NOTICE

CERTAIN DATA CONTAINED IN THIS DOCUMENT MAY BE DIFFICULT TO READ IN MICROFICHE PRODUCTS.

BNL-47832
INFORMAL REPORT

BNL--47832

DE92 019008

Cogeneration and Beyond: The Need and Opportunity for High Efficiency, Renewable Community Energy Systems

Submitted by:

Thomas C. J. Gleason
Consultant
2425 18th Street, N.W.
Washington, D.C. 20009

June 1992

Prepared for

Energy Efficiency and Conservation Division
Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

Under Contract No. DE-AC02-76CH00016 with the
United States Department of Energy

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

ABSTRACT

The justification, strategies, and technology options for implementing advanced district heating and cooling systems in the United States are presented. The need for such systems is discussed in terms of global warming, ozone depletion, and the need for a sustainable energy policy. Strategies for implementation are presented in the context of the Public Utilities Regulatory Policies Act and proposed new institutional arrangements. Technology opportunities are highlighted in the areas of advanced block-scale cogeneration, CFC-free chiller technologies, and renewable sources of heating and cooling that are particularly applicable to district systems.

TASK 1, PART 1

Introduction: The Global Environmental Context of U.S. Energy Policy

Table of Contents

Introduction: The Global Environmental Context Of U. S. Energy Policy

The Global Warming Crisis

Energy production and use are a primary cause of much of the global environmental crises which currently beset natural and human systems. The most significant environmental threat is global warming or the greenhouse effect. Global warming has the potential to inflict a level of disruption of human societies and economies and natural ecosystems which has been compared with the effects of global nuclear war. The United Nations Intergovernmental Panel on Climate Change (IPCC) has estimated that if nothing is done to reduce the rate of growth of greenhouse gas emissions that the magnitude of sea level rise would be about 20 cm by 2030 and about 65 cm by the end of the next century. Global mean temperatures were predicted to increase by about 1 degree centigrade above the present value by 2025 and 3 degrees C before the end of the next century. The IPCC has concluded that increases in atmospheric concentrations of greenhouse gases may lead to irreversible change in the climate which could be detectable by the end of this century.

The United States is the world's leading producer of greenhouse gases. Although the U.S. has only 5% of the world's population it accounts for over 20% of the gases which cause global warming. With only 20% of the world's population, the industrialized countries account for 75% of greenhouse gas emissions attributable to energy consumption. As such, the industrialized countries, especially the United States, have a global responsibility to ensure that their energy policies do not further exacerbate the crisis but rather provide the example, resources and leadership to extricate the planet from an environmental disaster which could engulf virtually all life on earth.

Emissions from energy production and use are a primary source of greenhouse gases which cause global warming. The IPCC estimates that the energy sector worldwide accounts for 46% (with an uncertainty range of 38% to 54%) of the global warming resulting from human activities. Therefore, global warming and related crises offer an unprecedented challenge to energy policy development. An American energy policy which is worth its salt should proceed from the premise that global environmental priorities are of paramount concern and should be the driving forces behind the development of energy policy. The highest priority at present is to reduce the emission of greenhouse gases which result from energy production and use to levels which will result in a significant slowing of the rate of global warming.

The U.N. IPCC has identified 4 greenhouse gases produced by human activity and estimated their respective contributions to global warming in the 1980's--carbon dioxide (56%), methane (15%), chloronated fluorocarbons (CFCs) (24%) and nitrous oxides (5%). The largest single human source of global warming is energy production and use. The consumption of energy from fossil fuels (coal, oil and natural gas) for industrial, commercial, residential, transportation and other purposes results in large emissions of carbon dioxide accompanied by much smaller emissions of methane from coal mining and the venting of natural gas.

Many industrialized countries, especially European countries have called for a 20% reduction in carbon dioxide emissions from the developed world by 2000 or shortly thereafter. Several nations have pledged to unilaterally freeze emissions at current levels or reduce emissions significantly from present levels. Although the realization of this goal is a primary objective of many countries and non governmental organizations working on a new global environmental treaty--the Framework Convention On Climate Change--it is quite evident that even if a 20% reduction in greenhouse gas emissions is agreed to and implemented by all industrialized countries this reduction would not even come close to stabilizing the atmosphere and climate at current levels. According to the IPCC and the U.S. Environmental Protection Agency (EPA) the stabilization of the atmosphere at current levels will require about an 80% global reduction in carbon dioxide emissions from current levels in addition to substantial reductions in the other greenhouse gases.

The longer it takes for concerted global action to be agreed upon to significantly reduce greenhouse gas emissions the greater the problem will become since not only will gases emitted today continue to have an effect for years to come but patterns of energy use put in place in the present will continue to result in emissions for decades into the future. Thus, the longer we wait to take action, the more expensive, ineffective, drastic and wrenching the transition away from the present fossil fueled energy economy and toward the sustainable energy economy of the future will be.

The Office of Technology Assessment of the U.S. Congress has noted that if no actions are taken to reduce greenhouse gas emissions through energy conservation and the use of renewable energy sources, U.S. emissions of carbon dioxide emissions are likely to rise by 50% during the next quarter century. Although much uncertainty surrounds the global warming issue and the magnitude of climatic effects from greenhouse gas emissions cannot be predicted with great accuracy, the OTA has stated that it is clear that the decision to limit emissions cannot await the time when the full impacts are evident. The lag time between emission of the gases and the full impact is on the order of decades to centuries; so too is the time needed to reverse any effects. Today's emissions thus commit the planet to changes well into the 21st century...Lag times between identification of policy options, legislation of controls and actual implementation can also be considerable. (source: "Changing By Degrees: Steps To Reduce Greenhouse Gases", Congress of the United States, Office of Technology Assessment, U.S. Government Printing Office, Washington, D.C., February, 1991).

It has been widely observed that humanity is engaged in a very dangerous experiment with climate change and the results of that experiment are unpredictable. Although the high degree of uncertainty surrounding the global warming issue has been cited as a reason for inaction, the potentially serious consequences of climate change for the global environment constitutes sufficient reason to begin to adopt response strategies that can be justified immediately even in the face of significant uncertainty. The IPCC has observed that in the short term energy policies could be implemented which are "beneficial for reasons other than climate change and justifiable in their own right, such as increased energy efficiency in general and cogeneration systems and the development of high efficiency renewable energy systems in particular.

It has been proposed that a requirement for a 20% cut in greenhouse gas emissions from 1988 levels by 2005 be incorporated into the Convention on Climate Change. Although the United States is apparently balking at this provision, it has been noted that even a cut of 20% is only a first step in the direction of alleviating the considerable increase in greenhouse gas emissions which is likely as a result of inexorable factors which are already in place.

The foremost of these factors is population growth. It is widely accepted that the population of the earth will double to over 10 billion within 30 years, or by 2020. It is also possible that, in the absence of vigorous family planning programs in all developing countries that this figure could be much higher. The doubling of the earth's population so rapidly at a time when local, regional and global environments are already under considerable stress does not bode at all well for the future. In terms of global warming this population increase could not be occurring at a worse time. Larger populations will be accompanied by increased consumption of energy and intensified land clearing for food production and other activities, all of which will cause an increase in net greenhouse gas emissions. Therefore, population control policies are a critical component in our response to global warming. However, even in the face of concerted efforts to bring down population growth rates the likelihood of a population doubling in 30 years is so high that unless other systems compensate the global warming crisis could spin completely out of control.

One of the most logical points on which we can press is energy policy since the reductions in greenhouse gas emissions through energy efficiency and the substitution of fossil for renewable energy sources are huge and virtually untapped in terms of their potential at this time. According to the UN IPCC as much of that potential will have to be brought to bear as possible if we are to stabilize the climate. That stabilization will ultimately require an 80% reduction in the output of carbon dioxide from current levels as well as significant reductions in other greenhouse gas emissions. A 20% cut in greenhouse gas emissions by 2005 should be considered the bare minimum required to begin the massive change in our energy systems which will be required if we are to achieve climate stabilization. The achievement of an 80% reduction is not a quixotic goal but rather a very realistic one given the opportunity for increased energy efficiency and the substitution of renewable energy sources for fossil fuels. The 20% cut in greenhouse gas emissions should be viewed not as the ultimate goal but rather as the first and most easily achieved incremental improvement that can be made.

The Stratospheric Ozone Depletion Crisis

One component crisis in the multifaceted environmental crisis known as global climate change which is deserving of special consideration is the stratospheric ozone depletion crisis. The ozone layer is an essential part of the earth's ecological balance because it absorbs ultraviolet B (UV-B) radiation. The phenomenon of ozone depletion as a result of the chemical reaction among chlorine, ozone and sunlight in the upper atmosphere has been dramatically demonstrated over the last half dozen years as a result of the Antarctic ozone hole which opens up in the late winter and early spring.

Chloronated fluorocarbons have been conclusively implicated as the cause of the ozone layer losses both over Antarctica as well as elsewhere. The United States consumes between 20 and 30% of the world's CFC-11 and CFC-12, the two most damaging chlorofluorocarbons in terms of the impact of CFCs on the ozone layer and on global warming. Roughly 60 to 70% of these CFCs are used in air conditioning or in the production of thermal insulation. Thus, policies regarding CFC phase out and substitution are issues which are inextricably linked with both U.S. national and global energy policy.

The impact of ozone depletion on biological systems cannot be minimized. The loss of even a small proportion of the earth's protective ozone shield threatens highly sensitive biological organisms on which all life depends. For example, ocean phytoplankton which form the basis of the food chain of the oceans are highly sensitive to even small changes in UV-B radiation. If the phytoplankton in the southern oceans were to be perturbed to a significant degree it could well disrupt all sea life in that region as well as others.

The ability of terrestrial plants to withstand even small increases in UV-B radiation is also in doubt but it is clear that even small increases of UV-B radiation, especially during spring planting times when the thinning of the ozone layer is greatest, could lead to significantly reduced agricultural productivity. There are a number of secondary impacts which are still quite significant such as the high probability of a significant increase in human skin cancers, decreases in the immune system function of animal life including humans and the degrading effects of radiation on plastics and other synthetic and natural materials.

Realizing the severity of this threat to life on earth posed by the loss of the ozone layer, in 1987, the Montreal Protocol was adopted by many nations including the U.S. It provided for reductions in CFC emissions by 50% in 10 years. More recent scientific data underlining the severity of the crisis prompted an updating of the Protocol in 1990. The strengthened agreement regulates 10 additional CFCs and requires participating countries with high per capita CFC use to reduce production and consumption by 20% of 1986 levels within 3 years; achieve a 50% reduction by 1997; and a 100% phase out by the year 2000. Developing countries have been given a 10 year grace period by the 1990 revised agreements and have been given access to a multilateral fund financed by the industrialized nations to facilitate technology transfer and to ease the cost of compliance by developing countries. The fund could reach $240 million for three years if both China and India join.

Many countries have chosen to go beyond the provisions of the revised Montreal Protocol. For example, in the new Clean Air Act Amendments the U.S. Congress included provisions to control ozone depleting chemicals which are a bit more restrictive than the revised Montreal Protocol. The U.S. law establishes a reduction schedule for HCFCs, a major CFC substitute refrigerant with a freeze in 2015 and production prohibited in 2030--10 years earlier than the Montreal Protocol's non binding deadline.

Despite this record of significant international and national action on ozone depletion, it has recently become apparent that even these actions may be far less than adequate due to the fact that the rates of stratospheric ozone depletion are proceeding much more rapidly than most climatic models had predicted. The Antarctic hole of 1990 was comparable to the worst years of 1987 and 1989. The decrease in ozone over the Antarctic can be as much as 50% in a bad year and about 5 to 7% over the entire Antarctic region. Losses of ozone over both the southern and northern polar regions over the last decade have made scientists believe that global ozone has declined by 4 to 6%.

Recent NASA studies have revealed ozone losses of 4 to 8% in the upper latitudes of the northern hemisphere (between 40 and 52 degrees north latitude) which includes the U.S. north of the latitude of Philadelphia and 4 to 6% for most of the rest of the continental U.S. This level of ozone loss is greatly in excess of that predicted by any of the climatic models in use. The impact of such a loss could be quite substantial in the very near term. Since the ozone is lost in the springtime, it has the potential to greatly perturb agriculture by reducing crop growth rates as well as impact the human population directly. For every percentage point of ozone loss the number of skin cancers are expected to increase 5 to 7%. Skin cancer cases in the U.S. are expected to increase from 500,000 to 800,000 per year under the latest estimate of ozone depletion with the number of deaths doubling from the current toll of 5,000 per year.

The recent data is all the more disconcerting given the fact that the current provisions of the Montreal Protocol will allow the current level of 3 parts per billion (ppb) of chlorine in the stratosphere to rise to 4 ppb by the end of the century. These levels are up from natural levels estimated at 1.5 ppb. The fact that the crisis is much more immediate and extreme than previously thought should give added impetus to a strengthening of the Montreal Protocol which should be revised to permit an accelerated and complete phase out of all CFCs in the near term. The date for a complete phase out which has been advocated by a number of countries is 2000.

Although the U.S. government appears reluctant to agree to the accelerated ban, not all Americans are of this mind. Many environmental groups as well as political leaders are supportive of a greatly accelerated phase out of CFCs. Many advocate that a nearly complete (98 to 99%) phase out of all CFCs be instituted by the mid 1990's. Although such a rapid phase out will be costly, it has been observed that such regulations will rapidly stimulate the development of a new mass market for CFC substitutes. The alternative--further delay--can be countered with the following question: How can we possibly weigh a relatively small commercial interest against the health and environmental conditions of all future generations? Conventional cost-benefit analyses are at best irrelevant when the environment of the entire world is threatened.

This position is basically in line with that of 13 signatories to the revised Montreal Protocol including Australia, Canada, Norway, Sweden and West Germany which have committed themselves to phasing out CFCs by 1997, three years ahead of the pact's provision. The timetable of CFC phase out by 2000 which was agreed to in the revised agreement will permit more than five times the 1986 production level of CFCs to be manufactured before the final phase out, according to David Doniger of the Natural Resources Defense Council. This is almost twice as much as provided for under the more stringent schedule suggested by Germany. As the largest producer and user of CFCs, the United States has a special responsibility to provide leadership on this critical issue. In this case, appropriate leadership would be to agree to the accelerated 1997 phase out timetable and to institute a vigorous program for the development and implementation of environmentally benign CFC substitutes.

To date the U.S. government has left private industry to take the lead in developing CFC substitutes. This has resulted in the rapid development of many new CFC substitutes particularly in the area of substitute refrigerants for use in energy conversion equipment such as air conditioning systems, heat pumps and refrigerators. However, the actual results have been mixed. Many of the substitutes still employ some CFCs albeit in much lower concentrations than many presently commercial systems utilize. The following chart (page 8(a)) compares the ozone depleting potential of CFCs with the CFC substitutes HFCs and HCFCs recently developed. (source: R&D Magazine, p. 60, May, 1990)

The primary focus of both private and public sector R&D in CFC substitutes for energy conversion and utilization equipment has been to develop refrigerants which can be employed in existing systems. There is approximately $135 billion worth of existing systems in the U.S. which use CFCs as refrigerants. R&D to date has been preoccupied with the development of "drop-in" non-CFC substitute refrigerants which can be used in these systems with a minimal amount of retrofit problems. Although many of the technical hurdles to accomplishing this goal have been overcome many problems appear to remain.

		[illegible] (years)	[illegible]	[illegible]	[illegible]
WHAT'S IN	HCFC-22	15	0.05	0.34	Air conditioning, refrigeration, foam packaging
	HCFC-123	2	0.02	0.02	Refrigeration, insulating foams, solvents
	HCFC-124	7	0.02	0.1	Air conditioning, insulating foams
	HCFC-141b	8	0.1	0.09	Insulating foams, solvents
	HCFC-142b	19	0.06	0.36	Insulating foams, solvents
	HFC-125	28	0	0.58	Refrigeration
	HFC-134a	16	0	0.26	Refrigeration, air conditioning
	HFC-152a	2	0	0.03	Insulating foams, aerosols
WHAT'S OUT	CFC-11	60	[illegible]	[illegible]	Insulating foams, refrigeration, air conditioning
	CFC-12	120	[illegible]	3	Refrigeration, air conditioning, insulating foams
	CFC-113	90	0.8	1.4	Solvents
	CFC-114	200	0.7	3.9	Foam packaging, aerosols
	CFC-115	400	0.4	7.5	Refrigeration

Source: World Meteorological Organization 1989 report

While HFC and HCFC compounds are not entirely benign, they cause considerably less damage to the ozone and contribute less to the greenhouse effect than the fully halogenated compounds they replace because of a shorter atmospheric lifetime.

Firstly, none of the new refrigerants are truly "drop-in". That is, all require additional and sometimes extensive modifications to the systems in the form of complete evacuation of the CFC refrigerant, new seals, new oils and new operating procedures which require changes in other parts of the system such as pumps and compressors. Moreover, each carries with it its own set of environmental and health related problems. For example, HFC compounds which use hydrogen in place of chlorine do not deplete the ozone layer but do contribute to global warming. HCFCs which use hydrogen as the trigger mechanism to make them degrade in the troposphere before they can reach the ozone layer in the stratosphere still deplete the ozone layer, though at a rate of 2 to 10% of that of fully halogenated CFCs. (source: R&D Magazine, May 1990, p. 60)

Because many of the CFC substitute refrigerants use appreciable amounts of CFC refrigerant with significant ozone depleting potential it is clear that it will also be necessary to ban these substitutes in the near future if we are to avoid an accelerated loss of stratospheric ozone. As it now stands, even the most recent revisions to the Montreal Protocol will result in significantly increased levels of ozone loss until about 2005. If all countries adhere to the 1991 revisions then ozone depletion rates are predicted to peak at that time. However, it will take the ozone layer quite some time to recover--depletion rates will only recover to 1995 levels by 2035 and significant levels of depletion will persist for most of the next century. This outcome will ensure that the earth's biological life will continue to be perturbed by unnaturally high levels of UV-B radiation for most of the next century.

Thus, the crisis is of such a magnitude that an extreme response is very much in order. Recent data have shown that the crisis is proceeding to develop at a rate which is greatly in excess of anything which the climatic models had predicted. It is now clear that most of the current crop of CFC substitutes will also have to be banned in the very near term. This conclusion casts very grave doubt on the efficacy of the U.S. Government's strategy of relying largely on private industry to develop CFC substitutes for use as drop-in refrigerants. The question must be asked: is extending the useful life of $135 billion in CFC using refrigeration systems for a decade or so worth the price of undermining large portions of the earth's ecosystem as well as directly impacting the ability of human economies and societies to survive? Clearly, the answer is no. The fact of the matter is that there are many viable technical options which have not been seriously pursued simply because they require the replacement of existing equipment with new and different systems which do not employ refrigerants which can be developed, patented and profited from by the large chemical manufacturers who currently control CFC replacement policies by default.

Numerous American environmental groups have subscribed to a program for Safe Alternatives to Protect the Ozone Layer. Safe alternatives are those which do not harm the ozone layer or human health in either their production or utilization. One goal of this proposed program is the banning of all ozone depleting chemicals including those which have been identified as interim substitutes for CFCs which contain some CFC. The program has four goals:

-- accelerate the phase out of all ozone destroying chemicals;
-- enact a safe alternatives policy to ensure that banned chemicals are not replaced with chemicals or other technologies that harm human health or the environment in other ways;
-- raise revenue to fund accelerated research and development on safe alternatives and provide assistance to workers displaced due to the chemical phase out; and
-- prohibit all preventable releases of ozone depleting substances.

(source: Testimony of Bill Walsh, U.S. Public Interest Research Group, Presented on Behalf of the Campaign for Safe Alternatives to Protect the Ozone Layer. Before the Senate Subcommittee on Environmental Protection Concerning Legislation to Regulate and Control Ozone Depleting Substances, May 19, 1989)

According to Bill Walsh of the Campaign for Safe Alternatives, several additional issues should be addressed by Congressional legislation. Firstly, the refrigerant manufacturers should not be allowed to reap windfall profits as a result of an ozone depletion crisis and refrigerant substitution policy for which they are primarily responsible. Such profits should be taxed away by the federal government which should use them to promote independent research efforts that compete with the substitute options developed by industry. The magnitude of the crisis and its potential impact on the earth's ecosystem and all of humanity is so great that responsibility for resolving it cannot be left to private industry which is primarily concerned with the bottom line and has no real financial interest in the long term survival of the planet. This is a task for the public sector which is the only entity capable of mounting a research and development program on the scale required--an R&D effort on the scale of the Manhattan Project to produce environmentally and economically viable alternatives to CFCs as soon as possible. Meanwhile, accelerated timetables for phase out of all CFCs should be agreed to without delay.

In addition to the fact that most of the "drop-in" refrigerants require extensive and expensive retrofit measures to accommodate the refrigerants to existing equipment and also that many still employ some CFCs or pose a threat to human health, these refrigerants also pose an indirect threat of exacerbating the global warming crisis. Most of the new refrigerants are much less energy efficient than the CFC refrigerants which they are replacing. Decreases in the energy efficiency of air conditioning and refrigeration equipment which use the substitutes of between 5 to 15% and capacity reductions of up to 18% have been experienced with the use of the new refrigerants in existing equipment.

If the "drop-in" refrigerants indeed succeed in being commercially implemented on a widespread basis their efficiency penalty will be translated into a need for significantly more electric generating capacity and electrical generation. If the additional capacity and electricity is generated using standard fossil fueled thermal electric power generation equipment, as seems likely given current U.S. energy policy, then that power will come from fossil fueled power plants and additional greenhouse gases will be emitted in proportion to the increased demand for electricity to supply the less efficient air conditioning and refrigeration equipment. Thus, the additional carbon dioxide and other emissions will exacerbate global warming. The extent to which this actually occurs will depend on the average efficiency penalty of all the substitute refrigerants used in place of CFCs as well as the type and efficiency of the electric generating capacity employed to meet the new demand and the type of fuel used.

Thus, the solution to one problem has the distinct potential to exacerbate another in a seemingly endless exercise in futility. However, the reason why the situation appears to be futile is not because there are a lack of potentially viable technical options which can be readied in the short term and which meet acceptable economic, environmental and toxicological criteria but rather because the U.S. government has abrogated its responsibility in energy policy leaving all important decisions for private industry to develop and implement on its own with little if any meaningful input and participation from the public or leadership by the public sector. This lack of a policy has left us with a set of very greatly constrained options for the near term in the case of finding acceptable alternatives to CFC refrigerants. However, many options can be readied within a few years given the sufficient support for the right type of technology research and development.

A Sustainable Energy Policy For The United States

As the major contributor to both greenhouse gas and CFC emissions and therefore the nation most responsible for global warming and ozone depletion, the U.S. needs to take a leadership role in the resolution of both crises. The most effective means of leadership would be for the U.S. to first put its own house in order through the implementation of a comprehensive energy program emphasizing greatly increased efficiency of energy use and renewable energy production. The fact that there is ample room for efficiency improvements is well known. For example, several European countries employ about half the energy per unit of GNP as does the U.S. Moreover, these same countries are also the ones which are pressing the other industrialized countries to commit to a 25 to 30% reduction in greenhouse gas emissions by 2005--much of which would be achieved through energy efficiency increases.

A commission established by the German Bundestag, the Enquete Commission has called for Germany to reduce carbon dioxide emissions by 30% by 2005 and the European Community to reduce such emissions by 20 to 25% by the same date. This would allow developing countries to increase emissions by 50%. Fifty percent of the reductions would be achieved by efficiency improvements and modifications in consumer behavior and would be based on available technology. In the second phase of the Enquete Commission's plan an additional 20% reduction in carbon dioxide emissions would be achieved by 2020 and another 30% reduction would be achieved between 2021 and 2050. The German cabinet has apparently approved a 25% carbon dioxide emissions target by 2005. Thus, over a 60 year period an 80% reduction in carbon dioxide emissions could be achieved--precisely the level which must be achieved to stabilize the global climate. It is important to note that this strategy is being seriously advocated for a country which is already twice as energy efficient as the U.S. in terms of energy consumption per unit of GNP. Thus, the level of greenhouse gas emissions contemplated by the Enquete Commission is about 10% of the current emissions of the U.S. economy on the basis of greenhouse gas emissions per unit of GNP.

In the recent past, the United States managed to achieve very significant gains in energy efficiency when it was necessary to do so. During the 1970's an extraordinary freeze in national energy consumption took place while the economy grew by 35%. This was 2/3 due to increases in energy efficiency and 1/3 due to structural changes in the economy. Investments in more efficient technologies were made possible both by higher energy prices and a regulatory environment which encouraged efficiency. Thus, the U.S. has demonstrated its ability to implement an effective energy efficiency program in the past and should be able to do so in the future.

Unless a comprehensive national en[illegible] efficiency and renewable energy program is implemented, it is fore[illegible] that U.S. energy consumption will follow the trend of the last half of the 1980's when fossil fuel energy consumption actually increased. If this trend continues unabated the U.S. Congress Office of Technology Assessment expects that this "business as usual" approach will result in a rise in carbon dioxide emissions of 50% over the next 25 years. The apparent causes of the trend toward increased carbon dioxide emissions and energy consumption was the decrease in energy prices in the mid-1980's and the Reagan Administration's dismantling of the national energy program put in place in the 1970's.

For example, the Federal government's R&D funding for renewable technology plummeted 90% from $1.3 billion in 1980 to $0.14 billion in 1990. In 1990, only about 5% of the $2.7 billion national budget for energy technology R&D was spent on renewables and only 7% went toward energy conservation. Meanwhile, fossil fuels were given 25%, nuclear fusion 12% and nuclear fission 9%. The OTA has concluded that with a comprehensive and intensive national energy program comprised of a package of aggressive energy efficiency, energy supply and forestry management options that the U.S. can achieve a 20 to 35% emissions reduction by 2015.

A variety of policy interventions will be required to reduce carbon dioxide emissions to within this range by 2015. These could include regulatory push and market pull mechanisms affecting both energy supply and demand and forestry and agricultural practices. However, the OTA also noted that without an increase in and refocusing of current Federal initiatives including performance standards, incentive programs, energy taxes and R,D&D activities--the use of greenhouse gas reducing technologies is unlikely to increase greatly in the next few decades. The costs of achieving a 35% reduction in carbon dioxide emissions are estimated by OTA to range from a savings of $20 billion to a cost of $150 billion per year by 2015, a range which is equal to saving a few tenths of a percent to a cost of up to 12.8% of GNP.(source: OTA, "Changing By Degrees", p. 5-10)

Thus, past U.S. experience as well as the experience of other industrialized countries shows that it is both technically and economically feasible with currently available technologies to achieve very substantial gains in overall national energy efficiency levels. Indeed, it also shows that current technology has the capability to achieve an average national energy efficiency which is double that which the U.S. presently has reached. With new energy efficiency and renewable energy technologies it should be possible to go well beyond even a 50% reduction to the 80% reduction in greenhouse gas emissions which is necessary if the climate is to be stabilized. The long term goal of developing an energy supply and utilization system which can achieve an increase of 80% in energy efficiency over today's levels within about 40 to 50 years should be the goal of U.S. energy policy if that policy were predicated on the assumption that the U.S. wished to become a global environmental leader and good planetary citizen rather than the global environmental laggard and odd man out which is our position under the current energy policy as articulated by the Bush Administration.

