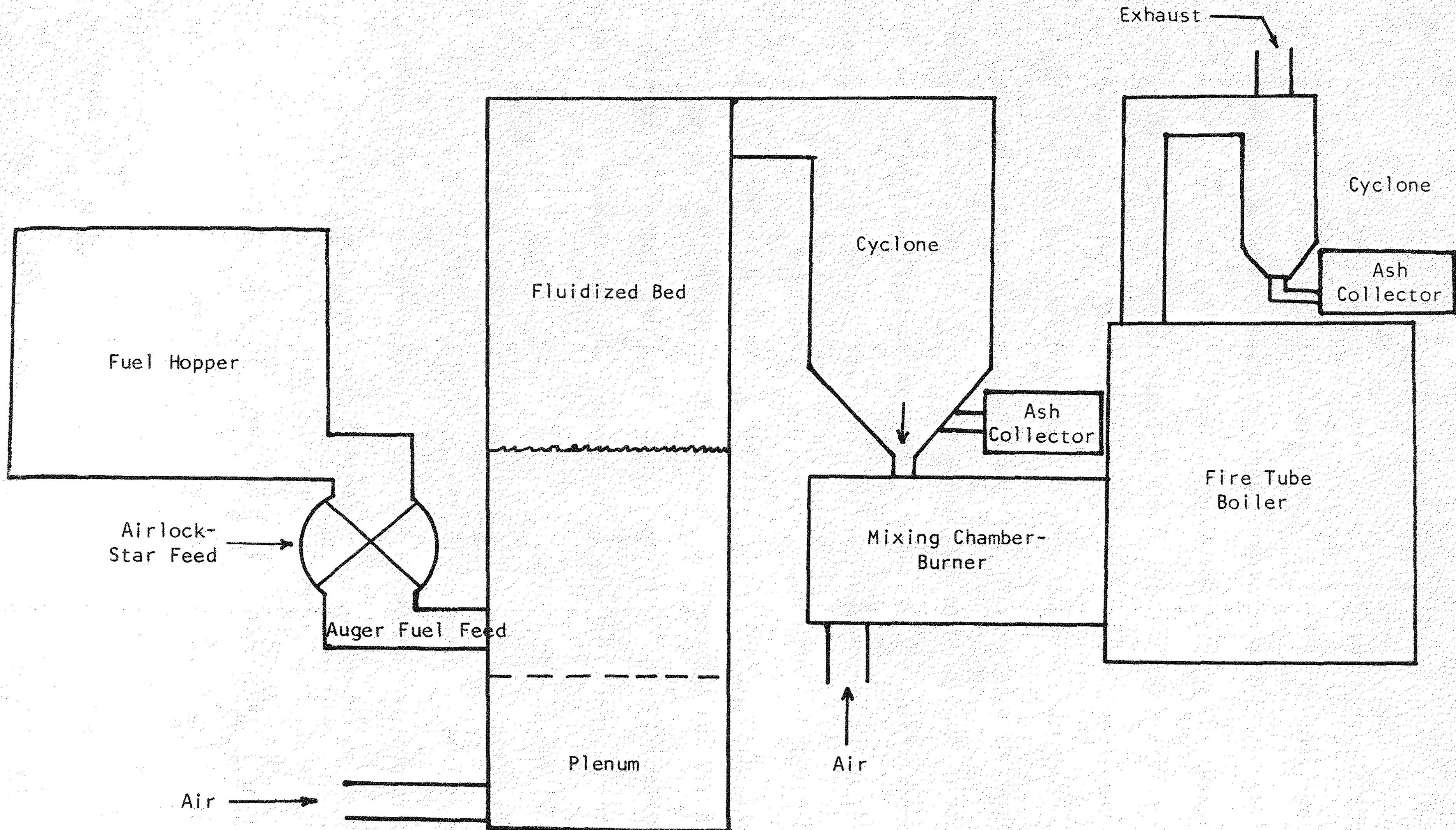


Figure 22. Schematic of fluidized bed biomass steam producing unit.