One significant component in a new U.S. national energy plan is energy research and development. It is clear that the implementation of existing technologies and known practices can significantly increase energy efficiency and also substitute a number of clean renewable energy sources for fossil fuels. The fact that several of America's chief economic competitors, Germany and Japan, utilize half the energy per unit of GNP as the U.S. is well known. It tells us that with known technology the U.S. can reduce its energy consumption by half. However, even such a radical increase in national energy efficiency will not get us to the point at which we have to be if we are to forestall global warming in the face of the doubling of the earth's population which is expected to occur in the Third World over the next 30 years. As previously noted, an 80% reduction in carbon dioxide emissions will be required of the industrialized countries in order to compensate for the increased carbon dioxide emissions which will result from population growth and additional resource demands in the Third World. In order to achieve a full 80% reduction in greenhouse gases new energy efficient and renewable energy technologies will have to be developed and deployed throughout the economy.

Despite this reality, both energy efficiency and renewable energy research and development were substantially reduced by the Reagan Administration in the early 1980's. In 1980 the funds spent on energy efficiency R&D by the U.S. Department of Energy totaled $1,221,549,000. In subsequent years the Reagan Administration slashed this budget repeatedly to the point in 1991 where only $504,153,000 was appropriated by Congress for R&D in energy efficiency. This amount would have been considerably less had not Congress appropriated significantly more funds than the Administration requested.

In April, 1991 a coalition of 24 national environmental and energy groups, the Energy Conservation Coalition, published an "Alternative Budget For Energy Conservation: Fiscal Year 1992". The alternative budget proposes to reverse the presently inadequate budgetary situation faced by energy efficiency research and development and significantly increase that budget to levels at which the enormous potential for new high efficiency technologies can begin to be realized. Thus, the Coalition proposed an energy conservation technology research and development budget for FY 1992 which totals $788,884,000. It is clear that if the United States is to achieve the increases in energy efficiency which are required as a result of the threat of global warming that funding at such levels for energy efficiency R&D as have been proposed by the Energy Conservation Coalition will not only have to be instituted for FY 1992 but will have to be maintained for decades to come if the potential for this option is to be realized.

A similar effort to formulate and present an alternative budget for the US Department of Energy's FY 1992 to 1994 budgets in solar energy was also undertaken by another coalition of 32 national environmental and energy groups. The recommendations of this coalition were published in the report, "Investing In Solar Energy: Recommendations for the U.S. Department of Energy's Research and Development Budget For Renewable Energy Technologies, FY 1992-1994". Beginning with the Reagan Administration's first budget in FY 1982 through the Bush Administration's first budget in FY 1990, renewable energy technologies suffered annual cutbacks in the U.S. Department of Energy's R&D budget which total an overall cut of 90% from peak levels in 1979. Despite these abysmal levels of funding renewable energy sources have the potential to supply most of the United States' energy requirements within several decades as long as sufficient funding for research, development and demonstration of new technologies is forthcoming from the federal government. Given the need to drastically reduce greenhouse gas emissions from energy production and conversion activities and that the fact that ultimately only a combination of greatly improved end use of energy coupled with greatly increased production of energy supplies from renewables is capable of achieving the 80% reductions in greenhouse gas emissions that is required, it is imperative that a strong and well funded renewable energy technology R,D&D program be put and kept in place for the foreseeable future.

As a result of these and other considerations such as national economic competitiveness and national security, The Coalition advocates a substantial increase in funding for a broad spectrum of solar energy technologies over the levels of funding to which this group of technologies was subjected as recently as FY 1991, $159.8 million. In FY 1992 it recommends that the total funding for renewable energy increase to $462.1 million, in FY 1993, $571.9 million and in FY 1994, $652.5 million. The Bush Administration's

Department of Energy budget is dominated by nuclear fusion, nuclear fission and clean coal technology R&D. These priorities are exactly the reverse of those held by most of the American people who, in poll after poll, have overwhelmingly supported making renewable energy technology R&D the top priority in the U.S. energy plan.

It is clear that if the United States is to fulfill its responsibility as the world's largest producer and user of CFCs and producer of greenhouse gas emissions that it will go along with the weight of world opinion on the global warming and stratospheric ozone depletion crises and agree to reduction schedules which have the potential to begin the process of instituting an effective international response to both crises. Once it has done so the next order of business is to face the task of completely restructuring the U.S. energy economy by first making it much more energy efficient than it is today--at least twice as efficient--second, meeting most of the remaining demand for energy from renewable energy sources and third phasing out those energy technologies such as nuclear power, coal, oil, and CFCs and some of the CFC substitutes which are deleterious to human health and the environment. There is no question that this process will be a long and costly one. However, there will also be many benefits in the form of increased national economic productivity and competitiveness, lower health costs, an improved environment and quality of life and most of all, the continued survival and prosperity of the earth's biosphere and of the human race. It is clear that the potential consequences of the alternative of doing nothing are simply unthinkable. Rather than toying with the destiny of the planet through inaction, the United States needs to begin the process of becoming an exemplary planetary citizen and one of the best ways it can do so in the near term is to put its own domestic energy situation in order on the basis of a greatly expanded role for energy efficiency and renewable energy.

There are a number of cogeneration and renewable sources for community heating and cooling energy system supply which can contribute very significantly to the replacement of CFC refrigerants and the resolution of global warming through energy efficiency which are the topics of this report to Brookhaven National Laboratory. These technologies offer such impressive environmental and efficiency benefits that they are a necessary component of any forward looking U.S. energy policy. Some of these systems which have been identified are as follows:

-- Ammonia air conditioning, refrigeration and heat pump systems. Ammonia has been used as a refrigerant much longer than CFCs which replaced ammonia as the refrigerant of choice in the 1930's. Ammonia has long been excluded from building air conditioning applications because it was categorized as toxic. However, many observers attribute this designation to the CFC refrigeration industry which successfully forced ammonia out of the commercial and residential air conditioning and refrigeration markets in the 1930's. Many contend that ammonia should be reclassified as a respiratory irritant instead of a toxin as long as its use is accompanied by adequate compensatory design factors which serve to limit concentrations and human contact with concentrated ammonia leakages in the even of a failure in the systems. Since ammonia is lighter than air, ventilation systems or placement of ammonia chillers on roofs or in central plants serving a number of buildings can obviate any potential health impacts. Ammonia systems can be more energy efficient than air conditioning systems which use CFCs. There is also excellent potential for the use of ammonia as a refrigerant in automotive air conditioning systems. Ammonia can be used as the basis of both vapor compression heat pumps and chillers as well as heat activated air conditioning systems. The development of new ammonia refrigerant using technologies is critical if we are to successfully address both stratospheric ozone depletion and global warming without exacerbating one or the other.

-- Absorption chillers, heat pumps and other heat activated chilling technologies. The energy for these systems is heat, not electricity, and they do not use CFCs as a refrigerant. One very inexpensive and efficient way to obtain the heat needed to drive an absorption chiller is via cogeneration, the simultaneous production of heat and power from a single energy conversion system. For example, combined cogeneration, electric ammonia refrigeration and absorption chilling systems can be 40 to 60% more energy efficient than conventional electric HVAC system (COP 3.0 to 6.0) designed for CFCs and 50 to 70% more efficient than those same electric chillers which must use a drop-in refrigerant. Other heat activated chilling technologies include jet refrigeration and organic Rankine bottoming cycle turbine technologies. Because of its high energy efficiency and its use of environmentally benign refrigerants, the cogeneration/heat activated chilling option offers one of the best technical opportunities to contribute to the resolution of both the ozone depletion crisis and the global warming crisis.

-- Community scale renewable energy systems. A variety of systems can be developed which can supply air conditioning and space heating at the community scale from renewable energy sources. These systems do not use any CFC refrigerants and would only employ a minimal amount of fossil fuels for the purpose of pumping hot and chilled water through a network of insulated district heating and cooling pipes used to supply groups of buildings, communities and cities with heating and cooling supplies from central renewable energy plants. For the production of cooling the technologies which are available include: ice ponds for the production of ice from cold winter air; spray ponds for the production of cold water from winter air; night sky radiation in arid areas for the production of ice or cold water in winter or summer; the use of bodies of water such as the oceans particularly where the coastline and continental shelf is located in close proximity enabling cold deep water to be accessed for community scale air conditioning; and direct solar absorption chilling. Many of these systems employ seasonal thermal storage and employ at most only about 1/5 of the fossil fuels which conventional systems use. Central solar heating plants with seasonal storage are also under development which can supply entire communities with solar heated water for space heating at potentially economical costs. The energy efficiency of these systems is so high that their use can facilitate an 80% decrease in the energy required for space heating and cooling--exclusive of gains which can be made in making end use systems more energy efficient--while in the process completely eliminating CFCs from air conditioning and space heating applications.

Although each of the aforementioned systems requires some R&D, most are sufficiently advanced that they could be made ready for commercial application within 5 years given sufficient levels of financial support. Thus, it is not at all difficult to see how at least one sector of the economy of industrialized countries, the building sector, could both eliminate CFCs and contribute to a resolution of the global warming crisis to the extent that is required of it and do so in the near term at costs which promise to be competitive with other conventional options as long as sufficient R&D is undertaken.

The Danish National Energy Plan--Example of An Environmentally Responsible Approach To Energy Policy

One national energy plan which is based on the need to achieve substantial increases in energy efficiency and in the use of renewable energy sources to achieve at least a 20% reduction in the emission of greenhouse gases is Denmark. The goal of the Danish government's "Energy 2000" Plan is to transform Denmark's current energy system into one which is sustainable over the long term. The new plan has been formulated to achieve maximum flexibility, reliability and efficiency of energy supply at the lowest possible cost. As compared with 1988, in the year 2005, Denmark's consumption of particular fuels will rise or fall by the following amounts: natural gas: +170%; renewable energy: +100%; coal: -45%; oil: -40%; and gross energy consumption: -15%. The environmental consequences of these actions will be to reduce emissions by the following amounts: CO_2: -20%; SO_2: -60%; and NO_x: -50%.

Increased building energy efficiency is slated for particular attention. By 1993 the heating demands of new buildings will be reduced by 25% and in 2000 by another 25% as a result of new insulation regulations, the use of low temperature radiators and other end use efficiency improvement measures. A key element of the plan is the improvement of the energy efficiency of district heating and an increase in the number of buildings connected to these systems (from the present level of 50% to 90% to 95%). An increase in the efficiency of Danish district heating systems will be achieved primarily through the increased development and optimal use of cogeneration systems of various types. Another approach will be to lower the supply and return temperatures of district heating systems to obtain greater levels of efficiency. Expected expansion of electricity supply will be achieved primarily by converting existing small district and block scale heating systems to decentralized or block scale cogeneration. For the most part, these block scale cogeneration systems will utilize diesel engine prime movers and will be fired by natural gas. As of 1986 small scale cogeneration supplied 450 MW of electric power to the Danish national electric grid. By 2005 this figure is expected to rise to 1200 MW. Cogeneration will also be expanded in the industrial sector. By 2005 400 to 500 MW or, half the market potential, will be established.

In addition to these measures which will be implemented over the next 13 years, Denmark is also expanding its energy R&D Program in the areas of renewable energy, the efficiency of energy use and the efficiency of energy production and distribution. Much of this R&D is focused around cogeneration and district heating and includes new gasification and fuel cell systems; new methods for developing electricity and district heating supply systems with a large share of renewable energy supply and extensive heat-linked power production, i.e. cogeneration; development of very low temperature district heating distribution and end user systems; new biomass conversion systems; new wind turbine technology; and community scale solar district heating systems.

Although the Danish government's commitment to reductions of greenhouse gas emissions by 2005 is impressive in its own right it is important to note that Denmark is quite likely already the most energy efficient of the industrialized countries which are members of the OECD. It achieves its leadership position in the efficient use of energy in large part due to its already extensive use of cogeneration and district heating. In addition, it proposes to cut its emissions of greenhouse gases by an additional 20% by 2005 in large part through the same strategy of making cogeneration and district heating more efficient and more extensively utilized. This is all the more impressive when one considers that the Danish energy economy is probably at least twice as energy efficient as the U.S. American energy planners would do well to learn from the Danish experience which places small scale cogeneration, advanced renewable energy supply systems and district heating at the cornerstone of its national energy plan and of its response to our global environmental problems.

Bibliography

Task 1, Part 1:

Introduction: The Global Environmental Context of U.S. Energy Policy

"A Sustainable Energy Future: Principles and Goals for A National Energy Strategy", Public Citizen, Critical Mass Energy Project, Washington, D.C. 1990.

"Alternative Budget For Energy Conservation: Fiscal Year 1992", Energy Conservation Coalition, Environmental Action Foundation, Takoma Park, MD, 1991.

"Climate Change: The IPCC Response Strategies", United Nations, World Meteorological Organization/United Nations Environment Program, Intergovernmental Panel on Climate Change, Island Press, Washington, D.C., 1991.

"Changing By Degrees: Steps To Reduce Greenhouse Gases", Congress of the United States, Office of Technology Assessment, U.S. Government Printing Office, Washington, D.C. February, 1991.

"Empowering The Future: Energy For A Clean and Prosperous America", Union of Concerned Scientists, Cambridge, MA, 1991.

"Energy 2000: The Danish National Energy Action Plan", Energy Department, Kingdom of Denmark, Copenhagen, Denmark, 1991.

"Investing In Solar Energy: Recommendations for the U.S. Department of Energy's Research and Development Budget For Renewable Energy Technologies, FY 1992-1994", Jonathan Becker (ed) Public Citizen, Critical Mass Energy Project, Washington, D.C., March, 1991.

"National Energy Strategy",USGPO, Washington, D.C., Feb. 20, 1991

"Nucleus", "Responsible Energy Solutions For America", (Journal of the Union of Concerned Scientists, Vol 13, No.1, Spring, 1991, Cambridge, MA.

Testimony of Bill Walsh, U.S. Public Interest Research Group, Presented on Behalf of the Campaign for Safe Alternatives to Protect the Ozone Layer. Before the Senate Subcommittee on Environmental Protection Concerning Legislation to Regulate and Control Ozone Depleting Substances, May 19, 1989.

TASK 1, PART 2

Institutional and Regulatory Strategies For Implementing Cogeneration and DHC in the U.S.

Table of Contents

Page

Introduction

Although the Danish plan for achieving a 20% reduction in greenhouse gas emissions in 13 years is an admirable one the average Americans response to the Danish goals might be that Denmark is a small country of 3 million people, with a strong public sector which is ethnically and climatically homogenous. Whereas, the U.S. is one of the most capitalist of the capitalist countries with a relatively small public sector role in energy policy as well as being ethnically, economically, ideologically, geographically and climatically diverse. Thus, the reasoning goes, what is good for a small, homogenous country such as Denmark is irrelevant for a large, diverse country such as the U.S. Although this argument is somewhat flawed since it ignores the fact that technical systems can be adapted to meet the conditions of other economic, institutional situations, it is instructive. For in the U.S. it is true that a very diverse and complex institutional, regulatory, political, economic and climatic environment must be addressed if effective solutions to a problem as basic as the development of a more efficient and environmentally sensitive energy supply and utilization system are to be devised and successfully implemented. Thus, although it is appropriate to look to public sector institutions such as the U.S. DOE for funding to develop new technologies, it is equally important to understand the requirements which other institutions will impose on those technologies. For, the regulatory and economic requirements of a number of institutions determine the technical and economic environment in which the new systems must compete. If the new technologies are attuned to the demands of the new marketplace they will have a chance of success. If they are not they are doomed to failure. In the following pages the demands imposed by a number of institutions and individual regulations which are important for new cogeneration and DHC technology will be reviewed and ways of either adapting the institutions or the regulations to the technology or vice versa will be suggested.

The Public Utilities Regulatory Policies Act (PURPA) and Cogeneration

Although the initial impact of PURPA after it was unanimously upheld by the U.S. Supreme Court in 1983 was to open the floodgates to the development of cogeneration particularly in the industrial sector, its interpretation by the Federal Energy Regulatory Commission (FERC) has led to an increasing divergence away from the initial intent of the law. One of the major goals of PURPA was to increase the efficiency of electricity generation through cogeneration. FERC then established minimum standards which a cogenerator must meet in order to obtain qualifying facility (QF) status and to thereby gain legal access to the electricity grid and to fair treatment by electric utilities in the purchase and pricing of power sales to and from the cogenerator. For a typical natural gas fired cogenerator the following operating and efficiency standards must be met on an annual average basis.

The FERC "Operating Standard" requires that at least 5% of the useful output (both electrical and thermal energy) must be in the form of thermal energy. The FERC "Efficiency Standard" calls for the electrical energy output plus 1/2 the thermal output to equal or exceed 42.5% of the energy content of the input fuel (except when the operating level is below 15% in which case the efficiency level must equal or exceed 45%. The result of these regulations have been the development of an industry which designs cogeneration systems around the standards, achieving in the process levels of energy conversion efficiency for cogeneration which can only be described as the bare minimum.

The application of these FERC formulas has resulted in the proliferation of very low efficiency cogeneration systems which typically serve a minimum thermal load in order to construct a power plant with significantly more electric power generating capacity than a particular facility could possibly require to meet its own needs. By greatly oversizing the electric generating capacity in relation to the thermal load, profits from the sale of electric power to the utility are maximized at the same time that energy efficiency is minimized. These systems are a creature of the FERC's interpretation of PURPA, could not exist without those regulations and have rightly been dubbed "PURPA Machines". Rather than designing a cogeneration system to follow the thermal load of an industry or district heating and cooling system, PURPA Machines follow the electric load and are dispatched by the utility without regard to the thermal load of the particular facility served by the QF.

The energy efficiency of systems which are true cogenerators and follow the thermal load producing power as a by product of thermal production usually can achieve overall electric and thermal generating efficiencies of 80-90%. The potential socio-economic benefits of true cogeneration are substantial and come in the form of conservation of energy resources, lower air pollution, lower electricity and thermal energy costs and greater overall levels of economic productivity. However, the benefits of PURPA Machines are confined to the very large profits generated for developers and the institutions which serve as their thermal hosts. Whereas, the costs come in the form of increased rates of utilization of energy resources, increased air pollution, increased electricity costs for most rate payers and decreased levels of economic productivity. The FERC PURPA regulations have succeeded in standing cogeneration on its head and turning its great potential benefits into liabilities.

Large electric capacity/low efficiency cogenerators which produce electricity greatly in excess of the amount required in terms of optimal thermodynamic efficiency, if allowed to proliferate as they have in many states, will ultimately preclude more efficient cogeneration and demand side management projects which might be developed in the future. This lost opportunity to save energy in the present will persist for the 20 to 30 year life of the cogenerator.

Future cogeneration project selection criteria which has as its overriding goal the achievement of the highest levels of energy conversion and utilization efficiency is likely to result in the development of many small cogeneration projects located nearby thermal loads. Such projects can be designed to follow the thermal load and to generate electricity as a by-product of thermal load following. In this way such systems can attain the highest levels of thermodynamic energy efficiency which are possible. A consequence of this strategy is that the ratio of the electric generation efficiency to overall thermal energy efficiency of these systems will be smaller than it would otherwise be if these systems were to be configured to follow the electric load as is the typical PURPA Machine. However, as long as appropriate prime movers such as advanced, high efficiency, natural gas fired diesel engines are employed the actual electric efficiency should not be less than that of a large PURPA machine's electric efficiency and yet the useful thermal energy from the small scale cogenerator will be greatly in excess of that from the PURPA machine.

The economic impact of many small cogeneration projects rather than one or several larger projects would be to distribute the economic benefits of cogeneration to a wider group of producers and consumers; increase the reliability of that part of the electric load which is cogenerated; increase air quality; avoid very large air pollution impacts in areas in which large plants are located; and last but surely not least, significantly increase the efficiency of both energy production and use.

It is high time that the criteria by which cogeneration systems are approved as QFs by FERC are changed to obtain better energy and economic efficiency from future systems. It has been suggested that state public utility commissions take the lead in forging and implementing new criteria since it is highly unlikely that FERC will institute any positive changes in the near future. One option is that states assess a pollution tax based on the degree of pollution a facility contributes to an area. The most efficient and thus least polluting cogenerator would pay the lowest pollution tax and the most polluting system would pay the highest tax.

Another option is for states to grant utilities benefits if some of the power the utility purchased was generated from a less polluting source. The state could give the utility a credit to offset pollution in its own operation. Thus, the utility would have an incentive to purchase power from a highly efficient cogenerator over a marginally efficient one. It might also be possible to incorporate high efficiency cogeneration into least cost electric utility planning. States might also be able to set more stringent standards for granting construction or operating permits for cogenerators to ensure that they do not contribute to but rather alleviate environmental problems. (source: Barney L. Capehart and Lynne C. Capehart; "Efficiency In Industrial Cogeneration: The Regulatory Role", p.23-24, "Public Utilities Fortnightly", March 15, 1990)

It has also been suggested that PURPA be amended to:

-- give QF status to energy efficiency investments;
-- require state regulatory reforms to provide financial incentives for utility energy efficiency investments and to include environmental and public health costs in their resource planning decisions on new or substantially renovated power plants;

-- require both FERC and state utility commissions to include environmental and public health costs in calculations of avoided costs under PURPA;

-- establish a federal tax credit of $0.02 on renewable energy power production to be phased in over a 2 to 10 year period;

-- prohibit taxes on utility rebates for energy efficiency investments by consumers;

-- require FERC to perform least cost analyses (including environmental and public health costs) of all energy efficiency, load management and renewable energy resource alternatives to proposed wholesale power purchases before approving utility purchased power contracts;

-- require utilities to provide open access to their transmission grids at reasonable rates, removing existing barriers to full development of industrial cogeneration and independent renewable energy resources. (source: Union of Concerned Scientists, "Responsible Energy Solutions For America: An Energy Policy Platform")

If PURPA is to be transformed into an agent for positive changes in the form of increased energy efficiency in both the supply and utilization of energy and in the form of increased use of renewable energy sources there ought to be some rational criteria for determining precisely which projects are granted QF status by FERC. Rather than the present formula which encourages low efficiency cogeneration, a new formula or formulas appear to be required which are based, at least in part, on a second law of thermodynamics or exergetic analysis of energy supply and demand systems. A number of methods of calculating second law efficiency have been formulated.

There have been relatively few worthwhile efforts to quantify the exergetic efficiencies of the systems considered in this paper and that task is one which should receive high priority in the near future. Such an effort should seek to quantify the exergetic efficiency of all of the components of the most promising systems reviewed in this report including electricity and thermal energy production, collection, storage, transmission and distribution and utilization systems. This is necessary if we are to determine precisely which system configurations offer the best opportunities for obtaining the greatest improvements in energy efficiency. From such an analysis a more rational and comprehensive energy efficiency standard might emerge which could be incorporated into PURPA and be used by FERC and/or state PUCs to prioritize among a wide variety of types of supply and demand side projects.

Although the development of such a comprehensive formula is beyond the scope of this paper, it is useful to take a brief look at cogeneration efficiency in terms of the second law. The present FERC efficiency formula for cogenerators computes the "overall efficiency" of a cogeneration system. This overall efficiency formula is primarily based on the first law of thermodynamics which states that energy is neither created nor destroyed but rather changed from one form to another, e.g. chemical energy to electricity or heat to electricity, the amount of energy remaining constant. The Second Law of Thermodynamics is that for any given energy flow, the amount of useful work which can be obtained is a function of the temperature difference between input energy and output energy. It also states that all processes involving useful work are irreversible.

The principles of the Second Law of thermodynamics can teach us much with regard to the potential for increasing energy efficiency. Many of the debates on the subject of precisely how much energy efficiency can be increased in order to achieve a substantive reduction in the amount of greenhouse gases emitted have concluded that we can reasonably hope to obtain about a 20 to 30% reduction in energy consumption and CO_2 output. The political and scientific leadership among the industrialized countries which are the leaders in the global effort to establish a coordinated international effort to reduce greenhouse gas emissions, countries such as Germany, Denmark, the Netherlands and Japan as well as most prominent American environmental groups tend to advocate savings in this range.

Although such numbers appear substantial in relation to present levels of energy efficiency and the current energy policies of even the most forward looking nations they are indeed quite conservative goals in light of the potential for increasing energy efficiency when it comes to increasing the efficiency of building heating and cooling energy supply systems. The greatest potential for energy efficiency increases lies not in belt tightening or energy efficiency increases at the point of utilization. Rather, it lies with increasing the efficiency of the supply system. Although cogeneration is an example of an energy conversion system based on second law principles, fuel fired cogeneration systems are only at the beginning of a continuum of increasingly efficient, integrated, complex energy supply systems which cascade energy from one process to the next first converting fossil fuels via cogeneration to electricity and useful heat, collecting heat from renewable sources such as the sun, converting ambient heat to useful heat via engine driven heat pumps, storing solar heat or winter cold from one season to the next and substituting it for fossil fueled heating and cooling systems and employing appropriate temperature, scale and efficiency heating and cooling distribution and end use systems which achieve as close a match as possible between end use and supply temperatures. Such combined, integrated and cascaded energy systems are potentially far more energy efficient than cogeneration as it is currently understood and applied.

The Second Law teaches us that the value of energy is its ability to perform work. The amount of work obtainable from different forms of energy varies according to its quality and temperature. Energy can be said to be comprised of two parts-exergy and anergy. Exergy is that part which can perform useful work , i.e. chemical, mechanical and electrical energy. When energy is transformed into heat, a certain amount of exergy is lost or converted into anergy. The higher the temperature above ambient, the more the thermal energy can be said to have a higher exergy value. Eventually all energy is degraded to heat at ambient temperature. At this point no further work can be performed, all exergy is dissipated and only anergy remains. Exergy is a very valuable commodity. In a rational exergy economy the maximum amount of exergy would be extracted from all energy and that energy would be used only for the highest quality tasks, i.e. conversion to mechanical/electrical energy and/or high temperature heat. Process temperatures would be as close to source temperatures as possible or energy sources matched as closely as possible to desired process temperature. In practice this means that the application should govern the choice of supply temperature, energy source and conversion process.