removed from the reactor by elutriation with the combustible gas, and the primary cyclone removes much of this ash and unreacted carbon particles. It was modified slightly after the original combustion work and was not intended to provide efficient work and was not intended to provide efficient cleanup; a separate study is being made to evaluate gas cleanup requirements. The normal exit of the cyclone was closed and a clay pipe was placed to permit the combustible gas to exit the bottom of the cyclone into the mixing chamber. An auger is used to discharge ash from the side of the cyclone into a collection hopper. High temperature ball valves are used to temporarily close ash removal ports for ash removal from the collection hopper. The secondary cyclone is for removal of finer particles remaining in the gas after passing through the boiler.

Gas Mixing Chamber-Burner. Combustible gas leaving the primary cyclone is mixed with air and ignited in a chamber before entering the boiler. Air is introduced into a refractory lined chamber in a swirling method to mix with the combustible gas exiting the primary cyclone, and the mixture is ignited using a natural gas pilot.

Fire Tube Boiler. A fire tube boiler with feed water pump and automatic water level controls is connected to the gas mixing chamber-burner. It was designed for natural gas operation but the natural gas burner was removed and replaced by the low energy gas unit. Boiler characteristics are shown in Table 12.

System Performance. Only a limited number of tests have been made with the system but several important observations have been made. The measurement techniques only enable average values for a period of time to be determined, and a means of measuring instantaneous fuel feed rates would be desirable

Table 12

BOILER CHARACTERISTICS

Steam Production	568 kg/hr.
Heating Surface	19.5 m^2
Firing Rate Gas (37.3 MJ/m^3)	 42.5 m^3/hr.
Boiler Shell O.D.	1.07 m
Overall Length	2.92 m
Overall Height	1.68 m
Furnace Size O.D.	41 cm
Tube Size	5 cm
Steam Working Pressure (max.)	862 kPa

and permit more accurate determinations. Also, leakage of air through the air lock system prevents accurate mass and energy balances to be established. Means of more accurately measuring and monitoring these parameters are being considered.

During stable operation of the gasifier at about 760°C bed temperature and with the gas air mixture burning before entering the boiler, a noticeable difference was observed in the ash from the two cyclones. Ash from the primary cyclone was black with large granules apparently containing significant quantities of carbon, but analysis of ash has not been completed. Ash from the secondary cyclone was similar in texture and color to portland cement and apparently contains no carbon.

There were also considerable quanties of fine particles in the stack gas but no measurements were made. In addition, considerable quantities of fine particles were deposited in the boiler fire tubes. The deposits were loose, apparently due to low air velocities in the boiler tubes. Gas temperature exiting the boiler gradually increased after approximately 24 hours of operation, which could possibly indicate a reduction in rate of heat transfer through the boiler tubes due to the deposits.

Composition of several gas samples from the primary cyclone is shown in Table 13; gas composition from the secondary cyclone is shown in Table 14. Notice that samples labeled Test 1 indicate complete combustion whereas samples labeled Test 2 show incomplete combustion.

Steam production has been measured at 334 kg/hr over a four-hour interval with a gin trash feed rate of 1.47 kg/min and a pilot gas flow rate of 0.0218 m^3/min. No pressure was generated at this rate and the steam temperature was 100°C. Inlet water temperature was 20°C. Heat value of the cotton gin trash

Table 13

GAS COMPOSITION IN PRIMARY CYCLONE

	Mole Percent		
	Test 1		Test 2
	Sample 1	Sample 2	
H_2	6.12	8.88	6.12
CO	11.24	14.08	11.61
CH_4	2.34	2.37	3.48
Higher hydrocarbons	0.85	0.91	1.20
O_2	0.86	0.84	0.87
N_2	61.17	56.53	58.38
CO_2	17.42	16.40	18.36