One of the most important recent efforts to quantify and describe the second law efficiency of a number of energy conversion systems was undertaken by a committee of the World Energy Conference in 1981. The following series of diagrams developed by this committee give examples of typical energy conversion systems in terms of both first and second law efficiencies. (source: World Energy Conference Report By The Joint Ad Hoc Committee On Combined Heat and Power and Heat Pumps, 1981)

The highest exergetic efficiency is obtained by diesel engine driven electric heat pumps (C7) which achieve a first law or energetic efficiency of 94% and a second law or exergetic efficiency of 28%. This is compared with the lowest level efficiency system considered--an oil-fired, heat-only boiler with a first law or energetic efficiency of 65% and a second law or exergetic efficiency of 04%. The drastic difference in second law efficiency between the 2 systems is due to the very high exergetic or electrical energy conversion efficiency of the diesel/heat pump combination vs the heat only boiler which degrades all of the exergy in high quality oil to low temperature heat without any electrical generation. (source: World Energy Conference, "Report By the Joint Ad Hoc Committee on Combined Heat and Power and Heat Pumps", 1981)

In designing a cogeneration system from a second law perspective, the goal should be to cascade energy flows to maximize the amount of useful work extracted, thus making the most use of the availability of the fuel. Although a simple comparison of cogeneration efficiencies is a reasonable starting point for an analysis of the desirability of different cogeneration projects, if this criteria alone is employed, the results will ignore the fact that the end use temperatures of various industrial processes and building heating and cooling requirements have an impact on a cogeneration system's thermodynamic or second law efficiency.

One formula which does incorporate end use temperatures as a factor in computing the second law efficiency of a cogenerator is that which has been suggested by Stecco and Manfrida:

Nex = (We + Du Qu)/X

Where:

Nex = exergetic efficiency (also availability efficiency)

We = work performed

Figure 3. Exergetic Efficiency of a Boiler Plant as a Function of the Use Temperature (Energetic Efficiency η_{en} = 0.65)

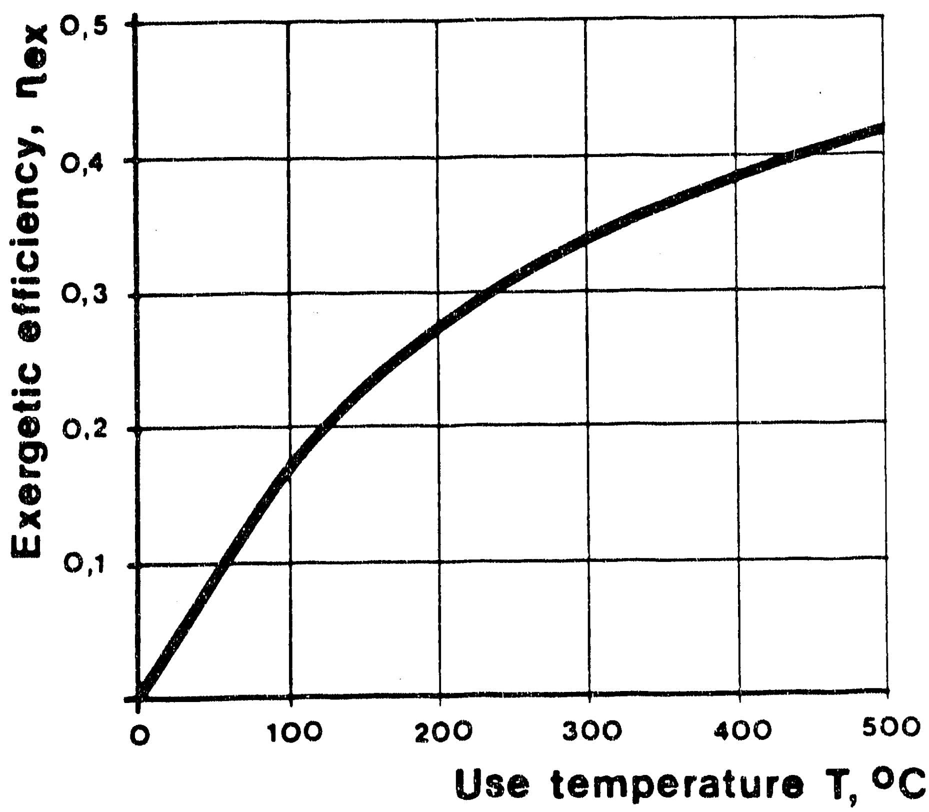


Figure 4. Characteristics of Space Heating Only Systems

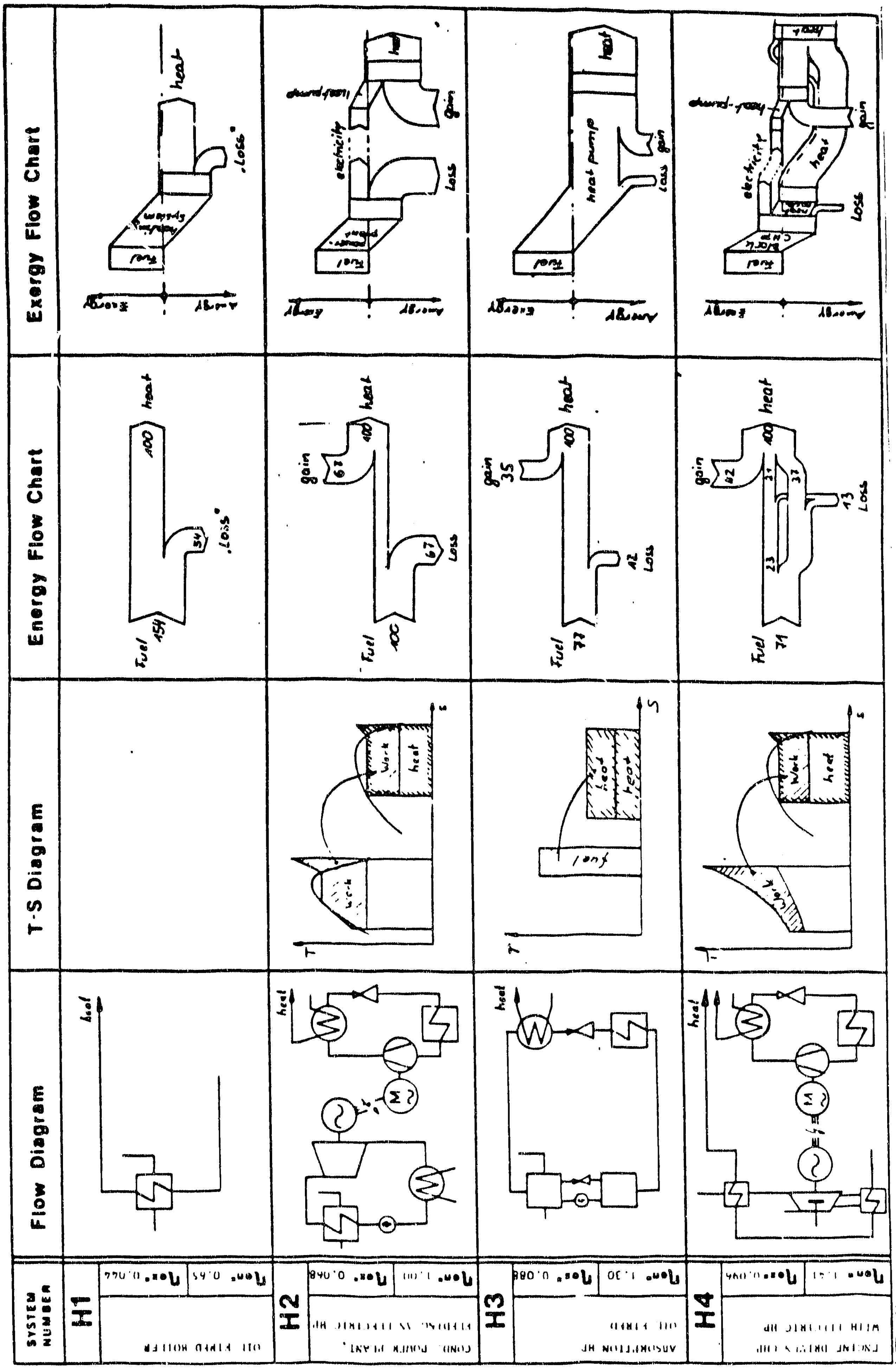


Figure 4, cont'd

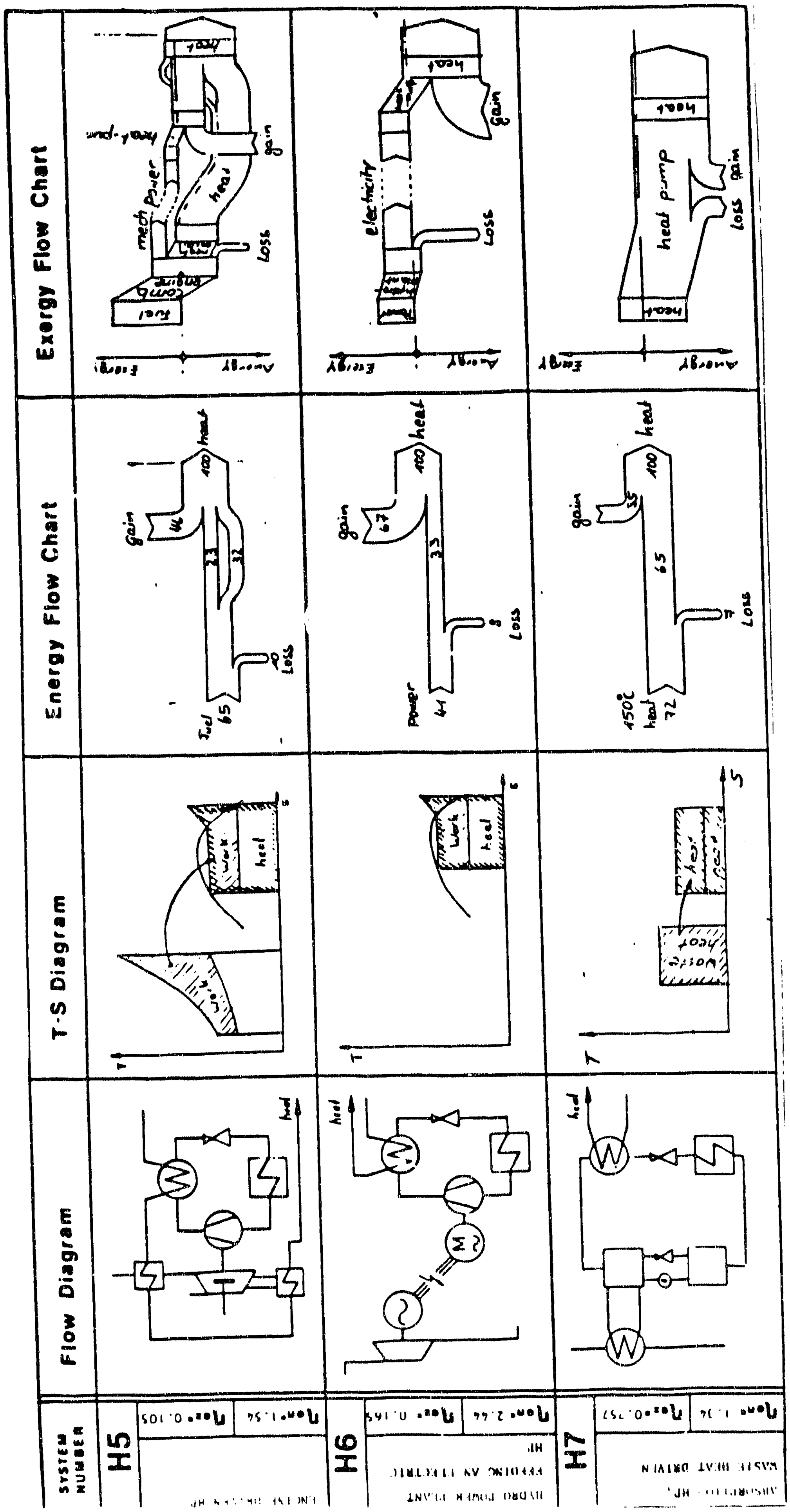


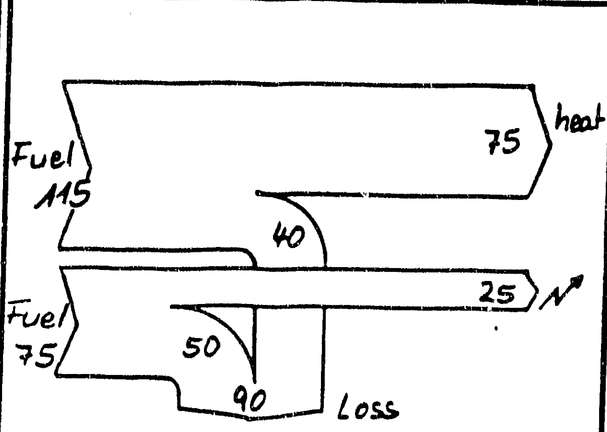
Figure 5. Characteristics of Systems Producing Heat and Power

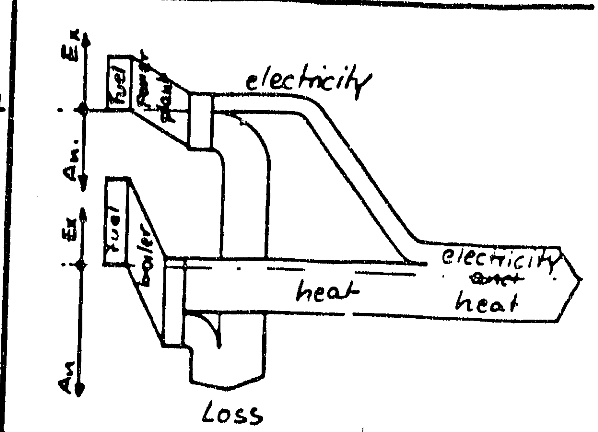
SYSTEM NUMBER	Energy Flow Chart	Exergy Flow Chart

C1

COND. POWER PLANT, PLUS OIL FIRED BOILER

η_{en} = 0.526 η_{ex} = 0.158

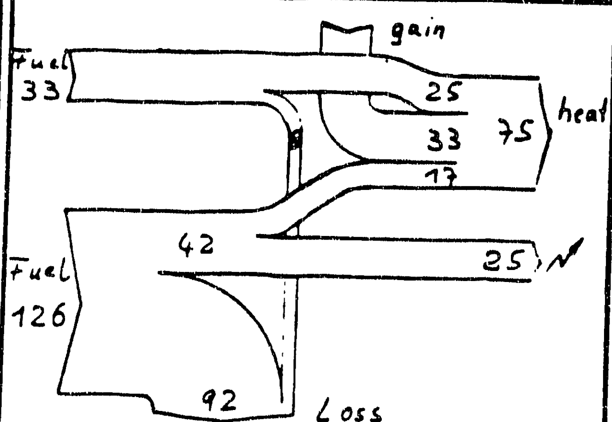


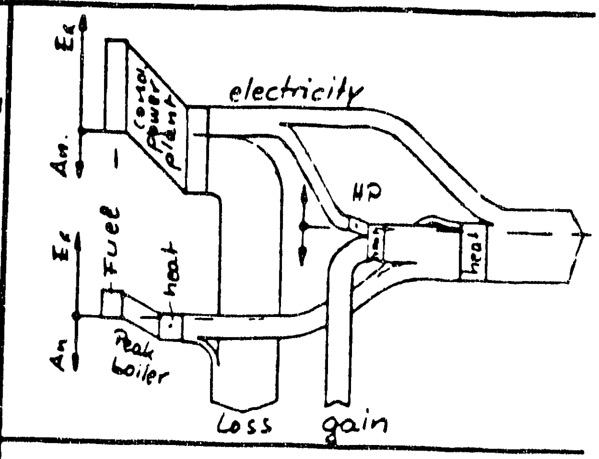


C2

COND. POWER PLANT, ELECTRIC HP WITH OIL FIRED PEAKING BOILER

η_{en} = 0.629 η_{ex} = 0.189

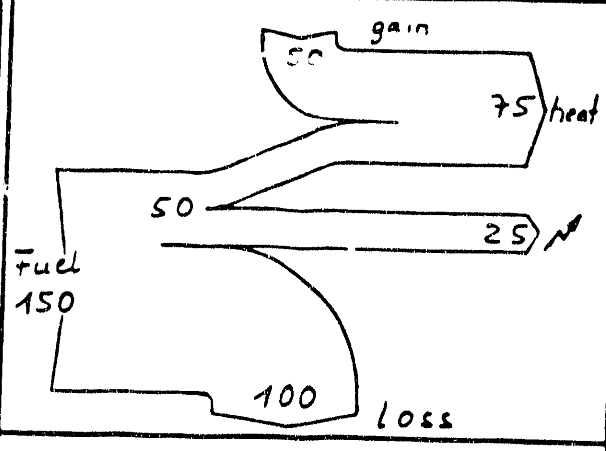


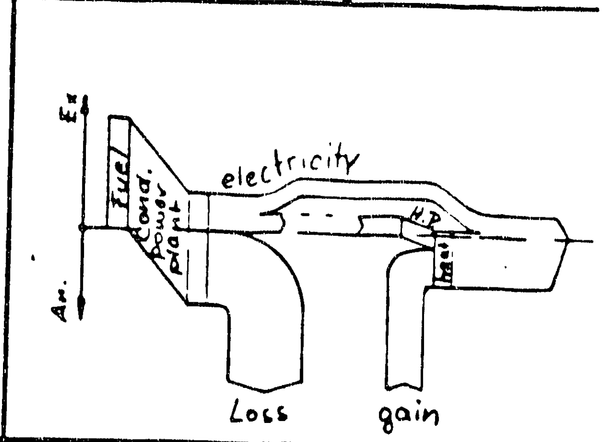


C3

COND. POWER PLANT; ELECTRIC HP

η_{en} = 0.666 η_{ex} = 0.200

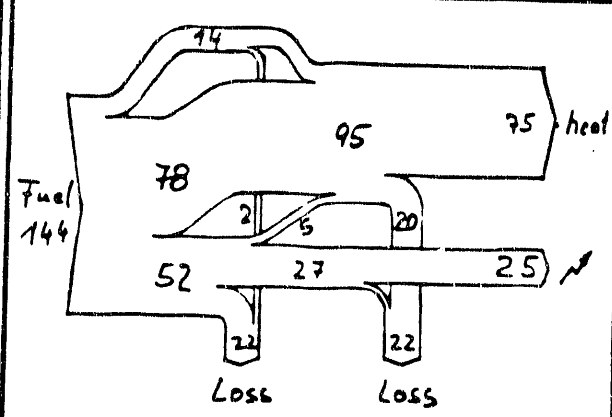


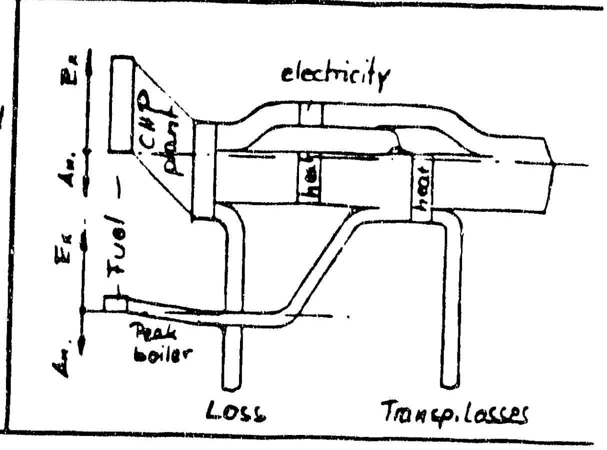


C4

BACKPRESSURE CHP WITH PEAKING BOILER

η_{en} = 0.694 η_{ex} = 0.209



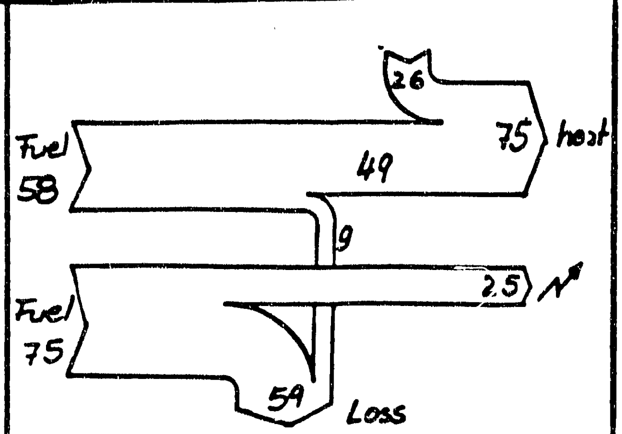


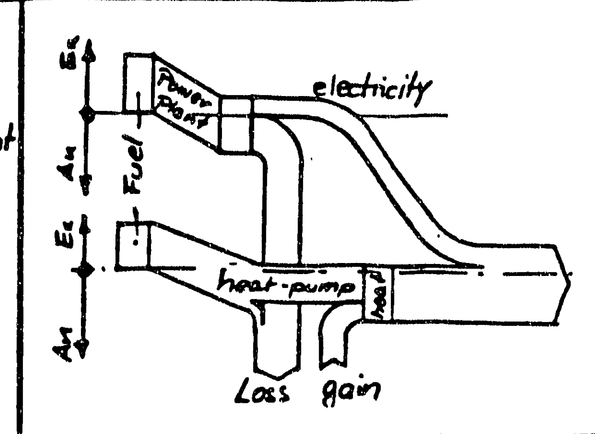
SYSTEM NUMBER | **Energy Flow Chart** | **Exergy Flow Chart**

C5

COND. POWER PLANT AND ABSORPTION HP OIL FIRED

$\eta_{en} = 0.750$ $\eta_{ex} = 0.226$

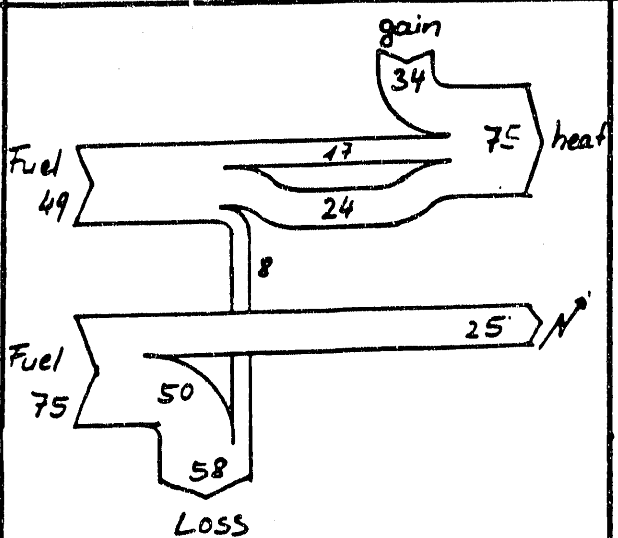


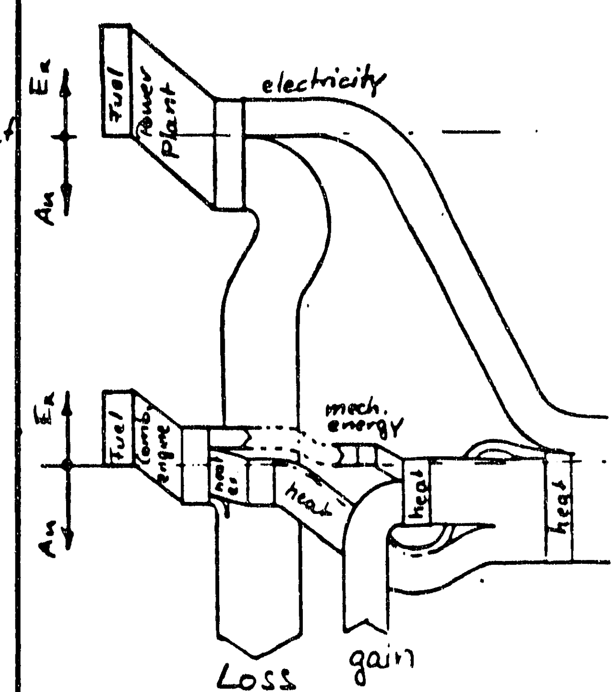


C6

COND. POWER PLANT, ENGINE DRIVEN HP

$\eta_{en} = 0.806$ $\eta_{ex} = 0.243$

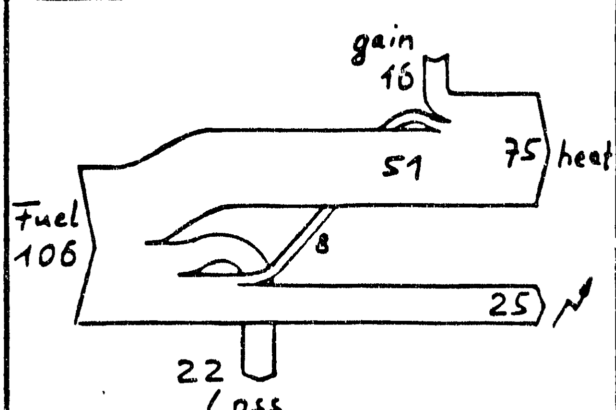




C7

ENGINE DRIVEN CHP ELECTRIC HP

$\eta_{en} = 0.940$ $\eta_{ex} = 0.284$



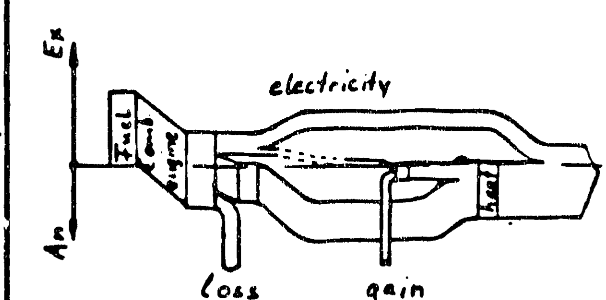
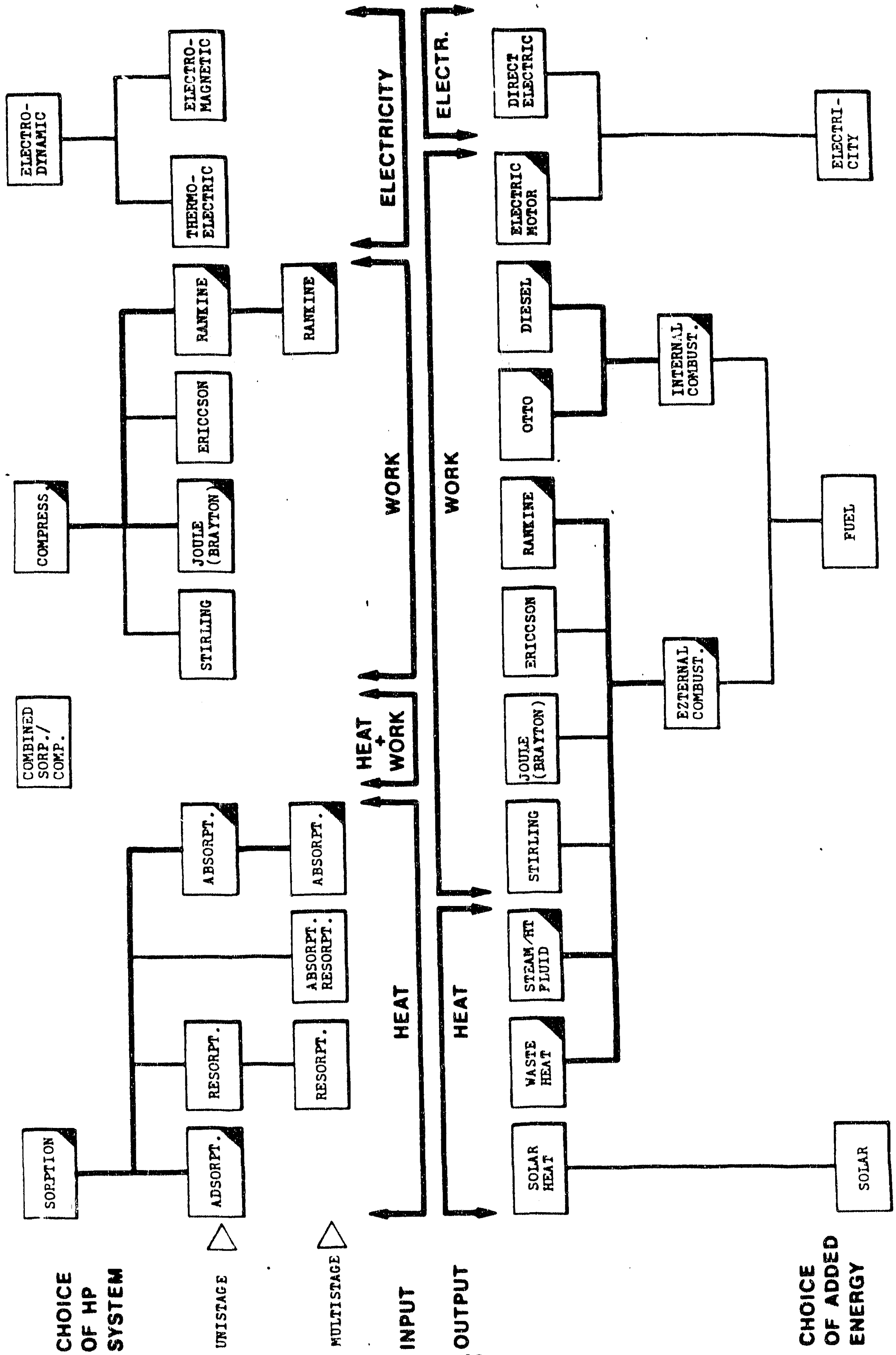


Figure 6. Range of Available Heat Pump / Drive Combinations



Du = Carnot Factor for thermal user (1 - To/Tu)
Qu = Heat Produced
X = Total energy entering the system
To = Outlet temperature
Tu = Equivalent temperature of thermal user

This formula takes into account various qualities of thermal process needs (via the efficiency of the Carnot cycle) rather than taking an arbitrary value for thermal energy as 1/2 that of electricity. (source: S. Stecco and G. Manfrida, "Optimal Choices of Gas Turbines For Cogeneration Applications", Proceedings of the 20th Intersociety Energy Conversion Engineering Conference, August, 1985).