Table 14

GAS COMPOSITION IN SECONDARY CYCLONE

	Mole Percent			
	Test 1			Test 2
	Sample 1	Sample 2	Sample 3	
H_2	0.07	0.07	0.08	0.48
CO	Trace	0	Trace	2.93
CH_4	0	0	0	0.60
Higher hydrocarbons	0	0	0	0.22
O_2	8.92	15.13	17.34	14.47
N_2	79.36	78.57	77.34	75.15
CO_2	11.64	6.08	5.14	6.14

was 15.82 MJ/kg as fired. For these conditions, slightly less than 60 percent of the total fuel energy supplied was converted to steam. In terms of gin trash fuel, 3.65 kg of steam were produced from each kilogram of gin trash. In addition to the steam produced, the ash contains carbon but its energy value has not been evaluated to date.

In another test of the system, steam was produced and used to distill ethanol fermented from grain. Steam was supplied to the alcohol unit at approximately 103.4 KPa at a temperature of 121°C. A substantial increase in the production rate of the ethanol plant was obtained by using the fluidized-bed stream production. Rate of distillation was increased from 30.3 L/hr to 52.2 L/hr with an average proof by volume of 180. This increase in production rate was due to higher steam production rate by the biomass steam production unit which enabled more efficient control of the distillation columns. The blower to supply auxiliary air in this test did not supply enough air for complete burning of the low energy gas and steam was produced at a low rate. However, it was adequate to demonstrate that a small-scale system can successfully convert low grade wastes into high grade fuel.

Site Specific Economic Analysis

A preliminary economic analysis was made for a specific gin site in west Texas. Data on total power requirements, bales of cotton ginned, and trash accumulation for a gin in west Texas were provided by Mr. Tony Price, Executive Vice President of the Texas Cotton Ginners Association. A summary of the gin is given in Table 15.

Using results of tests with the fluidized bed, components were selected to supply the electrical power and drying heat requirements of the gin. The

Table 15

ENERGY DATA FOR A COTTON GIN IN WEST TEXAS

Item	Year		
	1977-1978	1978-1979	1979-1980
Electrical Energy			
KWH for season	1,825,462	1,560,511	1,930,173
KWH for year	1,846,459	1,642,676	1,989,868
Bales Ginned	27,953	24,538	22,330
Trash per Bale* (kg)	445	445	681

Drying Fuel: Natural Gas

Cost of Natural Gas: $2.63/mcf

Connected Electrical Load: 1449 KW

*Trash estimated to contain 91 kg sand/bale.

components included:
- fluidized bed gasifier,
- cyclone ash removal,
- steam boiler, and
- steam turbine-generator.

A schematic illustrating the system is shown in Figure 23. Several manufacturers were contacted to obtain cost estimates for the various components for analysis purposes.

Turbine-Generator Selection. Two factors were considered in selecting a turbine-generator. First, it must provide 1500 kw 3-phase electrical power; second, it must operate on low to medium pressure steam. Efficiency was not the primary consideration so single stage turbines were considered for this application. A model 701-1 turbine-generator package manufactured by Turbodyne, Inc.* of Wellsville, New York, was selected for the application (Walker, 1981). Characteristics of this package are:

- electrical output: 1500 kw, 460 v, 3 phase, 60 Hz
- steam inlet: 17,000 kg/hr dry unsaturated steam at 1728 kPa and 260°C

Boiler Selection. Conventional boilers are designed for high heat value gas like natural gas; custom burner designs are required for low heat value gas produced with biomass. The boiler must provide steam output to match the input required by the turbine. J. L. Powell and Associates of Houston, Texas (Powell, 1981) recommended a custom designed boiler (Powell, 1981) manufactured by Nebraska Boiler Company of Lincoln, Nebraska. The boiler would have the following characteristics:

- steam rate: 17,000 kg/hr at 1728 kPa pressure and 260°C working rating; maximum pressure 2069 kPa
- heat requirements: 58,025 MJ/hr
- efficiency: 75 percent based on outlet temperature of 288°C

*Use of manufacturers' names does not constitute endorcement of product but is for identification purposes only.