Another interesting approach to develop appropriate criteria fro evaluating cogeneration projects from the viewpoint of their energy efficiency as well as other important criteria have been suggested by the California Energy Commission. The proposed analysis of potential cogeneration systems involves five steps:

1. Development of a data base of existing and technically feasible cogeneration applications. This data base consists of thermal energy requirements for industrial natural gas users.

2. Using a computerized cogeneration design model, develop conceptual cogeneration equipment configurations which would satisfy thermal energy requirements.

3. Analyze the electric generating size, thermodynamic efficiency and investment rate of return for each typical thermal energy user and those cogeneration equipment configurations which meet the thermal energy profiles identified in number 1 above, for both new industrial sites and for existing boilers.

The analysis would include the following:

-- the extent to which each equipment configuration contributes to the conservation of natural gas in the long term;

-- the inherent differences in achievable efficiency levels caused by differences in industrial thermal process energy requirements;

-- the changes in the utility resource mix, differences in demand level from one year to the next;

-- geographic transport of air pollutants from one area to another as a function of the locale where cogeneration projects are sited compared to the locale where existing utility and industrial sources of combustion related pollutants are located.

-- the ability and mechanisms for balancing the financial interests of potential cogenerators and the conservation and environmental concerns of the state.

-- the long range planning implications for fuel use policies resulting from the typically long lives of cogeneration projects.

4. Development of industry and utility specific quantitative criteria for the evaluation of natural gas fired cogeneration projects and the form those criteria take.

5. Establishment of a process through which criteria can be applied in site approval proceedings and be periodically adapted to reflect changes in electricity supplies and resource allocation policies.

Once a variety of potential configurations have been developed for each typical user, there is a need for a method of measuring how "good" a cogeneration proposal is with regard to efficiency. Several potential measurements include:

-- degree of thermal match; how far along the continuum between minimum qualifying facility and a completely thermally matched facility, measured in percent or measured by the relative amount of energy which is disposed of to the atmosphere;

-- actual net savings; the avoided utility gas consumption plus the avoided thermal process gas consumption minus the gas consumption by the cogenerator for the life of the cogeneration facility;

-- electrical to thermal ratio; the electricity output divided by the thermal output;

-- first law efficiency; the ratio between input and output energy not including availability;

-- PURPA type measurements; similar to the current operating and efficiency standards, but at different than current levels.

The California Energy Commission has noted that any measure which would be applied to cogeneration projects must have the following characteristics:

-- the measure must accurately reflect the underlying goal of cogeneration, i.e. to conserve finite natural resources, natural gas;

-- the measure must be easily understandable by regulatory decision makers, potential project proponents and equipment manufacturers and designers;

-- the measure must be readily calculable without the need to develop new extensive or complex analytical tools;

-- the measures must be applicable to the wide range of types of potential applications.

Procedurally, a combination of two different routes was considered by the staff of the California Energy Commission to be useful in analyzing and approving cogeneration project proposals:

-- Compare the efficiency of applications against one another. On a regular basis (6 to 12 months) applications would be evaluated on an efficiency basis measured in terms of thermal match and system wide gas savings. Only the most efficient ones would be found in conformance with the need for power established by the commission.

-- Modify needs test to provide more stringent siting approval tests for gas fired cogeneration projects which fall below an efficiency threshold. Essentially, with a higher efficiency threshold, the burden of proof (that a project would in fact conserve gas in the service area) for an applicant is reduced if the project is above that threshold. In other words, above the threshold the project is presumed to result in savings; below the threshold the applicant will be required to make an affirmative showing redesign of the project or find a service area with a lower threshold.

A combination of these two procedures will be formulated by the staff of the California Energy Commission for implementing the Commission's stated preference for "those cogeneration projects which are significantly; more efficient than the minimum level necessary to qualify under PURPA. (source: California Energy Commission, Assessments Division, Electricity Report Six, Staff Issue Paper, "Natural Gas Fired Cogeneration Efficiency")

Utility Markets For Electricity From Block Scale Cogeneration

One of the most important factors in the penetration of cogeneration into the building energy supply sector of the economy is access to long term contracts from electric utilities for both capacity and energy payments based on avoided costs. Such contracts will guarantee a stream of revenue over the long term which will make for easier and less costly financing and the proliferation of small scale cogeneration throughout a utility's service area. However, there are a number of built-in barriers which must be overcome, especially by small block scale cogeneration systems for them to be able to obtain long term contracts and widespread market penetration.

Currently, the market for independently produced power procured by electric utilities via bidding processes is booming. In 1990 the following market characteristics collected by the firm of Hagler/Bailly for IPP's and cogeneration QF's pertained:

Capacity on Line:	29,239 MW
Under Construction:	43,433 MW
Cogeneration Capacity:	59% of active capacity
Natural Gas:	Fuel of Choice
IPP Capacity:	9% or 8,300 MW of active capacity

Hagler Bailly noted that a regional market shift had taken place from California and Texas to New Jersey, New York, California, Virginia and Massachusetts. IPP capacity developments in these states accounted for 52% of capacity under development nationwide. (source: 4th Edition RCG Hagler, Bailly, "Profile of the Independent Power Market: Status and Trends")

A number of forecasts have indicated that IPPs could experience very high levels of growth during the 1990s of up to 12% per year. This would give IPPs an installed capacity of 81,000 MW by 2000. Between 45 and 50 IPP projects that do not quality under PURPA are likely to be developed in the 1990's adding about 11,500 MW per year. Typically, the electric utility bidding process has served as the basis for selecting IPP projects. IPP projects typically do not qualify under PURPA and therefore cannot gain access to avoided costs and so must submit bids for power supply contracts which are significantly under a utility's "avoided cost" in order to be competitive. The bidding process which began in the mid-1980's is gaining in popularity as a means by which utilities can gain access to long term cost effective supplies of electricity. Between 1986 and 1990 14 utilities initiated 26 power bidding processes. In the 1990's it has been forecast that 45 to 50 utilities will initiate 150 competitions for power supply contracts 80% of which will be for new capacity to be located along the Atlantic Coast.

In order for block scale cogeneration to achieve widespread market penetration it will be necessary to configure such projects so that they are acceptable to electric utilities and thereby become eligible to become recipients of long term utility power supply contracts and the revenues and other benefits which flow therefrom. One of the ways in which this might be accomplished is to combine block scale cogeneration and DHC with other approaches such as electric and thermal demand side management (DSM), electric and thermal end use efficiency improvements and the integration of building energy management systems (EMS) with cogenerator electronic controls and utility dispatching controls.

By combining these elements for either one group or several groups of buildings into a single package, a private cogeneration developer could submit a bid for a long term utility electricity supply contract coupled with DSM and energy efficiency improvements which would have as its goal the development of a projects which could demonstrate long term cost effectiveness and profitability. The key to such profitability would be access to the highest electric rates paid by the utility for electricity supply capacity and energy. Such access could be ensured if a project's load duration curve seen by the utility was as close to the utility's optimum as possible. This could be achieved through the combination of cogeneration electricity supply and electric load shifting to the thermal source, i.e. heat activated cooling and district cooling, thermal storage, DSM and EMS for single buildings, a group of buildings or several groups of buildings distributed around a utility service area.

The high efficiency supply, increased end use efficiency, DSM and EMS measures could then be submitted as a package in a single application to FERC for QF status and access to utility capacity and energy payments based on its avoided cost or submitted to the utility in its bidding process for supply capacity, DSM projects and efficiency improvements. Obtaining a long term contract for utility payments for both generating capacity and energy via FERC QF status or via the utility bidding process would enable a project to demonstrate to a financier that it has a guaranteed stream of revenue from several sources (electric energy and capacity credits and thermal sales). This would go a long way toward reducing the perception of high risk which cogeneration projects currently engender and could facilitate a much lower cost of capital for such projects which would, in turn, increase profitability and increase the number of potentially viable projects.

One research need in this area of assembling packages of cogeneration supply, efficiency improvement and DSM measures is in determining optimal combinations of each of these elements so as to generate electric load duration curves for the utility which are as close to optimum as possible as well as to generate the highest levels of profitability. The generation of such optimum load duration curves in relatively large aggregates of small projects could enable these supply/demand packages to compete successfully with independent power producers in utility bidding processes for long term contracts for supply and demand reduction via increased end use efficiency and DSM. Optimally profitable packages of measures might be submitted as applications to FERC for QF status.

Rather than perform the tasks of selecting a number of supply and demand reduction technologies for prototypical buildings and performing the analysis in the abstract, a more direct and effective approach might be to perform the analysis for a real case with real potential for implementation. The first step in this process would be to identify those utilities which will be requesting proposals for capacity and energy conservation in the next few years and begin discussions with at least one electric utility. The goal would be to work with a utility to determine its optimal load duration curve and also determine what it might be willing to pay for a project if through a combination of supply and demand side measures it generated a curve very close to the utility's optimum.

The next step would be to identify the types of buildings and supply demand measures which might be combined to produce the desired project in terms of both scale and load duration curve. The next step would be to work with an energy services company (esco) and cogeneration systems manufacturer or developer to identify an actual group of buildings and work with them to design a project which is as close to the utility's optimum load curve as possible in addition to being as profitable as possible. The resulting design should then be submitted as a bid to the utility in the course of its normal bidding process. Since many of the utilities in the northeast are expected to issue RFPs for both supply and demand reduction over the next few years and a number of escos and cogeneration manufacturers can be identified who would readily participate in such an innovative project there should be no lack of options.

Electric utilities may be attracted to the approach of combining supply and demand measures in a single bid since in their usual selection process involving both supply and demand side measures they must go through a lengthy process to determine an optimal mix of projects. If the utility was confronted with a bid which closely matched its optimum criteria for both demand and supply side measures it might pay a premium for that project. If this approach were successful and profitable for both the utility and the esco then it might be expected that other private developers would seek to replicate that success in their own projects.

In this way advanced cogeneration technologies in combination with other advanced demand side measures could be propelled into the marketplace via the profit motive. The best role for the DOE in such a project would be to organize it and provide the technical assistance necessary to formulate the first several project designs. If this approach were successful it would become market driven and that factor would obviate the need to undertake exhaustive surveys of the market potential of this approach in numerous regions of the U.S.

The DOE could undertake numerous different types of such projects which would focus on groupings of different types of buildings, combinations of supply and demand technologies, project scales and regions of the U.S. If a variety of successful approaches could be identified it could stimulate the development of a diverse marketplace for both cogeneration, demand side management and building energy conservation measures.

New Institutional Arrangements To Spur the Development of Cogeneration In the Buildings Sector

With the advent of numerous environmental and economic constraints on future energy supply strategies it is becoming increasingly apparent that the institutional structures which have governed energy supply to date will have to change. Utilities which heretofore have conceived of their business as being confined to the delivery of a single commodity such as electricity or natural gas and have viewed the other utility as a competitor may soon be confronted with crises and opportunities which compel cooperation and diversification. Many electric utilities have already accepted the reality of incorporating energy conservation, DSM and supply via IPPs and QFs into their rate base and generation mix. The next step may well be to cooperate with gas utilities in the development of natural gas fired cogeneration and DHC projects which are mutually beneficial.

Markets which are now viewed as markets for electricity or natural gas need to begin to be perceived as markets for thermal energy if cogeneration, DHC and related renewable systems are ever to make the huge efficiency impact of which they are in theory capable.

Of the approximately 90 quad of energy consumed by the U.S. every year approximately 22.7 quad of primary energy is used to supply low grade heat for buildings and industry. This includes the following: water heating: 3.7 quad; space heating: 12.0 quad; space cooling: 4.6 quad; and low pressure steam: 2.4 quad. In theory the bulk of this market could be supplied from cogeneration and renewable energy via DHC. However, in order for even a fraction of this market potential to be realized electric and gas utilities will have to drop their current competitive antagonism and technical parochialism in favor of cooperative innovation for the sake of increased energy efficiency, environmental quality and economic productivity.

As a result of a number of environmental constraints such as the Clean Air Act Amendments of 1990, the Montreal Protocol and Amendments governing CFC emissions and the impending International Convention on Climate Change which may call for a 20% cut back in greenhouse gas emissions by 2005, electric utilities will be under considerable pressure to achieve significant reductions in emissions. Traditional methods of attaining such goals such as the use of scrubbers and fuel switching (to natural gas) will achieve limited application due to high costs and cost and supply constraints over the long term. Ultimately, utilities may be forced by economic reality to turn to innovative, high efficiency supply technologies such as gas fired cogeneration and DHC to achieve the environmental improvements necessary.

Advanced forms of cogeneration which attain very high levels of electrical generating efficiency and utilize advanced thermally activated cooling systems enable the utility not only to increase its efficiency of supply but also to reduce peak demands. If sufficient amounts of high efficiency, small scale cogeneration, thermal cooling and DHC were developed in an electric utility's service territory the large gas fired peaking plants which currently supply building air conditioning at very low efficiency could be taken out of service with the result that the overall efficiency of the electricity supply system would improve substantially and emissions would thereby be reduced. The process of incorporating new high efficiency sources of supply such as gas fired cogeneration could be geared to removing the most polluting and/or inefficient plants from operation thereby achieving a great improvement in efficiency and decrease in air pollution.

Gas utilities also have a number of very good reasons to be interested in advanced cogeneration and DHC systems as a new line of business. The infrastructure of most natural gas distribution utilities is almost fully amortized. Demand for gas has actually shrunk over the last decade and is growing only incrementally at present. Over the longer term, the outlook is not very good due to the increasing cost of gas obtained further and further afield as domestic supplies become more expensive and scarce. One way in which natural gas utilities can grow over both the near and long term is to develop advanced, natural gas fired cogeneration, thermally activated cooling and DHC technologies. If gas utilities have access to such technologies then it would be a simple matter for them to calculate what it would mean for their profitability if such systems were developed in their service territories. It has long been the dream of gas utilities to develop markets which will utilize gas in the summertime when only 10% of their distribution capacity is used.

There are numerous benefits which will result from a cooperative approach to gas fired cogeneration and which need to be apportioned between electric and gas utilities. Either the electric or the gas utility could finance the development of such systems and include their capital costs in its rate base. Electric power could be sold to the electric utility. The gas utility's summer excess capacity would get greater utilization whereas the electric utility's high cost peak electricity supply problems could be significantly diminished. No matter how the benefits are apportioned, the ultimate winner would be the consumer since all consumers would benefit from lower cost electric, heating and cooling services. Eventually, the gas utility could be transformed into a DHC utility and the electric utility could derive a significant amount of its generating capacity from cogeneration even as the thermal output from cogeneration reduces its peak generating needs allowing it to shut down the most inefficient of its peak generating plants. When natural gas becomes too expensive to utilize in cogeneration or when new very high efficiency, renewably based DHC technologies become commercially available, the new DHC utility would be ideally positioned to merely plug these new thermal sources into its DHC system. Gas utilities appear to have all of the technical and managerial expertise required to become involved in the cogeneration and DHC business.

Many utilities, particularly those located in the northeast have electric and gas utilities located under the same corporate umbrella. There is a natural symbiosis between these two types of utilities since one, the electric utility, has serious summer peak power demand and supply constraints, while the other has substantial amounts of underutilized distribution capacity in the summer. It seems only natural that these two divisions of the same companies should become involved as partners in a jointly owned utility providing DHC services via natural gas fired cogeneration. The first step in the process of encouraging such cooperation is to determine why it has not yet occurred. The fact that this has not occurred to date indicates that each of these entities may either not appreciate the extent of the benefits which could accrue to each or may have other reasons for not cooperating such as the regulations of public utility commissions which may prefer competition rather than cooperation as a means of keeping consumer costs as low as possible. All of the entities involved need to be queried as to the opportunities and barriers to such cooperation.

It is also apparent that the development of a joint venture in the field of cogeneration and DHC will require new accounting methods for apportioning costs and benefits between gas and electric utilities. It may also be necessary to develop new methodologies for planning the expansion of the integrated, cogeneration and DHC phase of their businesses which results in the greatest overall economic, environmental and energy efficiency benefits to each utility and to all consumers.

The technological prerequisites for integrated gas and electric utilities to become involved with owning or cooperating fully with gas fired cogeneration and DHC system developers are: the development of less costly, more reliable, more efficient and less polluting small to intermediate scale natural gas fired cogeneration systems; the development of high efficiency low cost technologies for converting cogenerated waste heat into air conditioning; and electronic controls for integrating cogeneration systems and a number of demand side management and electricity conservation measures. In addition to the development of hardware there are also a number of analytical tasks which need to be undertaken such as new methods for distributing the costs and benefits of gas fired cogeneration and DHC among the gas and electric utilities and private developers; the development of cogeneration planning methodologies; and the undertaking of at least one project to demonstrate the above technologies and analytical methodologies to an integrated electric and gas utility.

In areas where gas and electric utilities are at a competitive impasse and cooperation is not possible other institutional mechanisms can be used to spur the development of cogeneration and DHC. In such a case a municipality could establish a mechanism for financing and implementing high efficiency cogeneration and DHC projects along with a variety of other demand side measures such as DSM, EMS and electric and thermal energy conservation. Since electric and gas utilities have not been granted franchises over any of these activities and all, including DHC, are unregulated in most places, there are no legal impediments for the establishment of what might be called a municipal energy conservation and thermal utility. Such a utility could merely provide financing to private projects which might initially focus on the public sector's own buildings or the municipal utility could build its own capability to finance, develop own and operate projects. The latter option may be impractical since fiscal constraints may preclude it. However, if low cost finance via the municipal bond markets were to be accessed and make available to private developers for cogeneration as well as energy conservation projects it might stimulate the markets for such activities within a municipality to a considerable extent and result in numerous projects which are not only profitable but which also have other desirable economic, environmental and energy benefits which accrue to the municipality or its citizenry. In the aggregate the benefits from such projects, as long as they are carefully designed and selected might be far greater than the cost of the financing to the municipality. In fact, the cost of the financing as well as any administrative costs associated with the establishment of the municipal utility could be allocated to the projects which result from it. Relatively small amounts of public funds from municipal bonds might also be used to establish revolving loan funds to finance energy service companies to perform the tasks of development, ownership and operation of any projects so financed.

Changes are not only necessary on the part of government and utilities; the private sector in the form of energy services companies or "escos" will have to undergo significant changes if they are to be competitive in the future. The escos of the future will have to go far beyond specializing in demand side management and end use energy conservation alone. Escos will have to be able to put together sophisticated packages of both demand and supply side systems which can attain QF status as well as compete with independent power producers in utility bidding processes. The esco of the future will have to be able to combine a wide variety of engineering, finance, operation and management expertise in DSM, energy conservation and cogeneration and DHC. Escos will also have to be able to work closely and effectively with gas and electric utilities and municipalities if they are to carve out a niche in the increasingly competitive energy markets of the 1990's. (source: Ambrose Spencer, personal communication, 6/91)

Bibliography

Task 1, Part 2:

Institutional and Regulatory Strategies
For Implementing Cogeneration and DHC In The U.S.

Aalto, Pentti J., "Written Comments Of Pentti J. Aalto (*) on Implementation of PURPA and Development of Cogeneration and Small Power Production Facilities", Before the Federal Energy Commission, 28 April 1987. Docket No. RM87-12-000: Cogeneration; Small Power Production. (*: PEQUOD Associates, 129 South St., Boston, MA 02111 (617) 542-8567).

Anson, Orris, "Preliminary Design of a 15 MW Solar Turbine Combined Cycle System For Georgetown University", District of Columbia Public Service Commission, Case, 888, 10/91 (Solar Turbines, San Diego, CA).

"Bidding For Conservation and Power: Trend For the Future?", Conference Proceedings, sponsored by Xenergy, October 24-25, 1988, Boston, Mass.

California Energy Commission, "Chemically Recuperated Gas Turbine", Draft Staff Report P500-90-001, January, 1990.

Capehart, Barney L. and Lynne C. Capehart, "Efficiency In Industrial Cogeneration: The Regulatory Role", "Public Utilities Fortnightly", March 15, 1990.

Capehart, Lynne C. and Barney L. Capehart, "Efficiency Trends For Industrial Cogeneration", "Public Utilities Fortnightly", April 1, 1991.

Congress of the United States, Subcommittee on Energy and Power, "H.R. 776: Title I: Energy Efficiency", Proposed Amendments to the Public Utilities Regulatory Policies Act (PURPA)".

Gleason, Thomas C. J., "Direct Testimony of Thomas C.J. Gleason On Behalf of the Citizens Coalition In Direct Case No. 888 Before the Public Service Commission of the District of Columbia", 10/10/91.

Janes, Jack, "A P,G&E Plan for Replacement of Aging Fossil Generation", California Energy Commission Memorandum, Sacramento, CA, July 1, 1991,

Lennon, Mark and David Myers, "Net Energy Use Impacts of PURPA Implementation", "Public Utilities Fortnightly", May 12, 1988.

Second Law of Thermodynamics--Papers, Reports, Books and Conference Proceedings

Ahern, John F., "The Exergy Method of Energy System Analysis", John Wiley & Sons, 1980

Ayers, Robert U. and Indira Nair, "Thermodynamics and Economics", Physics Today", November, 1984.

Ball, Ben, "Energy Aftermath", Ben Ball & Associates, Cambridge, MA.

Camel, Ali Bluent and Ahmad Ghamarian, "Second Law (Exergy) Analysis of Industrial Processes", Office of Energy Programs, George Washington University, Washington, D.C. 1981.

Gaggioli, R.A., W. Ling and J.R. Too, "Second Law Analysis Of A Total Energy Plant", ASME Symposium, Vol AES/1, 1985.

Gallo, W.L.R. and L.F. Milanez, "Choice Of A Reference State For Exergetic Analysis", "Energy", Vol 15, No. 2, pp 113-121, Pergamon Press, 1990.

El-Sayed, Y.M. and R.A. Gagglioli, "A Critical Review of Second Law Costing Methods-1: Background and Algebraic Procedures", "Journal of Energy Resources Technology", March, 1989, Vol. 111/1

Karakas, Ahmet, Nilufer Egrican and Seyhan Uygur, "Second-Law Analysis of Solar Absorption-Cooling Cycles Using Lithium Bromide/Water and Ammonia/Water As Working Fluids", "Applied Energy", Vol 37, pp. 169-187, Elsevier Science Publishers Ltd. Great Britian, 1990.

"Report By The Joint Ad Hoc Committee on Combined Heat and Power and Heat Pumps", 11th World Energy Conference, Conference Proceedings, pp. 359-391, London, U.K., 1981.

Soma, John*, "Exergy Transfer: A New Field of Energy Endeavor", "Energy Engineering", Association of Energy Engineers, Atlanta, GA.
*:Energy Engineering Management Consultant, Brooklyn, New York.

Soma, John*, "Exergy Analysis Elucidates Heat Pump Efficiency" "Energy Engineering", Association of Energy Engineers, Atlanta, GA.
*: Consulting Energy Engineer, Brooklyn, N.Y.

Soma, John, "Application of the Principles of Hamilton and Fermat to Energy System Productivity", "Energy Engineering", Association of Energy Engineers, Atlanta, GA.

Soma, John, "An Initial Iteration of a Boiler Wor. Efficiency Test Code", "Energy Engineering", Association of Energy Engineers, Atlanta, GA.

Spencer, Ambrose, Personal Communications 1990-1991 and various working papers of the New England Energy Task Force: Second Law Work Group, 1990-1991.
von Cube, Dr. Hans Ludwig and Prof. Fritz Steimle, "Heat Pump Technology", Chapter 3: "Thermodynamic Principles", Butterworths, London, U.K.

TASK 1, PART 3

Advanced Block Scale Cogeneration and DHC: Technology R&D Issues

Table of Contents

Electronic Controls For The Operation and Dispatch of Block Scale Cogeneration

The complexity of achieving a high degree of control over cogeneration systems which integrate a variety of demand side management and electricity conservation measures along with supply from cogeneration and DHC which must be dispatched by the electric utility in order to gain access to the maximum amount of revenues for capacity as well as energy generated will all require the use of sophisticated, highly integrated and remotely controlled electronic monitoring and operating systems. The technology for the design of such systems exists but has yet to be assembled for the precise tasks indicated. This should not present major problems. However, the development of software which has the capability of simultaneously undertaking load shedding, electricity and/or thermal energy generation and supply functions as well as responding instantaneously to the electric utility's demand for available capacity will be a complex task requiring the integration and coordination of numerous systems which hitherto have operated for the most part in isolation. Weather, building energy demand patterns, utility power supply requirements and numerous other factors will have to be able to be predicted. Sufficient slack will have to be built into the cogneration supply system in the form of thermal storage at the point of end use as well as at the cogenerator to ensure that the cogenerator can rapidly switch from operating in a cogeneration mode to an electric power generation mode. Complexity will increase as numerous such projects are developed by escos under contract to supply the utility with power as well as their thermal customers with heating and cooling supplies. Numerous supply and demand management systems will have to be coordinated and controlled remotely.

In addition to thermal storage two other important technological developments which will give such projects the operational flexibility and responsiveness they require are organic Rankine bottoming cycle turbines and turbocharging of gas fired diesel engine cogeneration systems. With these components along with optimally positioned thermal storage of both heat and cold, a cogenerator could suddenly curtail its thermal supply functions and significantly increase its output of electric power in response to electric utility requirements without jeopardizing its thermal supply responsibilities. Since the reliability of small cogeneration installations will also be an important factor for the electric utility it will be advisable to install a number of individual relatively small units in a cogeneration installation rather than a single large unit. The use of numerous small units will also increase system efficiency since individual units can be shut off when loads drop without compromising the efficiency of the system.

The flexibility afforded by these technologies could give block scale cogeneration systems a number of advantages including placement near the top of a utility's merit order thereby giving the cogenerator more operating time as an electrical generation source; access to high rates for capacity availability as well as for energy generated in the form of electricity. When such systems are combined with electricity efficiency increases and DSM capability which can also be sold to the utility in much the same way as is cogeneration capacity, then the private esco which would likely serve as the developer, owner and operator of this system would gain access to numerous revenue streams and many different ways in which capital and energy can be saved.

If numerous such projects were developed there would be a substantial impact on the utility. Expensive and inefficient spinning reserve and peak power capacity could be substantially reduced. As a result of a large number of dispersed high efficiency cogenerators throughout a utility service area, transmission and distribution system losses and costs would be reduced. The oldest and most inefficient and most polluting power plants and building boilers could be replaced by new, very high efficiency, low emission cogeneration systems. Inefficient chillers which currently use CFCs could be replaced with cogeneration systems driving ammonia chillers and heat activated chilling systems. Increasingly, renewable energy sources of heating, cooling and electric power could be incorporated into the mix of demand and supply technologies. It is at least technically possible that in the future electric utilities would come to be almost wholly powered by small to intermediate scale cogeneration and renewable energy sources. However, in order for this outcome to materialize a very different strategy for system wide control and pricing would have to be adopted.

Interactive Controls And Spot Pricing of Electricity

One of the reasons why utilities have historically opted for ever larger power plants was the need for centralized control. However, the advent of the microprocessor and the subsequent revolution in computing power and cost which it induced can now facilitate the efficient, economic, reliable and precise control and optimal integration of hundreds or even thousands of small plants as well as thousands of DSM systems. A strategy for controlling and pricing of power which has been proposed for managing the complex interactions of such a system has been developed which is called homeostatic or interactive load control. This proposed control strategy incorporates the spot pricing of electric power for both independent producers and consumers.

The mechanism for controlling the new, highly complex system is the spot price of electricity which is the same for both consumers and producers. The thousands of small producers and consumers decide to produce or consumer electricity based on electronic pricing signals sent out by the utility which is based on anticipated loads and the anticipated cost of power to supply a load of a given magnitude at a particular time. The thousands of small producers and consumers make their own decisions whether to generate or use electricity based on pricing signals and are not dispatched centrally. Pricing signals can be electronically communicated in intervals of 5, 20 or 60 minutes. At any given interval producers can decide to generate, remain idle or generate in varying proportions of electric and thermal energy.

Similarly, consumers can program their EMS or DSM systems to allow certain appliances to utilize power at a certain price or to stop utilizing it at a certain price.

Interactive controls based on market mechanisms will make it possible to integrate numerous sources of cogenerated power which to a certain degree is heating and cooling load dependent as well as numerous renewable sources. Under current centralized control and large scale centralized power production strategies it is very difficult for utilities to efficiently include large amounts of widely fluctuating power output from renewable sources such as photovoltaics and wind. Without such controls if wind speed suddenly increases or clouds disperse allowing direct sunlight to energize solar thermal electric or photovoltaic power plants, these services will suddenly increase their output of electricity and the utility will be overwhelmed with power it cannot efficiently employ since it cannot just suddenly turn on or off large centralized fossil fuel power stations without huge efficiency and economic losses as well as potential damage to the system.

With interactive controls, as the output from renewables and/or cogenerated power rises, the spot price drops and consumers begin to use more power at the lower price. Thus, there is no mismatch between supply and demand but rather, a regulation of supply and demand by the proverbial unseen hand of the free market. Under such an interactive mode of operation, the electric utility would maintain and rent out the electrical grid to thousands of dispersed small power producers, maintain the electronic controls of both producers and consumers, serve as an auctioneer of power and even out discontinuities between supply and demand by maintaining a relatively small amount of spinning reserve which would produce power in the event that demand exceeded supply. The amount of spinning reserve would, of course, be much less under an interactive control and spot pricing regime than under the former centralized system, of power generation and control. Moreover, the need to maintain huge amounts of reserve capacity (most utilities insist on a 20% reserve margin) with all of the attendant costs would also be unnecessary.

Similarly, the need to undertake expensive long range planning 15 to 20 years into the future would no longer be necessary since the time required to bring new capacity on line would not be the 5 to 10 years required to plan, design and build a major 500 to 1,000 MW power plant but rather would be on the order of the several months to several years required to install mass produced small to intermediate scale cogeneration and renewable energy sources of power and thermal energy which range in size from several 10's of kw to several 10's of MW.

The long range planning which would be necessary under the new system would be of a very different nature. Ideally, it would consist of the R&D in power and thermal energy production systems which are characterized by their increasing energy efficiency and economy with the participation of small power developers as well as consumers. When the new systems are commercialized they would presumably have certain economic advantages over existing systems. Private developers would invest in and install these systems to compete with higher cost, less efficient or less environmentally desirable producers, eventually forcing such producers out of the marketplace. Thus, the utility could take on the role of ensuring that the energy supply system evolved increasingly over time toward ever higher levels of energy efficiency, environmental compatibility and cost effectiveness.

The market penetration of block scale cogeneration systems is likely to be greatest under a system of interactive controls and spot pricing of power. It will be important for the DOE to investigate precisely how such control and pricing systems can be used to encourage maximum efficiency and economy. The role of small scale cogeneration in such a system needs to be analyzed and ways in which to move the present system toward the interactive model need to be explored. The primary source of economic and technical information on interactive or homeostatic controls is the MIT Energy Laboratory.

Cogeneration and DHC: Issues of Scale

There are a number of issues related to the optimal size of urban cogeneration systems. Most European district heating systems can be described as large scale since they usually provide services for entire towns, cities and in some cases entire urban regions. Many of these systems are highly efficient and profitable. However, when attempts were made to develop similar systems in the U.S. over the last 2 decades they invariably met with failure.

In its study for the DOE titled "DHC Market Potential and Penetration Methodology" (1986) Brookhaven National Laboratory uncovered several fatal flaws in the assumption that bigger DHC is better DHC. The BNL study showed that the large up front capital costs for utility power plant cogeneration conversion and long distance thermal transmission capacity impose prohibitive costs at the outset of a DHC development project which keep the DHC system in the red for a long period of time. This factor makes it extremely difficult to finance large DHC systems. In addition, the extreme institutional and political complexity of assembling thousands of users into a coherent customer base when the DHC utility is taking many customers away from electricity and gas utilities makes the development of large scale cogeneration and DHC systems very problematic and practically impossible. Ultimately, the reason for the lack of success of this large scale model is that exhibits a rather extreme diseconomy of scale.

Western European district heating systems have numerous institutional and financial advantages over their U.S. counterparts which facilitate the development of large scale systems. Nonetheless, most of these systems have developed organically by building up loads incrementally using mobile boilers. Only after a large thermal load has been assembled is that load connected to a large, efficient cogeneration system.

The BNL study also revealed that a prerequisite for DHC development is an inexpensive source of thermal energy. The one technology which was identified by BNL which satisfied concerns about both scale and heat cost was diesel engine cogeneration. These systems can be economical and efficient in very small to intermediate sizes (from 50 kw up to 10 MW) and thus can dispense with the large costs of a thermal transmission system as well as the extreme institutional complexity of large systems. Moreover, their production of electricity as well as heat ensures a substantial revenue stream from utility electricity sales which, in effect, makes the thermal energy produced relatively low cost. Moreover, the construction times for these systems is calculated in months not decades.

The most recent converts to small to intermediate scale cogeneration using diesel engines have been those very countries which have relied most heavily on the large scale cogeneration and district heating model. In recent years, Western European district heating utilities have resorted to the use of mobile cogenerators rather than boilers to build up the satellite loads of their district heating systems. Increasingly, district heating utilities are finding that it makes sense in terms of both energy efficiency and economy to develop small non-interconnected district heating systems served by block scale cogeneration systems using gas or oil fired diesel engines of several hundred kilowatts up to several megawatts. This is particularly true in Germany, the Netherlands and Denmark. Usually these systems are several 100 kw to several MW in scale and there are a number of modules in each installation. Thus, the thermal distribution systems employed by the block scale cogenerators are quite small linking a few blocks, several small neighborhoods or serving a small village or town.

Several near term technological and market trends both in Europe and the U.S. appear to have the potential to reinforce these developments. It is clear that very small scale cogeneration (as small as 50kw) have the potential to achieve electrical conversion efficiencies of 45% or more given improvements in engine mechanical efficiency and overall thermal efficiency with the addition of synthetic oils, turbochargers, ceramic engine components, bottoming cycle turbines, jet refrigeration systems and multiple effect absorption chillers.

These new components have the potential to make the optimal scale of block scale cogeneration very small indeed. The only reason to employ a thermal distribution grid given such high efficiency cogeneration may be to link diverse loads and thereby achieve a high load factor. If these improvements are coupled with other developments such as access to utility capacity and energy payments through the bidding process then the stage will be set for the opening of a huge market which in the American commercial and institutional sectors alone has been estimated by GRI at 70,000 MW(e).

The opening up of this market is likely to result in many technical and cost cutting improvements in cogeneration systems. A large and dynamically growing market will also permit cogeneration systems manufacturers to move from small scale fabrication of anywhere from several tens to several hundreds of units per year to several hundreds or thousands of units per year. It is at this stage, manufacturing, that economies of scale will be achieved in the high volume production of small scale systems. Production economies of scale will result in very substantial decreases in unit cost and a further expansion of the market.

Ultimately, it may be economically and technically feasible to service the heating and cooling needs of most urban and even suburban areas with advanced small scale cogeneration and DHC systems. If and when this development occurs it will be a relatively simple and low cost matter to thermally interconnect the many small discrete DHC systems served by small scale cogeneration and assemble a much larger thermal load which can be served by larger, more remotely located much higher efficiency renewable energy source of heating and cooling supply. It is likely that these renewable energy systems such as ice ponds and solar ponds will be located at the periphery of urban areas due to the intensity of their land requirements.

There are a number of reasons why such systems may be developed in the future and small scale cogeneration systems gradually phased out. Although this period may be several decades in the future it is likely that by such time fossil fuels will be much more expensive and scarce than today and that environmental pressures will be greater. Each of these factors will argue for the substitution of large scale renewable sources of heating and cooling since these systems will be several times more energy efficient than the most efficient diesel engine cogeneration system and will result in greatly reduced air pollution. If a full transition is made to a largely renewably supplied DHC system the efficiency gain when compared to the present system could be on the order of about 90%. Such a development should be regarded as the ultimate goal of the initiation of the process of developing block scale cogeneration.

The Swedish Experience With The Environmental Impact of District Heating

Although there have been few noteworthy studies of the impact of advanced cogeneration and DHC on urban air quality in the U.S. there is one Swedish study of the air pollution impact of district heating which demonstrates that this technology can have a very positive effect. In the late 1960's Stockholm, Sweden undertook a number of measures which significantly reduced SO_2 emissions rates including restriction of the sulfur content in oil to 1%, greatly expanding the district heating system and implementing energy saving measures. As a result of these actions sulfur emissions dropped to 20% of their 1965 levels in 1985. Further expansion of district heating and extensive installation of large heat pumps and the use of fluidized bed coal burning plants was expected to reduce sulfur emissions to 5% of the 1965 level by 1990.

NOx emissions attributable to heating plants in 1980 were expected to be cut in half by 1990 as a result of the above measures. Similarly, dust or particulate matter from heating plants was reduced by 60% between 1965 and 1980 and by an additional 20% of 1965 levels by 1990. These results are in large part due to the use of effective environmental controls which can and were utilized on Stockholm's large district heating production plants. This relatively efficient and low polluting source of thermal energy was then substituted for many thousand small and intermediately scaled boilers serving commercial, institutional and residential buildings which did not then and do not now have access to effective and affordable air pollution control equipment either in Europe or in the U.S. (source: Lars Jacobsson and Bengt Westergard, "Energy Planning In Stockholm and Its Effect on the Environment", Stockholm Energi, p. 5,7,10)

The effective regulation of emissions from individual building boilers has been limited in most urban areas of the U.S. to the bare minimum, i.e. regulating the use of certain very polluting fuels such as coal and heavy fuel oil and regulating emissions directly only when smoke of a certain density and darkness of color can be seen by the eye and reported to authorities in time for the offending source of pollution to be caught in the act. In the U.S. the only alternative to this obviously ineffective means of regulation has been perceived to be individual building air pollution controls on inefficient boilers which, of course, is a prohibitively costly option. However, the Swedish experience with district heating strongly indicates that there are other, proven and cost effective ways of bringing this hitherto intractable urban air pollution problem under control while significantly increasing energy efficiency at the same time.

Cogeneration and DHC and The Clean Air Act Amendments of 1990

There are several provisions of the Clean Air Act Amendments of 1990 (CAAA) which might be more readily achieved if advanced cogeneration and DHC technologies were to be included in the mix of technological solutions utilized. One possible provision which might encourage the development of high efficiency cogeneration or renewably based community energy systems is the system of emissions allowances established under Title V of the CAAA: "Acid Deposition Control". Allowances are issued by EPA for an annual fee to plants which meet SO2 and NOx emissions rates. An allowance is a federal authorization to emit a ton of SO2 or NOx in a calendar year. Holders of these allowances are prohibited from emitting SO2 or NOx unless they hold an equivalent number of allowances. In Phase I, allowances may be transferred among effected sources within a state and within an interstate utility company. In Phase II allowances may be transferred among affected sources within two interstate regions of the country. Allowances may be transferred and banked according to regulations in both cases. NOx allowances may be traded for SO2 allowances and vice versa, at an exchange rate of 1.5 pounds of NOx for 1 pound of SO2. When existing sources shut down, they are allowed to keep and transfer their allowances. New sources will be required to obtain allowances.

The Phase I SO2 emissions reductions program requires all existing fossil fuel steam electric generating units larger than 100 MW(e) to limit their emissions after December 31, 1995 to the tonnage equivalent of a 2.5 lbs./MMBtu emission rate for SO2 on an annual average basis. The tonnage equivalent is determined by multiplying the 2.5 lb/MMBtu rate by the annual average fuel consumption for 1985-1987.

The Phase II SO2 reduction program applies to units 100 MW or larger with emission rates greater than 1.2 lbs/MMBtu which will receive SO2 allowances equal to the product of 1.2 lb/MMBtu multiplied by the unit's historic (1985-1987) annual average fuel consumption. Through the trading program allowances can be transferred among affected sources. NOx limits will be established by boiler types: for tangentially fired boilers, no more than .45 lb/MMBtu and for dry bottom wall fired boilers and cell burners 50 lb/MMBtu. (source: USEPA, "Clean Air Act Amendments of 1990: Section By Section Analysis", EPA External Affairs (A-102)).

A market for allowances is expected to develop as a result of EPA auctions of allowances and through the generation of excess allowances by utilities with relatively low marginal abatement costs which are likely to create as many excess allowances as possible. Some utilities will keep or bank their excess allowances for system expansion while others will sell allowances. (source: "The Cogeneration Letter", Dec., 1990, p. 1,2)

Allowances might be generated by a utility by shutting down the most polluting of its generating plants. Such shut downs could be facilitated through the substitution of cleaner electric generating capacity, energy conservation at the point of end use or the substitution of very high efficiency cogeneration, renewably energized DHC plants which significantly reduce SO2 or NOx related to the generation of electricity for either space cooling or heating. Unfortunately, commercial and residential boilers are not covered under the 1990 CAAA and so there is no direct credit for reducing SO2 or NOx emissions from these plants as a result of more efficient, less polluting source substitution. However, there may be a way to ensure that high efficiency cogeneration or renewable DHC systems can benefit from the allowances.

States which are designated as "non attainment" areas by the EPA for a number of pollutants, e.g. SO2, NOx, CO, must promulgate "State Implementation Plans" which will bring them into attainment for such pollutants within a certain limited number of years. High efficiency cogeneration and renewably based DHC could do so, especially in the northeast where oil is used extensively for space heating. If such a system were also to supply space cooling it would simultaneously reduce emissions from oil fired boilers as well as from electric HVAC systems supplied with electricity from oil fired plants. States could require that utilities use their allowances in such a way as to facilitate the attainment of EPA pollution limits by extending a credit from the sale of allowances generated by substitution of higher efficiency, less polluting sources for more polluting ones.

In the future, it is hoped that the CAAA of 1990 might be further amended to tighten pollution allowance markets and extend SO_2 and NOx emissions regulations to commercial and residential boilers as well as to include CO_2 in all regulations as an additional spur to energy efficiency. Although the extension of emissions regulations and of allowance generation potential to small stationary sources of air pollution would impact small scale cogeneration systems and perhaps would require them to attain much cleaner emissions levels than currently this is not worrisome since current R&D programs appear to be well on their way to producing a new generation of very high efficiency clean burning engines. More importantly, it would also have the effect of making increased building thermal supply efficiency via cogeneration and DHC a major option for achieving cleaner air. If regulations and emissions allowance generation is extended to small stationary sources of air pollution, utilities will have yet another option for complying with the CAAA of 1990 by developing cogeneration and DHC.

Technology R&D In Reducing Emissions From Gas and /or Oil Fired Cogeneration Systems

The reduction of the emission of air pollutants from natural gas an/or oil fired diesel engines has been given high priority for both mobile and stationary applications in research and development programs in a number of countries. These efforts have taken several approaches including increasing the mechanical efficiency of diesel engines and thereby decreasing the amount of pollution per unit of electrical or mechanical output and directly addressing the issue of reducing emissions through the addition of various components, processes or engine modifications.

Germany has led this effort in Europe in response to the likely prospect that block heat and power systems (Blockheizkraftwerke or BKHW) will proliferate by the thousands as a result of the substantial energy efficiency advantages of these systems over virtually all other new energy conversion systems available in the near to intermediate term. The prospect of hundreds of small to intermediately scaled (50 kw to 10 MW) gas or oil fired block heating and power stations throughout many German cities has raised the prospect of deteriorating air quality at a time when efforts are being made to improve the situation. Therefore, the reduction of emissions from BKHW systems have been given high priority by the German federal government and by German diesel engine manufacturers. Several noteworthy government-private sector R&D projects are currently on going.

One line of inquiry focused on the amount of air introduced with the fuel in the combustion process. Although this resulted in a decrease in NOx emissions it also was found to increase the emissions of unburnt hydrocarbons and also to reduce mechanical engine conversion efficiency. This research was discontinued due to these results which were deemed unsatisfactory. This R&D was undertaken by Mannheim Motor Works in Mannheim, Germany with the participation of the federal government. Another related German research effort focused on the use of catalytic converters. This option was also found to be lacking due to the formation of a strong crust inside the catalyst which rendered it ineffective. This research was conducted by Bavarian TUV ev of Munich, Germany with federal participation.

One very promising research effort focused on the treatment of waste water or condensate from gas and oil fired diesel engines operated as block heat and power stations. When exhaust gases are condensed immediately after their production in the engine before reaching the ambient air, the pollutants are trapped in the condensate. However, the liquid mixture has been found to be unstable resulting in the need for treatment to stabilize the mixture of acidic pollutants in the condensate waste water prior to the introduction of the waste water into municipal waste waters or sewer systems. This effort focused on the use of municipal waste waters which typically have high PH values with the acidic low PH condensate. By mixing the two waste waters the combined effluent was found to neutralize it, i.e. to result in intermediate PH levels. Tests of this method of exhaust gas scrubbing with municipal waste water was found to eliminate 23.5% of the NOx and 2.7% of the CO from the exhaust stream.

An exhaust gas-waste water scrubber with an 11 stage cascade with counter current flow was developed as a result of these tests. The positive results of the system were found to be due to the longer contact time between the exhaust gases and the waste water and the counter current flow operational mode. This research was conducted by the Research Institute for Water Technology, RWTH College, Aschen, Germany and was supported by the PBE Office for the Biology, Ecology and Energy Research Program, KFA, Julich, GmbH, P.O. Box 1913,5170, Julich, Germany.

Another German R&D project has investigated "scrubbing" or condensation as a means of reducing emissions from BKHW plants with only "conditionally satisfactory" results. This project encountered problems in connection with long term stability of the gases in the condensate effluent. However, it was indicated that a number of efficient and stable processes could be developed for entrapping the gases in the effluent. (source: Dr.-Ing. W. Kunz & Dr.-Ing Goddke, Technishe Bewachungs Verein, Bayern, e.v. Germany.)

The results of these projects should be obtained and evaluated by the DOE since this approach of stabilizing the gases in condensate and thereby allowing the condensate to be flushed down sewers without any deleterious effect might be achieved at low cost and with a high degree of effectiveness in removing the offending pollutants. The detailed results of these projects should be obtained by the DOE and translated from the German into English. The technologies should then be evaluated for use as air pollution control systems for American diesel engine cogeneration systems. If models of these systems are available they might also be purchased and tested with American cogeneration systems by the DOE.

Similar R&D as that undertaken in Germany has been supported in the Netherlands for the last several years. The most significant work is in the area of NOx control in gas engines. The Dutch have focused on the use of lean gas mixtures, i.e. low ratios of natural gas to air, as a means of reducing NOx formation. It has been found that these lean mixtures lower the adiabatic flame temperature in the combustion chamber which results in low NOx emission levels. The high compression, lean burn approach is necessary to generate enough power per cylinder. This method has also been combined with the use of catalytic converters to further reduce NOx and CO emissions. Although it was found that the high compression lean burn method reduces NOx and CO to a considerable extent, it was also found that as the ratio of air to fuel is increased that power output or efficiency as well as NOx and CO emissions falls off considerably. Thus, this research corroborates the German experience with this pollution control method. (source: J.J. Hof and W. van der Veen, N.V. KEMA, Utrechtseweg 310, P.O. Box 9035, 6800 ET Arnhem, the Netherlands)

Research has also been conducted in Finland by the Finnish government and Wartsila, a major manufacturer of intermediate to large scale diesel engines for use as both the power plants of large ships as well as stationary power and cogeneration applications. Wartsila has focused on the development of selective catalysts to abate NOx emissions. The catalysts under development dissolve the NOx to nitrogen and water due to the reaction of the emissions with the ammonia in the catalyst. Reduction in NOx emissions of 80 to 90% have been achieved when applied to a natural gas fired diesel engine. (source: Timo Vuokko, "District Heating With Dual Fuel Gas Engine Plants", Oy Wartsila, Ab, License Engines, 20810 Turku, Finland)

American engine manufacturers which have retrofitted catalytic converters to diesel engines also claim an 80% reduction in NOx. However, catalysts are viewed as too expensive to purchase, operate and maintain and hence the search continues for an effective low cost way to reduce NOx emissions.

In the United States the federal government is providing the impetus for reducing harmful emissions from diesel engines. The focus of these efforts has been placed on mobile applications of diesel engines used in trucks and buses. The impetus for these efforts have been government regulations in the form of tightened emissions regulations for diesel engine powered trucks and buses. In 1988 the EPA limited heavy truck particulate emissions to 0.6 grams per horsepower hour (g/hp-hr). A second phase of the regulations mandate dropping particulate emissions to 0.1 g/hp-hr by 1994. NOx emissions set at 10.7 g/hp-hr were reduced to 6g/hp-hr in 1988 and 5 g/hp-hr in 1991.

One method of achieving the lower emissions levels which appears to be gaining favor is the conversion of diesel engines which would ordinarily run on diesel fuel to either dual fueling with natural gas (20% diesel oil as a pilot or ignition fuel and 80% natural gas) and the use of spark ignition systems on diesel engines as a means of operating these engines on 100% natural gas. The addition of spark ignition is required for a 100% gas fueled engine since natural gas requires a higher combustion temperature than can be achieved in a compression ignition engine such as a diesel. New spark ignition diesels operating on 100% natural gas have been found to achieve NOx emissions levels of 2-3 g/hp-hr, a level which is well below the new EPA standards. However, most of the engines which achieve these low emissions levels employ lean burn technology which employs a prechamber for ignition which also reduces mechanical efficiency levels. This can be partially attributed to low compression ratios which lower peak pressure and temperature in the engine. NOx levels from high compression gas engines may have about the same NOx levels as do dual fueled engines which are reported to run at about 4.5-6 g/hp-hr of NOx.

The Clean Air Act Amendments of 1990 (CAAA) are likely to create an additional impetus for cleaner diesel engine development. The most pertinent section of the CAAA for cleaner burning diesels is Title II, Section 201, "Clean Fuel Requirements" which requires new urban buses operating in metropolitan areas with populations in excess of 1,000,000 to be capable of operating exclusively on clean alternative fuel. This regulation will be phased in by the EPA between 1991-1994. It will require diesel engines used in buses to attain 0.25 g/hp-hr for particulate emissions.

Section 203 of the CAAA, "Emissions of Hydrocarbons and Carbon Monoxide From Light Duty Trucks" also establishes new emissions standards. For light trucks (<3,750 lbs.) under 0.41 g/hp-hr of total hydrocarbons and 4.20 g/hp-hr of CO. Heavier trucks (>3,750 lbs) must attain 0.50 g/hp-hr of total hydrocarbons and 5.50 g/hp-hr of CO. Fifty percent of each auto maker's 1994 light duty trucks and 100% of 1995 and later model year light duty trucks will be required to meet the tighter standards.