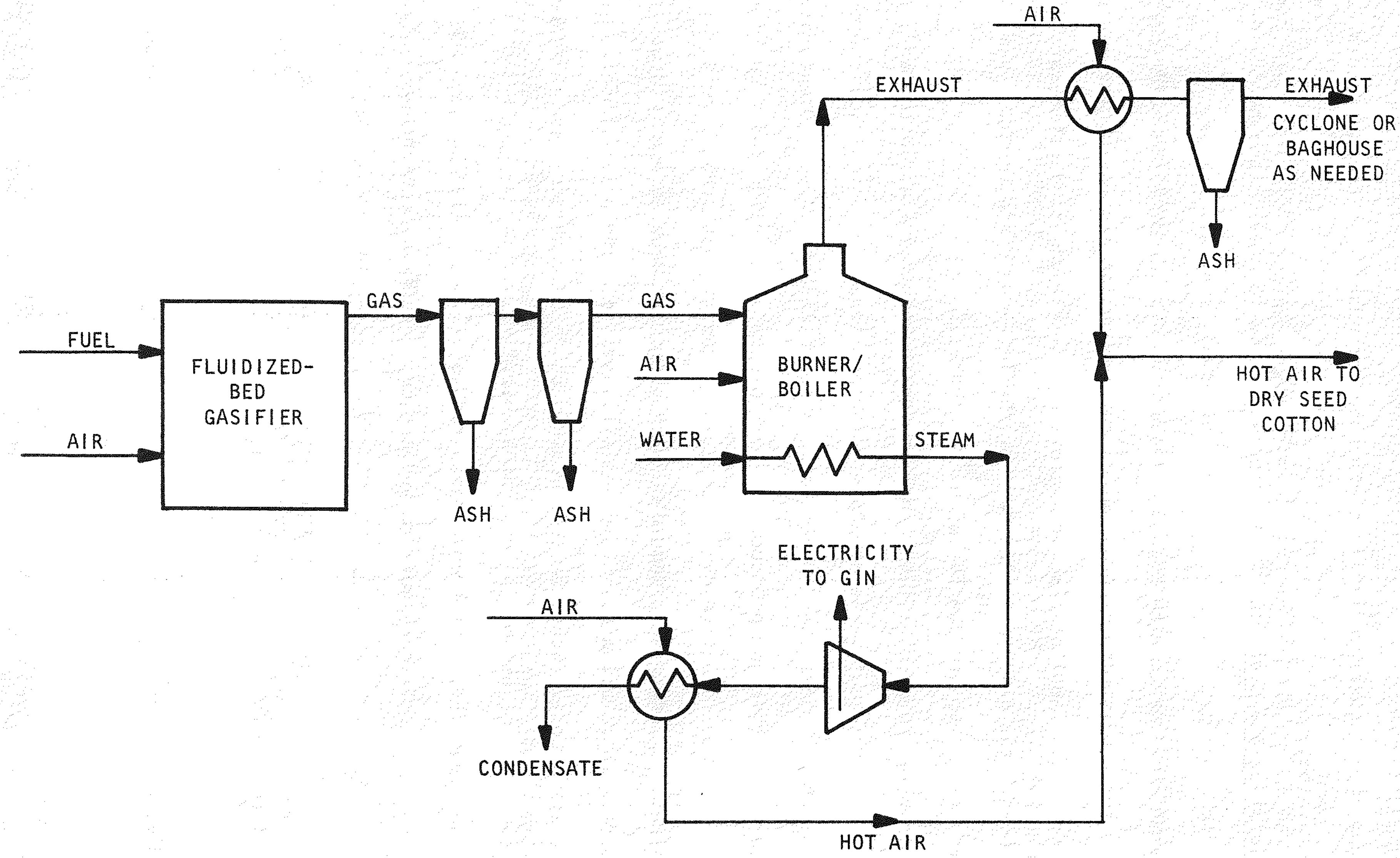


Figure 23. Schematic of proposed biomass electrical generation system.

The steam output characteristics of this boiler exactly match the requirements of the turbine.