U.S. diesel engine manufacturers are responding to the new regulations with R&D programs aimed at increasing the mechanical efficiency of new diesel engines as well as dealing directly with emissions. A General Motors and John Deere joint venture has been reported to have achieved the development of an advanced diesel engine which can attain an efficiency of 44%. If such an engine were to be commercially produced in the near term and packaged by American cogeneration manufacturers it would very probably revolutionize the small packaged cogeneration industry.

Another interesting option for emissions reduction in diesel engines might be borrowed from gas turbine technology. The injection of small amounts of steam or water in stationary gas turbines for control of NOx emissions has been found to be quite effective. (sources: Allen, R. and Kovacik, J, "Gas Turbine Cogeneration:

Principles and Practice", ASME, J. Eng, Gas Turbines and Power 106: 725-30, 1984 and Touchon, G., "Influence of Gas Turbine Combustion Design and Operating Parameters On Effectiveness of NOx Supression By Injecting Steam or Water", ASME, J. Eng. Gas Turbines and Power, 107: 707-13, 1985) It is possible that this technique could be applied to control of NOx in gas fired diesel engines. The exhaust from such an engine could be used to generate a small amount of steam which could be injected into the exhaust gas stream to lower NOx emissions. The condensate could then be stabilized and flushed down the sewer.

Air pollution regulations are becoming increasingly restrictive of emissions from internal combustion engines for most applications, including cogeneration. New environmental regulations from that environmental bell weather state, California, will soon regulate emissions from engines having a capacity of 50 brake horsepower or 35 kw(e). If one of the largest markets for small scale cogeneration in the U.S. adopts very restrictive emissions standards for such equipment, it will be necessary for cogeneration manufacturers to develop technology which meets these standards which are likely to be much more restrictive than current or future federal standards. Thus, the development of clean burning diesel engines is critical to the success of block scale cogeneration. It is likely that this effort will be led by diesel engine manufacturers but it is also likely that their efforts as well as those of the U.S. federal government will focus on mobile applications for trucks and buses. Because these efforts are likely to ignore many of the emissions reducing options which have as their primary focus stationary applications it will also be necessary to mount an R&D program which is specifically focused on these applications, especially for urban cogeneration applications.

It is important to note that although California's emissions restrictions may soon apply to very small engine sizes (35 kw(e)) the EPA's regulations currently do not require that stationary power plants be regulated until they emit NOx at a level of 250 tons per year. This is about the emissions level which could be expected from about a 10 MW(e) gas engine power plant. At this level of emissions a full environmental impact statement is required by the EPA.

However, in the not too distant future if block scale cogeneration indeed begins to achieve a substantial level of market penetration in certain high density urban areas the levels of pollution in the aggregate could be so great as to stimulate environmental review and perhaps the promulgation of new regulations which would apply to stationary diesel engines used in cogeneration applications. This might occur initially if a number of cogeneration, DSM and energy conservation projects for a group or several groups of buildings in a single urban area are packaged as a single project and submitted as a bid in response to a utility RFP for generating capacity. In such a case it might be argued that in the aggregate the emissions from a number of small projects in fact equals or exceeds the level which would trigger an EIS. It might then appear to be only logical for regulators to begin to view such projects in terms of a single emissions source rather than separate projects. Thus, if block scale cogeneration is to achieve a very high level of market penetration in urban areas it appears that these systems will also have to attain very low levels of air pollution.

For these reasons it will be important to not only closely monitor the efforts of diesel engine manufacturers to develop cleaner burning engines but also to evaluate European emissions control systems developed for stationary applications and adapt these technologies to U.S. conditions if that is warranted.

Although there is much to be said for focusing on the reduction of air pollutants from diesel engines there is also much to be gained in this area by focusing on increasing engine mechanical and overall thermal energy efficiency.

R&D In More Efficient Diesel Engines

Many manufacturers of both diesel and otto cycle engines have on-going R&D programs aimed at the development of very high efficiency engines, automobiles and trucks. One area which appears to be receiving a great degree of attention worldwide is the development of ceramic-coated engine components. By coating the internal surfaces with a ceramic layer friction between moving parts is dramatically reduced--up to 75% friction reduction has been reported by at least one U.S. manufacturer, Cummins.

Ceramic coatings of key components such as pistons, cylinders and other components can reduce friction and thereby increase engine mechanical efficiency as well as reducing engine wear and maintenance costs and thereby increase the duration between major overhauls. Another important impact of ceramic coatings when employed extensively throughout the internal surfaces of an engine is that the engine becomes insulated to a much higher degree from heat losses through the engine walls than with purely metallic components. This insulating effect keeps more heat inside the engine permitting higher mechanical efficiencies. It also increases the temperature of the engine jacket heat while increasing the temperature of the exhaust. This factor is of particular interest since it would increase the quality while decreasing the quantity of thermal energy produced by the engine. This might have the effect of making a number of thermally activated cooling and electricity production systems more efficient and economical at the same time as it reduces their output or capacity.

Germany appears to be particularly active in the field of ceramic coatings for use in engine components for stationary applications such as cogeneration and fuel fired heat pumping. One reason for this R&D is to enable the new ceramic engines to utilize highly corrosive gases directly such as biogas from landfills and also for the burning of coal/oil and coal/water mixtures in large diesel engines. One German project of particular interest involves the development of ceramic components made of SiSiC and Al2 TiO5 for a low emission oil-vapor ceramic engine of 5 kw for use as a fuel fired heat pump or cogenerator for individual dwellings. This might have application in the U.S. with the American fuel oil industry, enabling that industry to offer a much higher efficiency home heating (and cooling) system or home cogeneration system in place of the current heat only boiler. The company responsible for this R&D is Hoechst CeramTech AG, Wilhelmstr. 14, 86762, Selb, Germany and the project director is Dr. Jurgen Heinrich. Another company involved is Ficht GmbH of Kirchseon, Germany. This project is supported by the PBE Project Office for the Biology, Ecology and Energy Program, KFA Julich, GmbH, P.O. Box 1913, 5170, Julich, Germany.)

Many automobile manufacturers throughout the world are conducting R&D Programs on a new generation of very high efficiency automobiles which attain efficiencies of 50 to 110 mpg. Because much of this R&D is aimed at completely reformulating the design of the entire automobile much of it is not relevant to cogeneration. However, that portion of the R&D which is focused on the development of very high efficiency engines is quite relevant. Many of the engines under development are diesel engines which utilize a significant number of ceramic components, plastics, special high efficiency variable transmissions and turbocharging. The achievement of very low emissions levels is also a primary design concern in these new engines. The new automotive diesels are reported to range in size from about 40 to 60 hp (35 to 42 kw(e)). This new generation of small diesels could revolutionize cogeneration making high efficiency, low polluting engines capable of running on numerous types of fuels available for relatively small applications. It is possible that the engine technology could be forthcomming from manufacturers before the completely redesigned automobiles become available. Therefore, one follow-on project from this effort should be to obtain as much relevant technical information as possible on the design of these new engines and their development status.

The manufacturers involved in these R&D efforts are, mostly, foreign. The most important programs are being conducted by Volkswagen, Volvo, Renault, Toyota, Ford, GM, Izuzu and Kyocera, Mitsubishi, Mazda and Nissan. One U.S. public interest group which is tracking developments in this field is the International Institute for Energy Efficiency in Washington, D.C.

There are also a number of near-term options. Currently, one U.S. cogeneration manufacturer, Modular Cogeneration Corporation has developed a 62 kw gas-fired diesel engine which has been tested at a 38% mechanical efficiency level. If the efficiency of this laboratory model is corroborated in the field, it would have the highest efficiency small scale cogeneration system which is commercially available. The nearest competitor is a system which attains a 32% mechanical conversion efficiency.

There are a number of new components which could be used to significantly upgrade the mechanical efficiency of such an engine, perhaps enabling it to achieve an efficiency comparable to that of the highest efficiency power plants now commercially available over at least the next 5 years. One such option is turbocharging which reportedly can increase mechanical efficiency by 3-5%. If a 3% efficiency increase could be achieved, the mechanical efficiency could reach 41%. Another option is to develop a bottoming organic Rankine cycle turbine to generate additional electricity from the engine exhaust gases, lube oil and cylinders.

Research has been carried out in Holland to determine which type of fluid would be most suitable for the organic Rankine cycle. Ammonia, freon, petane or hexane were evaluated and determined to be appropriate. Using these working fluids, it was determined possible to increase the electrical efficiency of a diesel engine cogeneration system by more than 20%. This increased efficiency would result in an engine of 42-45% efficiency, according to the Dutch results.

In the organic Rankine bottoming cycle the working fluid is heated up by the exhaust and cooled down as a result of passing through a turbine or cylinder type expansion engine. When it is expanded in the turbine or engine it drives a generator. The Dutch have determined that a cylinder-type expansion engine would be a good choice for a bottoming cycle since such a system could be built on the same crankshaft as the main engine. In this way an integrated, efficient and compact system can be built. (source: J.J. Hof & W. van der Veen, "Advanced Gas Engine Cycles For District Heating", N.V. Kema Utrechtsweg 310, PO Box 9035, 6800 ET Arnhem, the Netherlands.

There are a number of different types of bottoming cycles which could be developed. Such a device could be based on the Rankine cycle (using organic or non-organic working fluids), the Brayton cycle and the Sterling cycle. The most feasible option over the near term is likely to be an organic Rankine cycle since this technology is proven in much larger sizes so technical R&D tasks are limited to downsizing equipment and optimizing its design for applications with small diesel engines. Modular Cogeneration Corporation reportedly has developed a design for such a device which could be brought to commercial status in a relatively short time and at relatively low cost. That design uses a turbine.

Since the Dutch research assumed the use of about a 35% efficient engine which could be improved in efficiency by 20% for an overall mechanical efficiency of about 42-45%. If the same technology were applied to a 41% efficient engine and it was possible to improve its efficiency by 20% then an overall efficiency improvement of 8% might be possible resulting in a mechanical efficiency of 49%. The addition of insulating, lower friction, ceramic components might boost efficiency to even higher levels. At 49% mechanical efficiency such a system would be equal to the efficiency of the most advanced power generation systems expected on the market over at least the next 5 years. The details of the Dutch R&D effort in the field of organic bottoming cycles needs to be evaluated in detail. If this research is promising a collaborative effort between the U.S. DOE and its Dutch counterpart should be explored.

Interconnection With Utility Grid By Small Cogenerators

A GRI study of electric utility interconnection requirements for small cogenerators has shown that these requirements are not at all standardized and, in fact, vary considerably from utility to utility. Utilities often impose rather arbitrary requirements for interconnection on small cogenerators in an effort to discourage this type of cogeneration by making it more costly. GRI has attempted to address this barrier to small packaged cogeneration by developing guidelines for standard, cost effective and safe interconnection practices between utilities and cogenerators. However, utilities have apparently not adopted GRI's guidelines and the same difficult relations continue between small scale cogeneration developers and many utilities. (source: J.R. Iverson and R.D. Vavrina, "Closing The Grid-interconnect Gap", Onan Corp.)

If continued resistance is met from utilities on this issue and the cost of interconnection makes certain projects uneconomic, a cogeneration developer may have no alternative but to either abandon the project or reconfigure the "cogeneration" project as an engine driven heat pump/chiller project supplying all thermal energy in the form of heating and/or cooling services rather than electric and thermal. Since the highest cost service which the community scale engine driven heat pump/chiller would displace is peak electric power used for air conditioning it would appear that it would be very important to generate cooling at the highest efficiency and lowest cost possible. This would seem to argue for maximizing the production of cooling from an engine driven heat pump/chiller by developing thermally driven air conditioning technology.

The initial application of small cogenerators as fuel fired heat pump/chillers might also reduce the substantial skepticism of potential users toward any new product and in this case, particularly one which tends to engender significant electric utility opposition. Moreover, as a gas-fired heat pump/chiller it would almost certainly retain the allegiance of local natural gas distribution utilities which would tend to boost the confidence of potential users.

Conclusions and Recommendations

The major conclusion of this report is that cogeneration has a very large market potential of at least 70,000 MW in the commercial and institutional sectors alone. (The potential for cogeneration in the residential sector has not yet even been estimated.) However, that potential can only be realized if cogeneration technology is sufficiently energy efficient, cost effective and environmentally benign. In addition, technological innovation must be coupled with institutional innovation if cogneration is to be introduced into building and multiple building applications. There is so much that needs to be done to bring cogeneration to the point at which it can realize its potential that the establishment of a separate DOE Block Scale Cogeneration R,D and D Program would appear to be necessary. Block scale cogeneration technology addresses a number of pressing national issues including the impending electricity capacity shortages in many regions of the country; the emerging role of privately developed, high efficiency independent power production; and the need to significantly improve the energy efficiency and reduce the environmental externalities of our energy supply system. Although small, block scale cogeneration systems have the potential to address all of these issues, the industry is presently so small and fragmented that it is not able to exploit the opportunities which exist to improve efficiency, economy and environmental benefits. Thus, federal government support for R,D and D is clearly necessary. It is estimated that about $10 million/year will be required over a period of about 5 years to fully exploit all of the technical opportunities which exist. The major technologies which need to be developed are as follows:

-- Improve the mechanical efficiency of small scale diesel engines for use in cogeneration by developing and incorporating the following components: turbochargers, synthetic oils, ceramic engine components, bottoming cycle turbine systems.

-- Develop thermal cooling technologies to convert low cost engine waste heat into much more valuable air conditioning. The following technologies should be developed: jet refrigeration and single, double and triple effect absorption chillers.

-- Improve the emissions characteristics of gas fired, dual fuel and oil fired diesel engines. In particular, focus on thermal cooling systems' ability to condense exhaust gases, the stabilization of the exhaust gases by neutralizing the PH of the acidic exhaust and the disposal of the stabilized effluent in sewers.

-- Develop new analytical methods for evaluating cogeneration and other very high energy efficiency thermal and electrical supply systems which can supplement and perhaps supplant FERC's efficiency formula for determining QF status as well as outline other criteria which should be incorporated into state PUC "Mini-PURPAs". The efficiency formula should be based at least in part on a second law of thermodynamics analysis of efficiency.

-- Analyze a variety of advanced thermal and electrical supply systems in terms of second law efficiency including the following: all applicable types of cogeneration systems, cogeneration systems coupled with bottoming cycles and thermal cooling technologies, engine driven heat pump/chillers using preheating and precooling from renewable energy sources, renewable sources of district heating and cooling, particularly ice ponds and solar ponds.

-- Develop strategies and methodologies by which combined electric and gas utilities or separate electric and gas utilities can collaborate in the development of gas fired cogeneration and DHC and equitably share in the benefits.

-- Develop new utility capacity planning methodologies which maximize the market penetration of high efficiency, small scale electric generation and cogeneration systems. In particular, Analyze ways in which utilities can move toward homeostatic or interactive controls and spot pricing systems which can facilitate maximum development of cogeneration systems and renewable energy sources.

-- Develop new institutional mechanisms which have the potential to greatly accelerate the penetration of cogeneration into the commercial, institutional and residential building marketplace such as municipal finance utilities and more sophisticated escos. In addition, methods of packaging multiple cogeneration, DSM and demand side efficiency projects in one or several groups of buildings into a single bid for utility contracts for capacity and energy should be demonstrated.

-- Develop new interactive electronic controls and software with the capacity of integrating numerous functions such as the following: building EMS, utility DSM controls, cogeneration system operations and dispatch, utility load prediction and dispatch.

Bibliography

Task 1: Part III

Advanced Block Scale Cogeneration and DHC: Technology R&D Issues

Allen, R. and Kovacik, J., "Gas Turbine Cogeneration: Principles and Practice", ASME, J. Eng., "Gas Turbines and Power" 106: 725-30, 1984.

Andrews, D.C., "Homeostatic Control Can Optimize Utility Load Management", Open University Energy Research Group, Milton Keynes, U.K., 1982.

Berrie, Tom, (FIEE), "Interactive Load Control: Spot Pricing Questions and Answers", Electrical Review Vol. 210, No. 23, 11 June 1982.

Burns, Robert E., et. al., "The Appropriateness and Feasibility of Various Methods of Calculating Avoided Costs", the National Regulatory Research Institute, June, 1982.

"Blockheizkraftwerke: Stand Der Technik und Umweltaspekte", Tatung, Essen, June, 1987; Conference Proceedings published by VDI Verlag, Dusseldorf, 1987.

Casten, Thomas R., "Using Clean Air Regulations To Reduce Fossil Fuel Use", Trigen Energy Corp, 1990.

Cogeneration Letter, "Clean Air Act Amendments Exempt QFs, IPPs For New Emissions Levels" and "CAA Allowances: Key To Year 2000 Plants", Lilburn, GA, December, 1990.

Dietrich, Werner R., "Gas Engine Drives, Optimized for the Emission of Pollutants, For Block Heating and Power Plants and Heat Pumps, Based on the Lean Concept" in "District Heating and Cooling R&D Project Review, IEA DH R,D&D Programme, Novem, 1989, p. 148.

EPA External Affairs Div., "Clean Air Act Amendments of 1990: Section By Section Analysis", USEPA, Washington, D.C. 1990.

Federal Ministry of Research and Technology, PBE, Federal Republic of Germany, Program For Energy Research and Energy Technologies, "Report On Studies and Basic Research on Cogeneration"

Hein, Karl, "Unitized Combined Heat and Power Plants In the Federal Republic of Germany", Energie Spektrum International, 1987.

Hein, Karl, "Unitized Combined Heat and Power Plants In The Federal Republic of Germany", "Packaged Cogeneration Systems Conference", San Diego, CA, 1989.

Hof, J.J. and W. van der Veen, "Advanced Gas Engine Cycles for District Heating and Industrial Application", in "Advanced District Heating Production Technologies", Ove C. Morck and Thomas Pedersen (eds), International Energy Agency, DH R,D&D Programme, published by the Netherlands Agency for Energy and Environment, 1989, pp. 277-295.

"IPPs Can Make Up Electrical Shortages" and "Independent Capacity Seen At 81,000 MW By Year 2000", in "World Cogeneration", Fall, 1989.

Iverson, J.R. and R.D. Vavrina, "Closing The Grid-Interconnect Gap", Onan Corp. for GRI, 1989.

Jacobsson, Lars and Bengt Westergaard, "Energy Planning in Stockholm and Its Effect on the Environment", "Stockholm Energi", 1988.

Larjola, Jaakko, "High Speed Technology: Oil Free Compressors and ORC-Power Plants for Heat Recovery" in "Advanced District Heating Production Technologies", Ove C. Morck and Thomas Pedersen (eds), IEA DH R,D&D Programme, Novem, 1989, pp. 656-663.

Schweppe, F.C., Tabors, R.D. and Kirtley, J.L. "Homeostatic Control: The Utility/Customer Marketplace for Electric Power". MIT Energy Laboratory Report, MIT-EL 81-033 March, 1982.

Seisler, Jeffrey, Natural Gas Lets Trucks Run Clean: Stricter Pollution Limits May Boost The Appeal of Methane Power", High Technology, August, 1986.

Staff Report, "The Economic Impacts of Self Generation", California Energy Commission Report # P500-87-002, March, 1987.

Teislev, Bjorn, "ER-Unit (Energy Recovery Unit", in "Advanced District Heating Production Technologies", Ove C. Mork and Thomas Pedersen (eds), IEA DH R,D&D Programme, Novem, 1989, pp.603-638.

Touchon, G., "Influence of Gas Turbine Combustion Design and Operating Parameters On Effectiveness of NOx Suppression By Injecting Steam or Water", ASME, J. Eng., Gas Turbines and Power, 107: 707-13, 1985.

van der Linden, Septimus*, "Future Power Markets and Turbine Technologies" (*: V.P. ABB Energy Services Inc., North Brunswick, N.J.) in "World Cogeneration", Vol 3, No. 1.

Vuokko, Timo, "District Heating With Dual Fuel Gas Engine Plants", in Ove C. Morck and Thomas Pedersen, (eds) "Advanced District Heating Production Technologies", IEA, DH R, D&D Programme, Novem, 1989.

Williams, Robert H., et. al., "Aeroderivative Turbines For Stationary Power", in "Proceedings for the Second Annual Conference of the American Cogeneration Association and the Cogeneration and Independent Power Coalition of America", Chicago, Illinois, September, 1988.

TASK 2

Advanced District Cooling Technology: R&D Needs and Opportunities

Table of Contents

Introduction: The Advantages of Commercially Available District Cooling Technology

Although there is much which can be done to greatly improve and even revolutionize district cooling technology, existing systems seem to have evolved to the point in recent years where they have some important advantages over the competition. Although these advantages are by no means overwhelming ones, they are sufficient in some cases to tip the economic argument marginally in favor of district cooling. A brief review of these advantages seems appropriate so that a discussion of R&D needs and opportunities might be placed in proper perspective.

One important distinction between district cooling and district heating is that the former was developed in the U.S. whereas the latter was developed, for the most part, in Europe. District heating technology has been subjected to decades of heavily funded public and private sector R&D in Europe, whereas, district cooling has received scant R&D attention from either the private or public sector in the U.S. until very recently. Many of the improvements in district cooling technology have been borrowed from district heating. However, increasingly, district cooling is being recognized as a very important technology in its own right. It is now apparent that district cooling will prove to be far more important for America's energy future than district heating.

District cooling was developed in the U.S. initially along with district heating primarily by single institutional owners of multiple building complexes such as college campuses, military bases and medical centers. The advantages which accrued to these institutions are some of the same which make district cooling attractive today: building space saving; fewer operational personnel; greater load diversity yielding higher levels thermal generator capacity utilization; higher levels of energy efficiency; greater levels of environmental control; and better economy. Although in the 1970s and much of the 1980s district cooling systems did not grow appreciably and, in fact, barely held their own against increased competition from lower cost, higher efficiency, individual building electric HVAC equipment, in the late 1980s district cooling began a resurgence due to a number of factors: the use of cogeneration, thermal storage, electronic controls, better operational practice, better engineered systems and more reliable and sophisticated technology throughout the system. Many district cooling systems regained a competitive edge as a result and began to grow again.

In recent years a number of additional critical advantages are propelling the increased growth and profitability of district cooling. The primary factor has been increased electricity costs, particularly in the form of peak electricity demand and energy charges. The electric utility's need to undertake demand side management measures to reduce peak demands to avoid the construction of new, expensive peak generating capacity has made for a less antagonistic relationship between district cooling utilities and electric utilities, allowing the expansion of those systems or the development of new systems.

This is particularly true of electric utilities which have DHC subsidiaries. In several cases such as in New York City with Consolidated Edison and in Indianapolis with Indianapolis Power and Light, district cooling is being used as a load management tool by the electric utility. Essentially, district cooling permits load shifting off the electric peak and onto the district cooling system which derives its thermal energy from cogeneration or waste incineration. The incorporation of large scale cooling storage facilities by district cooling utilities in places like Hartford, Connecticut and Trenton, New Jersey has further accelerated the ability of district cooling to act as a load levelling and load shifting mechanism. This trend can be expected to accelerate in the future.

Another trend favoring district cooling has been the changes in building energy demand patterns over the last decade. The energy required to heat buildings is on the decline due to increased lighting, computerization, automated office equipment and the better thermal integrity of the building envelope. Higher internal heat loads coupled with the need for greater levels of ventilation required to maintain adequate levels of internal building air quality as building envelope efficiency has increased have all conspired to increase the level of building air conditioning even as building heating requirements decline. As cooling demands have increased so have costs and in many cases increases in demand have not been in proportion to increases in cost. This is due to the trend toward higher cost electric power, especially for the peak power capacity required by building air conditioning systems. The capacity and energy charges for peak electricity services have driven building air conditioning costs to very high levels and provided district cooling systems which are efficient and economical with a distinct competitive advantage. In the future these trends are likely to continue and additional trends are expected to develop which also favor district cooling.

One of the most significant new trends is the increased restrictions which will soon be placed on CFC production and use. The new CFC "drop-in" refrigerants will require extensive retrofit to most on-site CFC based chillers especially in large office buildings which use centrifugal chillers with R-11 as the refrigerant. The additional costs, efficiency penalties and additional regulatory compliance costs are widely seen as having the potential to accelerate the trend toward district cooling which simply offers building owners and managers a means of getting rid of this problem once and for all by merely hooking up to district cooling. Even if the district cooling utility continues to employ CFCs or the new "drop-in" refrigerants it can afford to meet the new regulatory requirements since it already has the personnel and technical capability to rapidly get up to speed and into compliance with a minimum of time and cost.

Although these advantages will continue to accelerate growth trends in district cooling making it much more important than district heating for the future U.S. energy supply system, there is much which needs to be done to make the technology much more energy efficient, environmentally beneficial and cost competitive than it is today.

In the near term, district cooling can become increasingly more competitive, more efficient and more environmentally beneficial through the use of advanced cogeneration systems. Since most district cooling systems have to start out small, these systems will probably be well advised to use small, block scale gas-fired cogeneration systems. However, a significant barrier to the widespread use of these systems is the lack of heat activated cooling technology which is cost effective. As the CFC replacement issue becomes more immediate in the late 1990s district cooling will acquire an additional advantage if it can generate all of its cooling at very high levels of energy efficiency without having to resort to CFCs or CFC "drop-in" substitutes which may also be outlawed in the near future. It is possible that most of the $135 billion in CFC based air conditioning equipment will have to be replaced within 20 years. This creates a huge opportunity for high efficiency, low cost, non-CFC based district cooling but one which can only be exploited with significantly improved technology.

Over the longer term it will become increasingly important for the district cooling industry to move beyond cogeneration to utilize renewable sources of cooling which offer the advantages of much higher levels of efficiency, much lower environmental impact and potentially better long term cost effectiveness and reliability than any form of fossil fuel based cogeneration. However, without significant levels of federal government R&D such technology is not likely to be available when it is needed.

In addition to new technologies for district cooling production it will also be necessary to develop more economical and efficient methods of thermal distribution and utilization. Ice slurries, high dT chilled water district cooling, thermal pulsing distribution of hot and chilled water in one or two pipes; more sophisticated electronic controls, distributed thermal storage and other new technologies are required to reduce the present high capital and energy costs of existing district cooling technology. Again, high levels of federal government R&D are necessary to bring these technologies off the drawing boards, out of the laboratories and into widespread commercial utilization.

The most important new district cooling technology which can be developed by the DOE in the near future is clearly new advanced heat activated chilling technology which is designed to use the waste heat from small to intermediately scaled gas fired diesel engine cogeneration systems. This technical category was the top priority item in a survey of 20 such technical categories which were ranked by attendees at a national district cooling conference sponsored by the IDHCA. The most promising heat activated chilling technologies include: organic Rankine bottoming cycle turbines, jet refrigeration systems; and single, double and triple effect absorption chillers. If these technologies were to be made commercially available to the industry they would give the industry a considerable boost which might propel it into a period of long term growth.