Fluidized-Bed Reactor. A gasifier was sized to provide the heat requirements of the boiler. The size was determined by using a linear scale-up from results of experiments with the 30 cm reactor. A value of 3,114 MJ/hr per square meter of distributor area was chosen for design and was achieved with the 30 cm unit. The linear scale factor relates the gas production rate of the small unit to the gas production rate of the large unit and results in a 4.88 m diameter reactor to produce 58,025 MJ/hr of heat.

The design value of 3,114 MJ/hr per square meter of distributor area includes sensible heat value of 305.5 MJ/hr per square meter of distributor area, or slightly less than 10 percent of the total heat value. Others have reported much higher gas produced per unit area so the design based on these values is very conservative and assures that adequate gas production rates can be supplied. A larger unit should be more efficient because there is less wall surface in relation to volume and will have relatively lower heat losses than the small unit. Other factors would need to be considered but diameter provides a means of estimating cost of a unit.

A two-stage cyclone system for ash removal is considered part of the fluidized-bed reactor package. To prevent cyclones from becoming excessively large, gas flow will be divided and the two-stage cyclones operated in parallel. For example, this design is based on gas production of 236 m^3/min and would result in a very large cyclone. Reasonably sized cyclones can be designed by dividing the flow in 2 or 3 parallel paths.

Power requirements to operate the feed system and fluidized blower are needed to estimate net energy production. The air handling system was estimated based on flow requirements, static pressure and efficiency. Blower power requirements were determined to be 30 kw. Multiple feed augers were assumed for injecting fuel into the fluidized bed with a total power requirement of 60 kw. The total power requirement for the system was estimated at 90 kw and will be supplied by the system after startup.

Waste Heat Recovery. The overall system efficiency from fuel feed into electrical power production is 10 percent. Some of the waste heat representing 70 to 90 percent of the input can be used for drying seed cotton. The drying requirement at 17 bales per hour represents a heat requirement of 7174 MJ/hr. Based on input feed rate, almost 100 GJ/hr of heat will be produced. If 10 percent is converted to electrical power and 20 percent carbon remains in the ash, approximately 70 GJ/hr of waste heat will be available. A heat recovery system with slightly over 10 percent efficiency will provide adequate heat to dry seed cotton and eliminate the need for natural gas purchases. Air-to-air heat exchangers should meet this efficiency requirement and provide drying air with no fire hazard or contamination. Points of heat recovery are illustrated in Figure 23.

System Costs. Estimated costs of capital equipment are shown in Table 16. All units are assumed to be package units which would be connected at the site. If specifications are coordinated, installation expenses should be minimized. Electrical connections, pads, and heat recovery will be the predominant installation costs.

Operating and annual repair costs are difficult to estimate because of the new application. For this analysis, one additional individual was charged to the energy system at $20,000 per year. To save storage space and maintain

Table 16

ESTIMATED CAPITAL EQUIPMENT COSTS FOR

BIOMASS POWER GENERATING PLANT

Item	Initial Cost
Fluidized Bed Gasifier	$ 650,000
Steam Boiler	300,000
Turbine-Generator	155,000
Installation	145,000
Cotton Module Builder	20,000
TOTAL	$ 1,270,000

Table 17

ESTIMATED BENEFITS FROM BIOMASS POWER GENERATING PLANT

Item	Annual Benefit
Electricity not purchased (1.83 million kwh @ $.07/kwh)	$ 123,900
Natural gas not purchased (297,470 m^3 @ $.112/$m^3$)	33,300
Excess electricity sold (3.21 million kwh @ $.035/kwh)	112,350
Trash disposal savings (13,100 metric tons @ $3.85/metric ton)	50,435
TOTAL	$ 319,985

quality of the gin trash, it was assumed it was compacted into modules each weighing 20,000 pounds. The gin would need to purchase the module builder and incur costs of operation. An additional $25,000 per year was estimated for repairs of the system. Costs assumed for operation of the module builder were $1.64 per ton of trash or $14,350 per year (Moore, Lacewell and Parnell, 1982). Thus, total annual costs of operation were set at $59,350. It is assumed that the ash will have a value to offset its disposal costs so this is not included as an expense.