Heat Activated Chilling Technology For Block Scale Cogeneration and District Cooling

There are a number of economic, environmental, institutional and other factors which appear to be making the development and extensive use of advanced heat activated chilling technology a very attractive option for the near term. Firstly, the economic advantages of using waste heat from natural gas-fired cogeneration for heat activated chilling as compared with electric vapor compression chilling are compelling. The heat produced from gas-fired diesel engine cogeneration is estimated to cost only $1 to $2/MMBtu. When this heat is used in a double effect absorption chiller with a COP of 1.2 the energy costs (not including capital costs) are $1.20 to $2.40/MMBtu. Whereas, peak electricity costs including charges for energy capacity are frequently in the range of $0.10 to $0.15/kwh, if converted to air conditioning in a state of the art electric chiller (COP, 6.5) the cost per MMBtu is in the range of $4.50 to $7.00/MMBtu. Since most existing chillers obtain COPs of considerably less, usually half as much or about 3.0, the actual cost of building air conditioning to most users is very likely much greater, possibly as much as double or $9.00 to $14.00/MMBtu. Thus, cogenerated heat based chilling has an energy advantage over electric chilling of between 2.25:1 and 7:1. However, currently available heat activated chilling equipment exhibits numerous technical, economic and scale disadvantages which have left this huge cost differential essentially unexploited to date.

A second factor arguing in favor of heat based chilling is that none of the technologies which convert cogenerated waste heat into cooling require the use of CFCs. Virtually all of the electrical vapor compression equipment used in commercial and residential building air conditioning currently uses CFCs. The production of CFCs will begin to be curtailed within the decade and it is possible that the refrigerants designed to replace CFCs which also contain small amounts of CFC will also be phased out soon thereafter.

The "drop-in" replacement refrigerants which have been devised for systems designed to use CFCs will apparently result in a 5-10% capacity and COP loss and also require numerous equipment modifications in the form of motor gasket and seal replacements. Moreover, the use of several of the replacement refrigerants has raised numerous additional health, safety and environmental issues. These replacements may also be banned by future amendments to the Montreal Protocol as a result of the increasing realization by the scientific community as well as by political leaders that the ozone depletion problem is much worse and deteriorating much faster than any of the computer models predicted only a short time ago.

Thus, it is likely that not only commercial buildings which employ chillers using R-11 and R-12 but also the R-22 used in most smaller air conditioning and refrigeration systems will have to begin to be replaced within a decade with systems which do not use CFCs. Since there is $135 billion invested in existing air conditioning equipment which will have to be replaced before the end of the useful life of this equipment it is practically certain that a huge new market for non-CFC air conditioning equipment will open up over the next decade. Thus, the ozone depletion crisis will spawn a huge marketing opportunity for non-CFC refrigeration technology. Because of inherently low energy costs, heat-based chilling systems could be ideally placed, given adequate R&D, to take a leading role in the development of this new market.

Another advantage is energy efficiency. A cogenerator generating electricity at 38% efficiency and recovering 58% of remaining energy in the form of waste heat has an overall first law efficiency of 96%. Such a system has a distinct advantage over electric vapor compression chilling. If it is assumed that the electrical output of the cogenerator is used to drive an ammonia (non-CFC) vapor compression chiller with a COP of 6.5, the resulting effective COP is 2.47 (.38 X 6.5). If 58% of the energy used by the cogenerator is captured for use as waste heat in an absorption chiller with a COP of 1.2 for an effective COP of .69 (.58 X 1.2), then the overall effective COP of the combined system is 3.1. A state of the art mechanical vapor compressor using CFC refrigerant is assumed to have a COP of 6.5 and is supplied with electric power at a typical electric utility system wide efficiency of .30 then the effective COP is 1.95. If this performance is degraded by 5% due to the use of a "drop-in" CFC substitute refrigerant, the effective COP is reduced to 1.86. Thus, the cogeneration/absorption chilling option has a 40% efficiency advantage. If the competition is assumed to be an existing vapor compression chiller with a COP of 3.0, a more typical case, then the efficiency advantage is 3.1 vs 0.9 or 71%.

If an organic Rankine bottoming cycle turbine can be developed for use with a small gas fired diesel cogenerator with a mechanical conversion efficiency of 15% then the overall COP of this system would be [(.38 X 6.5=) 2.47 COP + (.15 X .58=) 0.087 X 6.5=) +0.56 COP =] 3.035 COP or 39% more efficient than the state of the art mechanical chiller with a COP of 1.86 and 71% more efficient than the more typical mechanical chiller with an effective COP of 0.9.

If the cogenerator's waste heat is used to power a jet refrigeration system with a COP of 0.6 then the efficiency advantage would be (.38 X 6.5=) 2.47 COP + (0.6 X .58=) + 0.348 = 2.81 COP. This system would have a 34% efficiency advantage over the state of the art chiller and a 68% efficiency over the more typical, lower efficiency chiller.

It is important to note that these calculations do not take into account that if the cogeneration/heat activated chilling system and the electric chiller driven by the cogenerator are designed to also produce hot water at a sufficient temperature to be utilized in either domestic hot water heating or low temperature space heating that the efficiency would be even higher than is indicated here. Furthermore, it is also possible to increase the electric conversion efficiencies of small scale cogeneration systems to much higher levels than have been assumed in the above cases through the application of such technologies as turbocharging, the use of synthetic oils and the incorporation of ceramic engine components.

Due to its high energy conversion efficiency and its use of non-CFC refrigerants, advanced cogeneration/heat activated chilling technology has the capability to significantly favorably impact two of the most pressing global environmental crises--stratospheric ozone depletion and global warming. Since these systems will likely use gas and/or diesel oil there will be no additional positive environmental impact when these systems are used to replace gas or oil fired electric power generating capacity. However, a substantial additional beneficial impact will occur when these systems displace coal fired electric generation. In addition, the 5 to 10% COP loss resulting from the use of drop-in refrigerants will also result in the need to generate 5-10% more electric power than is presently used by CFC-based vapor compression chilling. This will result in substantial additional air pollution which will exacerbate the global warming problem even as it attempts to resolve the ozone depletion crisis. Clearly, a more farsighted strategy is called for which should involve cogeneration, heat activated chilling and ammonia chilling.

Another factor which could prove significant in the development and commercialization of cogeneration and heat based chilling is the new interest on the part of the U.S. gas industry in heat based chilling. In 1991 the American Gas Association (AGA) proposed a greatly increased R&D program for gas fired cooling to be undertaken in conjunction with the U.S. Department of Energy (DOE). The AGA recommended a budget of $18 million per year to be spent on natural gas fired cooling and heat pumping by the DOE.

The AGA has noted that current progress in this area is slow due to the very low levels of DOE funding. However, if adequate levels of funding are expended on gas cooling and related high efficiency systems such as gas engine driven chillers and desiccant dehumidification systems that competition will assert itself between gas and electric utilities in the building air conditioning marketplace. The gas industry has good reason to push for the development of these systems since gas cooling will increase the use of off-peak, lower cost summertime gas and more fully utilize off-peak gas transmission capacity while reducing the use of on-peak, high cost summertime electric power. The gas industry contends that such a strategy will more efficiently utilize both natural gas and electric capital infrastructure including transmission networks thereby producing the least cost energy mix for consumers.

Furthermore, under the auspices of the AGA the American Gas Cooling Center was established with 34 corporate members from gas utilities serving 25 million customers. The tasks which the AGCC has set for itself include assessing market opportunities, selecting products for support, supporting market entry of new products, providing installation data, preparing case studies and participating in user groups. The Center will also support development of codes and standards, equipment certification programs, economic analysis software, marketing training programs, equipment selection programs and market research. The center has to date begun supporting several new products including engine driven Rankine cycles, absorption cycles using ammonia and adsorption cycles using ammonia. Of particular interest to the Center according to its Director, Mr. Anthony Occhiniero, is the development and commercialization of gas fired cogeneration waste heat driven multiple effect absorption chillers which are both highly efficient and cost effective.

There are also other institutions involved in gas cooling R&D including the Gas Research Institute which has supported R&D in gas engine driven chillers, direct gas fired absorption chillers, cogeneration waste heat driven absorption chillers and desiccant dehumidifiers.

Although there is considerable interest on the part of a number of institutions in gas cooling the market has been increasing at a moderate pace from a very small base over the last few years. Gas cooling equipment shipments above 15 tons of cooling capacity have increased 40% from 421 units in 1988 to 599 in 1990. The largest number of shipments occurred in the absorption category. Between 700-800 units of direct gas fired absorption systems in the 3-5 ton residential category were installed in light commercial applications in 1990.

Estimated Gas Cooling Equipment Shipments (units)

Chiller Type	1988	1989	1990
Absorption Chillers	345	325	376
Gas Engine Driven Chillers	28	45	49
Direct Expansion (D/X)	NA	NA	87
Desiccant Dehumidification	48	53	87
Totals	421	423	599

(source: AGA, "Planning and Analysis Issues: Issues Brief, 1991-5", February 26, 1991)

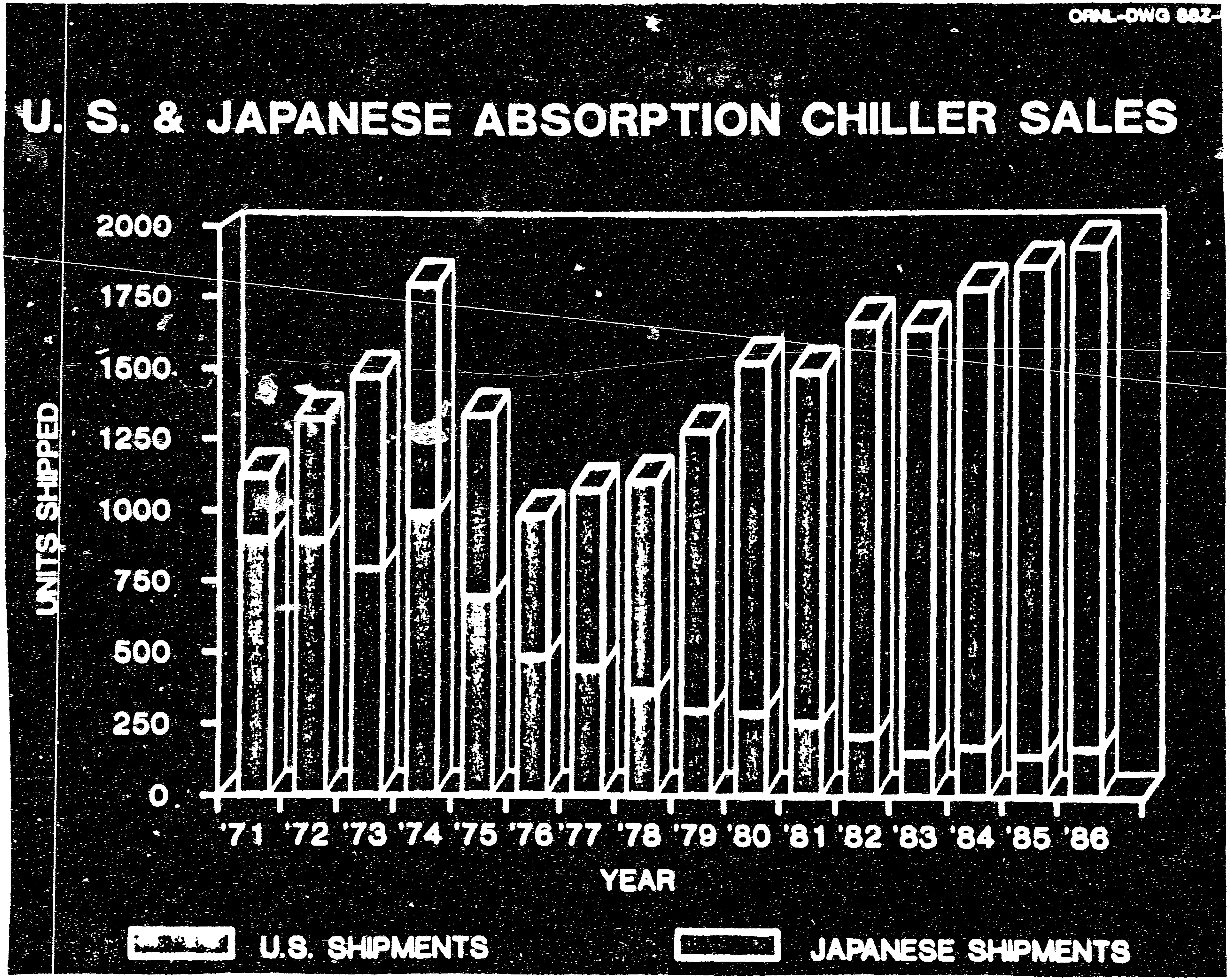
Although a 40% increase in sales over 2 years is impressive, the overall numbers are quite small considering the status of the absorption chilling industry in other countries, particularly Japan. Japan's shipments of absorption chillers to its domestic markets now exceed those of centrifugal and other rotary compression units. This is in sharp contrast to the U.S. where electric turbo chillers have the largest share of the market with over 3,000 units sold. Japan shipped more absorption than compression machines in 1990, about 1,000 compared with just over 600 electric systems, although in terms of capacity the 2 systems had roughly equal shares.

The major difference between the U.S. and Japan is the attitude toward energy conservation in Japan which favors the more efficient absorption systems. The Japanese domestic market is growing rapidly particularly in the demand for small to medium sized absorbers in the 20 to 70 kw range. With few U.S. competitors and none in Western Europe, the Japanese absorption industry rightly claims the position of world leader in this technology.

The figures on absorption chiller shipments for the U.S. need to be placed in perspective to see where the industry is today and where it is going. Absorption was a big business in the U.S. in the early 1970s. Up until the mid 1970s more than 26,000 large lithium bromide/water chillers were manufactured in the U.S. American manufacturers were virtually without competition until the 1970s. Sales peaked in the late 1960s and began to decline thereafter. By 1974 sales reached 1,000 units and by 1986 they were down to 150 units. This was the direct result of an aggressive push into U.S. markets by Japanese manufacturers. The decline in U.S. manufactured absorbers occurred as a direct function of the rise in Japanese shipments. This can be seen in the following chart. Japan now dominates world absorption chiller manufacturing and sales. These consist principally of single effect systems. Presently sales are over $200 million annually and Japanese manufacturers are known to be aggressively improving their products.

If the United States is to gain the competitive edge over Japan much will have to be done to improve the performance and cost effectiveness of absorption refrigeration as well as other thermal cooling technologies. The coupling of these systems to cogeneration appears to be a prerequisite due to the competitive advantages which the high overall energy efficiencies which this combination of technologies offers. However, absorption chilling technology exhibits very strong economies of scale and is hence very expensive on a per unit cost basis in very small sizes, especially when it comes to very efficient multiple effect machines. Although coupling cogeneration with absorption chilling may significantly improve absorption's chances in the marketplace against the Japanese, there is no reason why Japan will not be able to follow suit in short order. If the U.S. is to take back the absorption market from Japan as well as exploit the huge domestic potential which lies virtually untapped in the market for small cogeneration/absorption chillers for use in building air conditioning applications, then it is likely that drastic cost reductions will have to be achieved for absorption chillers in small sizes.

The cost of absorption chilling technology is directly related to the amount of tubing which these systems use. If new materials and fabrication methods for heat transfer could be developed and applied successfully in absorption chillers then the cost of these systems might be significantly decreased. The work of Brookhaven National Laboratory on thin film metallic foil heat exchangers is particularly relevant here. The new thin film heat exchanger technology has the potential to drastically reduce the costs of absorption chilling since this highly efficient heat exchanger material with its very low level


ORNL-DWG 88Z-
U. S. & JAPANESE ABSORPTION CHILLER SALES
UNITS SHIPPED
2000
1750
1500
1250
1000
750
500
250
0
'71 '72 '73 '74 '75 '76 '77 '78 '79 '80 '81 '82 '83 '84 '85 '86
YEAR
U.S. SHIPMENTS
JAPANESE SHIPMENTS

of material intensity and cost would directly substitute for the most expensive component in all absorbers--the tubing. This technology is particularly important for the development of high efficiency multiple effect absorption chillers which are extremely intensive in their use of tubing. With existing heat exchanger technology it is difficult to see how new absorption systems such as high efficiency double effect absorbers with COP of 1.3 and triple effect absorbers with COP of between 1.8 and 2.0 might be feasible.

In addition, in the future when it becomes increasingly necessary to maximize efficiency and the use of low grade heat, particularly from renewables such as solar, the efficiency and cost of absorption equipment will be a critical factor in determining if this and other low grade heat sources can be used cost effectively for cooling production. However, the new thin film heat exchangers hold out the promise of making such absorption chilling applications economically viable. Thin film heat exchanger technology has the potential to revolutionize absorption chilling and should be accorded the highest priority by the DOE. (sources: Leigh, R.W., et. al., "Cost Reductions In Absorption Chillers", 1986, BNL, GRI and Leigh, R.W., et. al., "Cost Reductions in Absorption Chillers", Phase II, BNL, GRI, 1989)

One of the problems with most absorption chilling systems using LiBr/water as well as other refrigerants is that these systems can only produce chilled water, not ice. This problem can be overcome to a certain extent through the use of the absorber to produce chilled water at about 40-45F for input to a cogeneration driven mechanical vapor compression chiller which can use the chilled water to produce ice. However, this option is somewhat inflexible and it would be advantageous to have a heat activated chiller which could produce ice directly.

The development of some form of high efficiency, low cost heat activated chiller which is able to produce ice from the waste heat of a small diesel engine cogeneration system would allow such a system maximum flexibility. Of all of the heat activated systems it is likely that the most flexibility is derived from the organic Rankine bottoming cycle turbine which can generate electricity for sale to the grid as well as power for driving electric chillers. However, the ice making capability of the jet and of the ammonia absorbers is also an important feature since it facilitates the production of ice during off-peak periods which can be stored much less expensively than chilled water. Ice is also more valuable than chilled water for use in ice slurry distribution systems.

Several heat activated chillers have the potential to perform this task. An organic Rankine bottoming cycle turbine can produce ice directly by converting the cogenerated waste heat directly into mechanical power which can be used for vapor compression. It has been suggested that diesel engine turbochargers could be employed as bottoming cycle turbines. One advantage of this technology is that it is available off the shelf and needs only to be adapted to the task at hand. Modular Cogeneration Corporation is known to be working on this system as well as a jet refrigeration system which it is developing with Brookhaven National Laboratory. Although the turbocharger with a COP of 0.56 has the potential to be 40% more efficient than the jet refrigeration system with a COP of 0.34, the jet refrigerator is expected to be much less expensive than the bottoming cycle turbine. However, both are likely to be much less expensive than most absorption systems of any number of effects as long as those systems use conventional heat exchanger technology.

Ammonia Absorption and Vapor Compression Technology

One absorption system which is designed to generate sufficiently low, sub-freezing temperatures to make ice is ammonia absorption chilling which has traditionally been confined to use in the industrial sector to produce very low sub-freezing cold air at temperatures from -70F to 30F which are necessary for a number of industrial processes. However, commercially available systems are not available in small sizes. Ammonia absorbers which are considered economical are commercially available in minimum sizes of several hundred tons of refrigeration capacity. These systems are most economical in very large sizes of 1,000 tons or more. The largest manufacturer of this equipment is Borsig GmbH of Berlin, Germany. The smallest size unit Borsig manufactures with a 30 degree F production capability is 500 tons. Borsig equipment costs are very high at $2,000/ton. This equipment is usually financed over 10-15 year periods.

The scale and cost of this technology appears to be far off the mark which absorption equipment must reach if it is to be competitive in a cogeneration building air conditioning application. However, it is useful to note that absorption technology has been around for a very long time; the ammonia absorption chilling industry has been in existence since the turn of the century. The industry flourished in both the industrial and commercial markets until the 1930's when Carrier introduced freon refrigerants which came to dominate the commercial markets, in part due to the perceived health dangers posed by old ammonia refrigeration systems. According to a manufacturer of ammonia absorbers, Henry Vogt of Louisville, Kentucky, there are many designs of absorption ammonia chillers in a wide range of sub-freezing temperature applications. The equipment at the scale required for use in block scale cogeneration (as small as 30 tons) is not commercially available at present but most companies in this field have designs available for small scale equipment which was manufactured several decades ago. (source: Ambrose Spencer, personal communication, June, 1991)

Most of these systems have not been manufactured since freon based electric chilling began to dominate the commercial markets. Ammonia was forced out of the commercial markets due to the perception of health and safety risks. Building health and safety codes were established which required all ammonia chilling equipment (both absorption and mechanical vapor compression) to be located outside commercial buildings. The debate over ammonia's toxicity or lack thereof continues today in light of the need for a substitute for

CFCs. However, a consensus appears to be forming that ammonia equipment could be reintroduced into the building envelope as long as it is isolated from that part of the building which is occupied by people and adequate ventilation to the exterior is provided. The codes governing the siting of this equipment could be altered in the near future reopening commercial and residential building air conditioning markets to the ammonia chilling industry.

Although existing codes presently restrict the use of ammonia chilling inside buildings these restrictions can be circumvented through the use of ammonia chillers in a central DHC production plant or in a block scale cogeneration system located in a separate facility apart from the commercial and/or residential buildings which it supplies with DHC services.

The fact that small scale ammonia absorption systems have not been produced for decades seems to indicate that the basic technology might benefit from an analysis which would consider how such systems might be redesigned in light of 40 years of accumulated experience in absorption refrigeration to achieve lower costs and higher performance in systems designed to convert the waste heat from small scale cogenerators into ice for storage and eventual use in ice slurry district cooling. Small scale ammonia absorbers as well as the larger systems currently in use in the industrial sector might be able to employ the thin film metallic foil heat exchanger technology currently under development at BNL. If it were possible to significantly decrease the cost and increase the performance of these systems with the BNL thin films then redesigned ammonia absorption technology might be pressed into service as yet another technical alternative to the use of either CFCs or their dubiously named "drop-in" replacements.

Although vapor compression R&D occupies center stage at present several companies are known to be pursuing R&D in heat activated ammonia chilling systems of various types including Phillips Engineering Company of St. Joseph, Michigan which is developing absorption chillers using ammonia/water as the working fluid.

DOE should undertake an investigation of the potential to redesign both small and large scale ammonia absorption equipment so that it can be used in cogeneration and district cooling applications. The DOE could enlist a number of present and former manufacturers of ammonia absorption chilling technology in the proposed effort. Some of these firms are: American Borsig, Rocky Research, Standard Refrigeration, Lewis Refrigeration, Henry Vogt, Trane, Carrier and York. The support of the International Institute for Ammonia Refrigeration in Chicago could also be enlisted.

The Potential For Ammonia Vapor Compression Refrigeration In District Cooling

Over the last several years, ammonia refrigeration has receieved a great deal of attention as a potential substitute for CFC refrigerants and their "drop-in" substitutes. A primary focus of this attention has been the health and saftey characteristics of ammonia. The following conclusion regarding ammonia appears to more or less have been accepted by the scientific community.

"Although ammonia is a toxic material, moderately flammable and explosive and an eye and lung irritant with a pungent smell it is not damaging to the global environment, not an unmanageable poison and not suspected to be carcinogenic. Thus, from a health and safety perspective ammonia use as a refrigerant can be broadened with reasonable precautions." The following table compares the properties of various refrigerants, including ammonia. (source: Ryan, Dr. Michael, Health and Safety Aspects of Ammonia's Use As a Refrigerant", ICF, 1990)

There are many advantages of ammonia refrigeration which have attracted attention. The following are the most significant.

-- low cost;
-- better cycle efficiency at most temperatures;
-- higher heat transfer coeficients;
-- lower liquid pumping costs for liquid recirculation;
-- can convey necessary refrigerant flow with small diameter pipes;
-- higher critical temperature;
-- easier to detect leaks;
-- more tolerant of water contamination;
-- favorable behavior with oil; and
-- no effect on ozone layer.

Some of the disadvantages of ammonia as a refrigerant are as follows.

-- behavior with oil;
-- not compatible with copper or copper alloys;
-- high adiabatic discharge temperatures; and
-- toxicity.
(source: Stoecker, W.F., "Expanded Opportunities For Ammonia As A Refrigerant", University of Illinois, 1990)

Since ammonia's heat transfer characteristics are so much better than most of the CFC refrigerants, little R&D has been done in the area of enhanced heat transfer for condenser tubing in ammonia systems. As the market fro ammonia refrigeration develops aluminum tubes with some type of enhanced heat transfer capabilities may be developed. This could lead to smaller condensers than those now employed in CFC systems. The focus on R&D in ammonia refrigeration has been on vapor compression systems, not on heat activated systems. The focus of the R&D in ammonia vapor compression has been on improved heat exchangers, equipment controls modernization, reduction in refrigerant charges and reduced evaporator costs. The International Institute for Ammonia Refrigeration is leading the reseach effort in ammonia vapor compression systems.

One of the most important reasons why ammonia mechanical vapor compression technology is deserving of attention in the context of district cooling is that these systems attain higher levels of energy

REFRIGERANT PROPERTIES

	CFC-11	CFC-12	CFC-114	Ammonia	HCFC-22	HCFC-123	HCFC-124	HFC-134a
Chemical Formula	CCl_3F	CCl_2F_2	$CClF_2CClF_2$	NH_3	$CHClF_2$	CF_3CHCl_2	C_2HClF_4	CF_3CH_2F
Molecular Weight	137.37	120.92	170.93	17.03	86.47	152.9	136.5	102
Refrigerant Cost (Bulk)	$1.41/kg	$1.63/kg	$2.36/kg	$.80/kg	$2.51/kg	$5-$10/kg	?	$5-$10/kg
Acute Toxicity (1=high, 6=low)	5	6	6	2	5	5-6?	6?	5-6?
Flammability	No	No	No	Yes	No	No	No	No
Ozone Depletion Factor	1.00	1.00	1.00	0	.05	.01	<.05	0.00
Greenhouse Effect	.32	1.00	0.5 to 1.5	0	.07	.01	<.01	<.01

Slide 4

efficiency than comparable CFC based mechanical vapor compression systems. Thus, these systems could be used with cogeneration and district cooling systems to simultaneously substitute for CFCs at the same time as improving energy efficiency and addressing the global warming and stratospheric ozone depletion crises. If mechanical vapor compression systems could be made available at an acceptable cost in small sizes for use in small scale cogeneration applications then additional environmental and economic benefits would be added to the block scale cogeneration option. A system which combined the following components is about as close to ideal as near term technical realities will permit: a very high efficiency small scale gas fired cogeneration; a high efficiency form of heat activated chilling which could also produce ice; cost effective small scale ammonia vapor compression chilling; and advanced forms of thermal distribution such as ice slurry and/or DHC pulsing DHC distribution technology.

The first attempt to convert the above vision into reality was a study of a cogeneration/ammonia vapor compression and district heating and cooling system for a judicial complex in New Orleans which was supported by a recent DOE District Cooling Technology Assessment Program. The project involved the application of industrial ammonia refrigeration technology in an institutional setting requiring chilled water for building air conditioning. It is the first study of such an application of ammonia to the district cooling of buildings known to date.