System Benefits. Annual benefits of the energy conversion system include:

- eliminating 1.83 million kwh electrical energy purchases,
- eliminating purchases of 297,470 m^3 of natural gas,
- eliminating 13,000 metric tons of trash disposal, and
- sales of 2.89 million kwh of excess electricity generated.

The annual value of these benefits is estimated to be $320,000 and are itemized in Table 17.

Net Present Value Analysis. The energy system proposed here represents a capital investment for the primary purpose of decreasing present energy and trash disposal costs. One of the important factors in this will be changes in taxable income but consideration of tax implications require considerable knowledge of the companies' financial affairs. Tax implications were not considered in this analysis except for a 10 percent investment tax credit and 10 percent energy credit on all but the module builder.

The net present value method of analysis was used for evaluating this system (Williams and Bloome, 1980). The net present value is the present value of benefits less the equity requirements, or:

$$NPV = -K_o + \sum_{i=1}^{n} (B_i - C_i)(1 + d)^{-i} \qquad [1]$$

where: NPV = net present value,

K_o = initial capital cost net of tax disadvantage,

n = life span of plant,

B_i = benefits in period i,

C_i = costs in period i,

d - discount rate.

This method reduces the dollar value of future benefits in order to compare them to today's dollar value. When NPV equals zero, the internal rate of return generated by the investment is equivalent to the discount rate d.

Lifetime of the energy system is unknown at present but a minimum of seven years is needed to obtain investment tax credit. Net present value was determined for 4, 5, 6 and 7 years of lifetime by Equation [1] and are shown in Table 18. Net present value is negative for 4 years of life so the internal rate of return is less than the discount rate of 8 percent. For 5 years or more lifetime, net present value is positive so the internal rate of return on the investment is greater than 8 percent over the period.

These are preliminary economic estimates. For a complete economic analysis, a detailed cash flow would be needed. This would require cost and return figures for the specific cotton gin, equity situation and income tax bracket. However, it is highly recommended that the cash flow analysis be done before investment in this system be considered seriously.

Table 18

NET PRESENT VALUE ANALYSIS OF BIOMASS POWER GENERATING PLANT

Item		Cost
Capital Cost	$1,270,000	
Investment Tax Credit	- 127,000	
Energy Tax Credit	- 125,000	
INVESTMENT (K_o)		$ 1,018,000
Annual Operating Cost (C_i)		59,350
Annual Benefits (B_i)		320,000
Discount Rate (d)		0.08
NVP (n = 4 yrs)		- 154,694
NVP (n = 5 yrs)		22,700
NVP (n = 6 yrs)		186,954
NVP (n = 7 yrs)		339,041

CONCLUSIONS

Significant information has been developed for converting biomass into higher grades of energy which can be used in agriculture. These results were developed through:

1. Direct combustion experiments in a 61 cm diameter fluidized bed.

2. Gasification experiments in 51 mm and 30 cm diameter fluidized beds.

3. Gas cleaning experiments in the 30 cm diameter fluidized bed.

4. Steam production from a close coupled fluidized-bed gasifier and boiler.

5. Net present value economic analyses for a biomass energy conversion system at a cotton gin.

Specific conclusions are summarized below:

Direct Combustion Experiments

1. Direct combustion of cotton gin trash and sorghum stalks in a fluidized bed resulted in coatings on bed particles, fouling of stacks and cyclone, and hot metal corrosion of coupons exposed to exhaust gases. These are serious problems which must be overcome before a viable energy conversion system can be developed.

2. The mechanism causing the problem apparently is high concentration of chemicals and ash in the biomass feedstock. Chemicals such as potassium, silica, calcium, magnesium, and aluminum form complex compounds and eutectics in an oxidizing atmosphere which have melting temperatures below the operating bed temperature of 760°C. Liquids and vapors from these compounds apparently are responsible for the bed coatings, stack fouling, and hot metal corrosion.

3. An air distributor which provides a net downward bed particle flow near the side walls and net upward flow near the center was found to provide more efficient combustion than a distributor with uniform fluidization and random bed mixing patterns.

Bench-scale Gasification Tests

1. Sorghum stalks, rice hulls, corn cobs, and cotton gin trash can be converted to a low energy gas in a fluidized bed. Small differences exist in the composition of gases from the various feedstocks and fuel-to-air ratio is the predominant controlling parameter.

2. Heating value of gas produced in the 51 mm diameter gasifier from the four biomass fuels had a mean value of 6.62 MJ/m^3 and standard deviation of 0.832 MJ/m^3 where bed temperatures were near 760°C and fuel-to-air ratios were near 1.1 kg/kg.

3. Thermal efficiency based on ratio of energy in gaseous product to energy of biomass input fuel feed varied from 45 to 65 percent for the four fuels.

Gas Cleaning

1. A cyclone design model has been developed which appears to provide a conservative estimator of cyclone efficiencies for use with fluidized-bed gasification.

2. Tests with a two stage cyclone in the exhaust from the 30 cm fluidized bed showed a total particulate mass concentration of 163.4 g/m^3 in gas exiting the gasifier, 12.42 g/m^3 after the primary cyclone, and 1.42 g/m^3 after the secondary cyclone.

Steam Production

1. Operating the 61 cm diameter fluidized bed in a gasification mode and burning the low energy gas in a boiler has successfully demonstrated potential of fluidized-bed technology for upgrading biomass energy.

2. Limited experimental results showed that steam was produced at rates of 334.3 kg/hr. For each kilogram of cotton gin trash fuel used, 3.65 kg of steam were produced.

Economic Analysis

1. A biomass energy conversion system at a cotton gin which processes 25,000 bales of lint per year would realize benefits of approximately $320,000 per year by eliminating electrical energy purchases, eliminating natural gas purchases, eliminating trash disposal costs, and by sales of excess electricity generated.

2. A net present value analysis showed that an internal rate of return on investment is greater than 8 percent for a lifetime of a system greater than five years. These are preliminary estimates and a detailed cash flow analysis is needed which includes specific tax information.

RECOMMENDATIONS

Future research toward developing an on-site energy producing system to use biomass fuels should emphasize fluidized-bed gasification rather than direct combustion.

One of the primary reasons for selecting a fluidized bed for combustion studies was the potential for maintaining combustion temperatures below ash melting temperatures. Precise temperature control is achieved but the oxidizing atmosphere apparently creates complex eutectic mixtures having extremely low melting temperatures. These temperatures are lower than the permissible operating temperatures for sustained combustion. The vapors and ash produced from the complex chemical reactions have collected on combustor exit walls, cyclones, and metal coupons placed in the cyclone stack. Analysis of the corrosion of metal coupons indicates that elements having their source in the biomass fuel react chemically with low carbon and alloy steels. These problems must be overcome before such a system can be considered technically viable.

Additives have been demonstrated to reduce this problem in other fuels such as sludges and fouling coals and any further combustion work should be directed toward the chemistry of the fuel source and ash. Fouling and slagging characteristics should be identified and additives determined to counteract these characteristics.

By contrast, fluidized-bed gasification experiments have not been plagued by the fouling problem. The reducing atmosphere of gasification apparently eliminates formation of the complex eutectics causing problems in combustion. Gasification of cotton gin trash has been successful in this work using fluidized-bed techniques whereas gin trash has been reported to be an unsuitable fuel for use in a downdraft gasifier (Goss). However, material corrosion has not been evaluated at critical points in the fluidized-bed energy conversion system. This needs to be evaluated to assure selection of appropriate construction materials at various locations. Techniques to remove ash and particulates also need further evaluation.

Further experimental tests using the 30 cm and 61 cm diameter fluidized bed units operating in gasification mode with various feedstocks are warranted. A more detailed site specific cash flow economic analysis is also warranted.

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