The proposed cooling plant consists of 4 ammonia refrigeration trains each consisting of a compressor, evaporator and evaporative condenser. Chilled water flows in series through each of the four evaporators in turn finally emerging as 33-35F water which is sent out via a district cooling system to a judicial complex. Water is returned at 52F. Use of this relatively high dT system reduces the size of the district cooling piping from a 12" line to an 8" line. This design is based on industrial refrigeration practice and the chiller is one which is usually employed in the food processing industry. This system eliminates a substantial part of the normal operating energy cost by eliminating the cooling tower and the water system needed to remove heat. These tasks are performed instead by the district cooling system.

The pipes required to move ammonia through this refrigeration system are much smaller than those required to move some of the CFC refrigerants. The characteristics of ammonia require a different type of compressor than the centrifugal compressors used with most water chillers. Evaporators for ammonia are similar in principle to those used for CFC refrigerants but are available in a much wider variety of types to meet the wide variety of refrigeration needs of many industrial processes. The New Orleans project proposed to use a low temperature ammonia chiller which employs an evaporator designed for the food industry to cool water to near freezing. Ammonia compressors are of the positive displacement type with screw compressors being the most common. Modern screw compressors are almost as efficient as centrifugal compressors used with CFCs. The principle difference between the ammonia system proposed for the New Orleans project and conventional centrifugal water chillers is that the ammonia systems use evaporative condensers, resulting in a lower condensing temperature, with an accompanying reduction in energy use. The ammonia refrigeration system will be designed to deliver 33F chilled water at a relatively high efficiency of 0.65 kw/ton and the system is expected to achieve an efficiency of 0.57 kw/ton under typical operating conditions. The capital cost of the ammonia chiller has been estimated at $1,200/ton, about 10-15% below the cost of conventional CFC-based chillers. The high dT of the district cooling system of 19F, due to the very low supply temperature of 33F and return at 52F, results not only in the ability to use smaller pipe sizes but also reduces the pumping power required to about 40 hp for the 1,000 ton system.

The ammonia chilling plant is to be driven by a natural gas fired diesel engine via an electric generator and electric motors. The engine will also operate in a cogeneration mode since heat will be recovered from the process to supply district heating in the winter. The design was found to have a payback of 7.1 years. However, if expected electricity rate increases are factored in, the payback declines to 6.4 years. (source: Anthony L. Laska, Ph.D. and Robert W. Timmerman, P.E., "New Orleans District Cooling Project")

One of the drawbacks of this design is the far less than optimal use of cogenerated heat due to the lack of a cost effective heat activated chilling systems in the size required. When a similar design was applied in a setting with much higher electricity costs and a longer heating season, the payback was found to be 5.6 years.

One important outcome of the New Orleans project is that R&D requirements to adapt ammonia chilling technology to the needs of district cooling were identified.

The most important focus for R&D in ammonia vapor chilling has been identified as the evaporator. Conventional ammonia evaporators produce cool air for use in cold storage rooms. New ammonia evaporators have been developed for cooling beer and the water used for soft drinks. It may be possible to base a new water chilling evaporator on this design. Although evaporators for use in CFC-based chillers have been the subject of considerable R&D and many improvements have been made over the years, since ammonia corrodes the copper and brass tubes and fittings used in CFC chillers, the technology is not directly transferable. The material of choice for ammonia chiller tubes is steel. Special steel tubing with internal fins or corrugations to enhance heat exchange capability are reportedly available but have not been widely used in ammonia evaporators.

Because of the hazards of an ammonia leak it is advisable to use the minimum amount of ammonia; the evaporator contains the largest fraction of the system refrigerant charge. One type of commercially available evaporator, the sprayed surface type has a low refrigerant charge and high heat transfer rates but is very costly. There is also little experience with ammonia systems designed and operated as heat pumps as well as chillers. This capability would appear to be necessary if the ammonia chiller is to be designed for use in a system providing district heating as well as district cooling. Ammonia chillers also are lacking when it comes to system controls. Apparently, ammonia systems may be able to use very different and lower cost control systems than centrifugal chillers.

Ammonia Chilling R&D Needs

The goal of R&D in ammonia evaporators would be to develop an inexpensive, high performance ammonia evaporator with a low refrigerant charge. It would probably use sprayed surface on the ammonia side and internally finned tubes on the water side. By spraying the liquid ammonia over the surface of the tubes, heat transfer coefficients are high with only a small volume of liquid in the evaporator. The internally finned tubes give a good heat transfer coefficient on the water side.

Sprayed surface evaporators are commercially available but the design is not considered optimal for district cooling. The New Orleans project used sprayed surface evaporators for the last stage only due to a cost of $364 per ton of capacity. The conventional evaporators used for the higher temperature stages cost between $130 to $175/ton of cooling capacity. The design goal would be a sprayed surface evaporator available at a cost of between $130 per ton and $160 per ton with a leaving terminal difference of 4F and a chilled water range of 6F. This would save $45 to $75 /ton of capacity. Heat recovery and refrigerant subcooling also need study, redesign and optimization for use of ammonia chilling in district cooling systems. Particular attention needs to be paid to making the systems as safe as possible. (source: Robert W. Timmerman, "Proposed Research Program For Advanced Ammonia District Cooling",4/30/90)

One of the more interesting aspects of ammonia refrigeration equipment is that the economy of scale in ammonia systems is reached in much smaller sizes than CFC vapor compression systems. Thus, they are particularly suited for use in block scale cogeneration and DHC. This feature of ammonia refrigeration systems is due to the fact that ammonia requires a much lower compressor displacement per ton of refrigeration than the fluorocarbons. Ammonia vapor is much less dense than fluorocarbons. While the pressure ratio between evaporator and condenser is similar for ammonia, R-12 and R-22, ammonia has the largest pressure difference between evaporator and condenser. These differing physical properties dictate different compressor technologies: fluorocarbons use centrifugal compressors, while ammonia systems use positive displacement systems, either reciprocating or screw. The maximum size of screw compressors is much less than centrifugals: 2,000 tons vs 10,000 tons. (source: Robert W. Timmerman, "District Cooling as a Way To utilize Non-Fluorocarbon Refrigerants", April 21, 1988)

One of the more interesting aspects of the ammonia chilling system employed in the design of the New Orleans district cooling project is that it was intended for an industrial application requiring 33F chilled water. This led the design engineer to use a district cooling system which supplies 33F water and returns it at 52F for a 19F dT, nearly double the dT of many conventional systems. This design resulted in considerable savings in piping capital cost and pumping energy for the distribution system. It also reduced building energy requirements to lower levels than they would otherwise be with conventional chilled water at 42F since the colder water reduced the need for fan power in existing buildings and would permit the use of smaller diameter ductwork in new buildings. For these reasons low temperature/high dT chilled water district cooling may be competitive with district cooling systems using conventional supply and return temperatures.

The low temperature/high dT district cooling option has also been compared with ice slurry production. It has been found that the ice system requires 27% more power than a conventional chilled water system and 18% more than a low temperature system. Water can be cooled in an ammonia chiller from 60F to 33F with only 8% more power than in cooling from 55F to 45F. The ice system has capital cost advantages over the low temperature option due to lower storage costs and lower pipe diameters. However, the problem of using ice slurries efficiently and reliably at the point of end use has yet to be satisfactorily resolved. The comparative analysis of these two systems concluded that ice slurries will have an operating cost premium while saving capital. If the major reason to develop district cooling is energy efficiency, low temperature chilled water might prove to be a better candidate than either ice slurries or conventional higher temperature supply/low dT systems. This would be true except in cases where the ice slurry is obtained from very high efficiency sources such as ice ponds and if the energy use of the building cooling system can be greatly reduced by efficient use of the ice in the slurry. (source: Robert W. Timmerman, personal communication, July 11, 1989)

Since the use of ammonia chilling may make it viable to use low temperature/high dT district cooling and this option may be more efficient than other competing options, the DOE should investigate it and determine if, together with a redesigned ammonia chilling system, the low temperature/high dT district cooling option may be economically viable.

The Use of Friction Reducing Additives In District Cooling Distribution Systems

Recently, a study of the use of advanced fluids in district cooling systems analyzed the use of friction reducing additives which have been tested in an IEA district heating R&D program with apparently impressive results. The objective of the IEA study was to determine the degree to which such additives could improve the cost effectiveness of DHC systems by reducing capital costs by reducing pipe sizes, reducing operating costs by reducing pumping costs or by increasing system capacities without costly expansions. The IEA program tested additives in the Herning, Denmark district heating system with apparently very encouraging results. In this system, friction reduction additives (FRAs) decreased pressures to about 20% of normal system pressures throughout the system and in straight pipes pressures were reduced to only 10% of normal values.

FRAs for cooling systems are also under development and work to date has shown that pressure reductions of up to 70% have been achieved. Ice slurries have also been pumped at concentrations of over 30% with pressure drops equal to that of water. In some cases, FRAs have been found to work well with ice slurries and pressure drops of about 50% have been achieved at ice slurry concentrations of up to 25%. A Canadian study compared the use of FRAs in district cooling systems of a variety of types including conventional systems which do not use FRAs. The results of this study are summarized in the following paragraphs.

The cases considered by the study include the following:

Case	Description
1.	Conventional system with 7C/45F supply and 13C/55F return.
2.	Conventional system with FRA capable of reducing friction 70%.
3.	Low temperature with 1C/34F supply and 13C/55F return.
4.	Low temperature case 3 with FRA to reduce friction 70%.
5.	Ice slurry at 20% loading and a 13C/55F return temperature.
6.	Ice slurry case 5 with FRA reducing friction by 50%.
7.	Ice slurry case 5 with distributed storage in buildings reducing peak flows by a factor of 3.
8.	Ice slurry and storage case 7 and FRA as in case 6.

Benefits of Advanced Fluids

Technology	Capacity of Existing 200 mm Diameter Pipe	Annual Cost (est Dia mm) For a 30 MW System in Canadian $
1. Conventional	1.5 MW	310,000 (710)
2. (1)+FRA	2.5 MW	240,000 (600)
3. Low Temp	3.5 MW	200,000 (525)
4. (3)+FRA	5.0 MW	160,000 (440)
5. Ice slurry (20%)	7.5 MW	120,000 (380)
6. (5)+FRA(50% red.)	10.0 MW	110,000 (320)
7. (5)+Storage	23.0 MW	75,000 (215)
8. (7)+FRA(50% red.)	30.0 MW	70,000 (200)

The conclusions which were drawn from this data are as follows.

1. FRAs for chilled water systems are very valuable for expanding system capacities and for reducing first costs and operating costs for new systems. While FRAs appear to work in highly treated water some compatibility problems have been observed with commercial corrosion inhibitors. Outstanding issues resolving FRA development and compatibility with corrosion inhibitors should be resolved as soon as possible.

2. Using low temperature water supply systems can approximately double system capacities. Furthermore, customer air handling units, etc. can be downsized, reducing costs and improving use of building space. Alternatives for efficient low temperature chilling should be investigated and commercialized.

3. Ice slurry technology can considerably increase system capacities or reduce system costs. Economical slurry generation and storage technology should be seriously investigated and potential returns on utility investments further investigated. Design guidelines on the use of slurries need to be developed and made available to architects and engineers.

4. Sufficient information is not yet available to establish clear recommendations to developers and designers regarding cost effective advanced fluid technology application. Refine economic analyses & develop costs for implementing technologies described.

In addition to the current generation of FRAs which were the basis of this study, new high temperature phase change materials are also being investigated for use in district heating. These include transportable materials that can greatly increase the heat carrying capacity of water and facilitate distributed storage. These materials will generate the same kind of benefits that ice brings to cooling systems. New additives are also being developed which can increase the apparent specific heat of water at temperature ranges currently common for chilled water systems. This development might considerably increase the capacity of systems while still enabling the use of existing chillers. In addition, some materials may be applicable for steam district heating systems which could be applied to the task of reducing peak capacity problems. (source, Wiggin, Michael, "Advanced Fluids: The Benefits Are Real", Energy Research Laboratories, Energy, Mines and Resources, Canada)

There are a number of problems associated with advanced fluids which have yet to be successfully addressed. One of the primary problems is with heat transfe.. to end user systems. Apparently many of the new advanced fluids degrade heat transfer and thereby compromise their advantages. Thus, it may be necessary to develop end user heat exchangers to interface with DHC systems which have enhanced heat transfer capability and are compatible with the new advanced distribution fluids.

Another problem with advanced fluids concerns the production of ice from either vapor compression or heat activated chillers. Current technologies for ice production and collection have proven to be either high cost or technically problematic. A thin membrane heat exchanger under development at BNL appears to exhibit the potential for resolving both cost and performance problems. Preliminary tests of this device showed that it produced very thin sections of ice fragile enough to be pumped through a pipe in millimeter sized pieces offering little friction resistance and therefore potentially requiring little in the way of additional pumping power compared to chilled water. This ice production system is a critical component in ice slurry district cooling and deserves to be pursued further by DOE.

A related problem is the transfer of the ice fraction in a slurry to distributed storage systems at the point of end use. If a cost effective system could be developed to transfer the ice fraction as well as store and use it in an efficient manner, then the peak capacity of the distribution system might be reduced considerably since the cooling density of the ice would minimize storage requirements which are an important concern in urban buildings served by DHC systems.

The development of ice slurry district cooling using advanced distributed ice storage technologies might also pave the way for the development of thermal pulsing systems. This is due to the fact that ice slurries substantially increase the temperature difference between supply and return water and thereby reduce required pipe diameters to about half of those of conventional chilled water systems. The dT of ice slurry systems are much more in line with those of hot water district heating. If the two services can be designed with roughly the same dT then the stage would be set for the development of thermal pulsing systems via a single or two DHC pipes since the end use equipment might be shared by the two services. However, it may be necessary for each service to have separate end use storage systems for each service. In either case, the development of one or two pipe thermal pulsing DHC systems would have many beneficial attributes including lower capital cost distribution piping, lower civil costs and fewer institutional difficulties associated with installing the smaller piping in crowded urban streets. The DOE should give high priority to thermal pulsing systems using ice slurries and other advanced FRAs and PCMs. This technology needs to be developed along with appropriate end use systems.

Advanced distribution fluids will be especially important to block scale cogeneration and DHC since these systems will have to attain very low costs and high efficiencies in every system component if the block scale option is to reach its full potential. The block scale cogeneration and DHC option brings with it a very important distribution system advantage in that small systems eliminate the need for extensive thermal transmission systems and instead employ very small distribution line lengths merely sufficient to link together several buildings, groups of buildings or urban blocks.

Block scale systems may offer additional distribution system cost advantages if these systems are designed in an innovative manner. Instead of designing block scale cogeneration and DHC distribution systems as these systems have been traditionally designed with a large plant located at one end of a long transmission line, it seems advisable to opt for more compact distribution system development strategies. Systems serving smaller areas will have smaller diameter distribution pipes which can be more easily installed in streets as well as through basements and over rooftops.

In addition, it has also been suggested that a hub and spoke distribution system configuration be used instead of the traditional linear design. instead of locating the thermal source in a corner of the service area, the hub and spoke option would locate the thermal source at the center of the service area. Distribution lines would radiate from the plant like spokes on a wheel rather than like branches off a tree trunk. This hub and spoke system would grow by sending out small feeders to service satellite loads. As the satellite grows new block scale cogeneration capacity can be added to serve new and expanding loads. The line between the two plants is retained to provide back up for either plant. The costs and benefits of this and other distribution system development strategies need to be better understood if optimal strategies are to be developed for the widely different conditions which exist. The DOE should initiate a project in optimal distribution system configurations for block scale cogeneration and DHC.

Bibliography

Task 2

Advanced District Cooling Technology:
R&D Needs and Opportunities

Aaroen, Audun, "Heat Pump Energy Central For District Heating/Cooling System", in "Advanced District Heating Production Technologies", Ove C. Morck and Thomas Pedersen (eds), IEA DH R,D&D Programme, Novem, 1989, pp. 573-581.

Alefeld, Prof. G., "Investigation Into Advanced Absorption Heat Pumps", in District Heating & Cooling R&D Project Review", IEA DH R,D&D Programme, Novem, 1989, p.151.

American Gas Association, "Advantages of Natural Gas Cooling In The Commercial Sector: Equipment, Economics and Environmental Factors", Issue Brief 1991-5, Feb. 1991.

American Gas Association, "Introduction to the American Gas Cooling Center Product Commercialization Program", 1991.

American Gas Association, et. al., "USDOE FY 1992 Funding For Natural Gas Air Quality; Efficiency and Supply; and Research, Development and Demonstration: Recommendations", September, 1990.

American Gas Association, "Energy Efficiency, Air Quality, Energy Security: Compelling Reasons For Accelerated DOE Funding Of Natural Gas Research, 1991.

Anderson, M. Kent, "United States Research and Development Activities (in Ammonia Chilling)", paper presented at "International Conference on CFC & Halon Alternatives", Oct., 1989, Washington, D.C.

Ballou, Donald F., "Ammonia", paper presented at "International Conference on CFC & Halon Alternatives", Oct., 1989, Washington, D.C. (*: International Institute of Ammonia Refrigeration).

Bode, David, "Gas Engine Cooled Buildings--Wave of the Future?", in "Diesel Progress: Engines and Drives", Jan., 1991, pp. 6-30.

Borsig, Gruppe Deutsche Babcock, "Absorption Refrigeration Plants Using Ammonia and Water Refrigerants"

Kruse, Dr. Horst*, "Western European Research and Development Activities", paper presented at "International Conference on CFC & Halon Alternatives", Oct., 1989, Washington, D.C. (*: International Institute of Refrigeration).

Laska, Dr. Anthony L., and Robert W. Timmerman, P.E. "New Orleans District Cooling Project", City of New Orleans, LA, 1990.

Leigh, R.W., et. al., "Cost Reductions In Absorption Chillers", Phase II, Brookhaven National Laboratory, Gas Research Institute, 1989.

Menzer, Mark*, "Gasfired Chillers: Reducing the Need for CFCs", paper presented at "International Conference on CFC & Halon Alternatives", Oct., 1989, Washington, D.C. (*: American Gas Association).

Ryan, Dr. Michael, "Health and Saftey Aspects of Ammonia's Use As A Refrigerant", ICF for USEPA, Washington, D.C., 1990.

Skalafuris, Dr. Angelo J., and John A. Kocur, "Proposal To Develop An Innovative, High Efficiency, Natural Gas Fired, Non-CFC Air Conditioning System To Compete in Domestic and International Markets", Modular Cogeneration Corporation, Mt. Vernon, N.Y., April, 1991.

Spencer, Ambrose, Personal Communication, June 1991.

Stoecker, W.F., "Expanded Opportunities For Ammonia As A Refrigerant", University of Illinois, 1990.

Timmerman, Robert W., "Proposed Research Program For Advanced Ammonia District Cooling", Boston, MA., April 30, 1990.

Timmerman, Robert W., "District Cooling As A Way To Utilize Non-Fluorocarbon Refrigerants", April 21, 1988.

Timmerman, Robert W., Personal Communication Concerning Heat Activated Cooling Systems Using Heat From Small Diesel Engine Cogeneration Systems, Feb. 27, 1989.

Tsai, Charley, "Advanced Fluids District Cooling Systems", in "Advanced District Heating Production Technologies", Ove C. Morck and Thomas Pedersen (eds), IEA DH R, D&D Programme, Novem, 1989, pp. 707-716.

Wiggin, Michael, "Advanced Fluids: The Benefits Are Real", Energy Research Laboratories, Energy Mines and Resources, Canada, Ottawa, Ontario, Canada, 1991.

TASK 3

Renewable Energy Technologies for DHC Supply

Part I: Renewable Sources of District Cooling

Table of Contents

Freecooling

One of the most widely employed "unconventional" techniques for increasing the energy efficiency of chilled water production has been the use of existing cooling towers for the production of "freecooling" during the winter months. This process uses cooling towers for the production of chilled water during the winter months when ambient air temperatures are at or below district cooling system send out temperatures. When ambient air temperatures drop to levels required for district cooling supply, the cooling towers use that air to directly produce cooling supplies, by-passing the compressor and saving in the process the energy required to run the compressor.

The most simple application of this process involves the direct production of free cooling supplies upon demand for the district cooling system. However, this application achieves a minimum amount of savings since the availability of cold ambient winter air can be considerably out of phase with demand on both a daily and a seasonal basis. The energy saving potential of freecooling can be greatly increased if sufficient cold water storage capacity is employed to hold cold water produced during cold winter nights for use during the day.

The district cooling system serving Yale University in New Haven, Connecticut utilizes a large "cool pool" to serve as a thermal storage facility to hold chilled water produced from off-peak power. Since the off-peak period occurs at night when ambient temperatures are lower than at the peak demand period during the middle of a summer day, this design also results in chiller capacity and energy savings. The cool pool also permits the maximization of the inputs of freecooling into the district cooling system.

An Alabama company has developed a commercial cooling system using cooling towers to produce chilled water for seasonal storage in aquifers which can be tapped in the summer months to supply space cooling. The first commercial cooling tower/aquifer thermal storage system was installed in Tuscaloosa, Alabama and was designed and constructed by Schaetzle Associates. It is expected to provide most of the cooling for a 60,000 ft2 building. The total cost of the system was $150,000 and the expected payback was 3 years.

This system takes water from an unconfined aquifer and chills it in the cooling tower. In Tuscaloosa about 1400 hours of sufficiently cold ambient temperatures are available in which to make chilled water which is injected into the aquifer at a rate of 200 gallons/minute at an average temperature of 49F. Although most of the chilled water will be collected during the winter for use in the summer, in the fall and spring the double well system will work on a diurnal basis, cooling during the day and recharging at night. A similar system was also designed and constructed by the same company to air condition an 80,000 ft2 building at the University of Alabama.

Since most large urban buildings have cooling towers, freecooling is, of course, an option which is open to them and one which many have employed for some time. However, the lack of long term storage and/or a distribution system to hold and return the chilled water so collected to the user inhibits the maximization of the use of freecooling in urban areas.

The storage of chilled water produced by freecooling in aquifers, boreholes in rock or rock caverns underneath a city and linked by a thermal distribution system to and from buildings might be a relatively low cost means of initiating the development of a district cooling (and heating system) in an urban area. The customers of such a system would, at least initially, be the producers. Distribution systems would be as short as possible since the initial buildings served would have to be located as close as possible to the thermal store to minimize costs. Certain building chillers could be modified to attain optimal levels of energy efficiency in the production of both chilled water from cold winter air and in the production of heat rejected from the chiller during chilled water production.

Spray Ponds and Aquifer Chilled Water Storage

Supplies of freecooling can also be obtained from abundantly available cold winter air through the use of a less capital intensive and more energy efficient process--spray ponds. In this case cold is extracted from the air by spraying water at high flow rates from a number of spray nozzles directly into the cold air. This process can cool large volumes of water to within 3F of the wet bulb temperature. After cooling by this process the water is collected in a reservoir and subsequently injected into an aquifer for use months later to supply cooling demands. R&D in spray pond technology has been conducted at Texas A&M University since the late 1970's.

Experimental spray ponds which have been built and tested at Texas A&M have shown that it is possible to obtain large-scale supplies of cold water at about 45F for injection into aquifers with high recovery rates as far south as central Texas. Studies have shown that new district cooling systems using the technology could be competitive with individual building air conditioning.

Spray pond chilled water production and aquifer storage is considered a low cost source of district cooling for areas such as Texas and elsewhere in the southwest. Not only do these areas have a winter ambient air resource which is sufficiently low in temperature for use as a heat sink for spray ponds but they also have water resource conditions and regulations which are potentially quite favorable to the development of spray pond/aquifer systems for the production of district cooling. This is due to several interrelated factors. In order to tap abundant supplies of cooling from ambient winter air using spray ponds, an inexpensive, long term storage medium is necessary. Aquifer thermal storage is not only the most inexpensive method of long term thermal storage yet devised but appropriate aquifers for thermal storage are ubiquitous throughout the

United States, particularly throughout the south and southwest. However, the scarcity of water supplies and the fragility of the aquifers in the southwest have resulted in the development of a comprehensive system of regulation governing the use of aquifers. These regulations apparently rather severely constrain individual use of aquifers for all uses including thermal storage and other thermal uses such as well water source heat pumps. In order for the aquifer to be used as thermal storage capacity, a central authority would have to be established to undertake this task for a community. Thus, from regulatory and institutional viewpoints, spray pond cooling production and aquifer thermal storage seems to be well suited for use in supplying district cooling simply because there may be no other effective way of using aquifers for thermal storage purposes.

Although the market potential of the spray pond/aquifer storage and district cooling option appears to be quite large, such systems nonetheless must overcome a number of technical hurdles before commercialization is possible. One technical problem is the high degree of variability in the temperature of the cold water produced by spray ponds due to variations in ambient temperature, humidity and wind speed. Variable spray pond production and aquifer storage temperatures result in the supply of variable temperatures to chillers. This can present complications for efficient use of precooling for conventional chillers since this equipment is usually engineered to meet peak demands by varying flow rates rather than supply temperature. In order to produce constant temperatures at optimal levels of efficiency from chillers using water sources at variable temperatures it will be necessary to develop or to adapt chillers which can efficiently and cost effectively use variable temperature cold water sources.

One of the more technically advanced district heating and cooling systems in the world employs an aquifer as a source of heating and cooling for a heat pump/chiller-based system and serves a small part of St. Paul, Minnesota This system obtains a COP of 5.0 when operating in a cooling mode using 50F aquifer water. If spray ponds or cooling towers were employed to cool water and to interseasonally store it for use in district cooling in summer, it has been estimated that the effective cooling COP which could be realized would be greater than 10.0. This level of chilled water production efficiency is greatly in excess of levels which can be obtained by conventional means. Moreover, there is every reason to expect that if chillers were to be adapted to be able to run with optimal levels of efficiency using very low precooling water sources that the levels of energy efficiency obtained would be greatly in excess of a COP of 10.0 given 50F precooling water supply. It has been estimated that if chillers are redesigned to efficiently use 60F water for precooling that the electric power required to run these systems could be reduced by 40 to 50%. Such efficiency improvements could provide a compelling reason to develop district cooling since spray ponds are not compatible with existing buildings located in dense urban areas due to the relatively high land use intensity of this option. NOVA has estimated that the land area required for spray ponds is about 5% of the building floor area requiring air conditioning.

Future DOE R&D in spray pond technology should focus on the development of systems for those parts of the U.S. with insufficient cold winters for ice making. The southern states and the Pacific coast are two such areas. The winters in these areas are sufficient for the production of chilled water at 40F to 45F. In areas near surface water bodies winter water temperatures of 50F are typically reached. If sprayed into the air on cold winter nights when temperatures dip into the low 40s or high 30s it is reasonable to expect that the production of chilled water at 40F to 45F would be possible. Chilled water at these temperatures can be stored inexpensively in aquifers, subsurface soil or rock for use during the summer cooling season.

Ice Pond Technology For District Cooling

Ice pond or natural cycle cooling systems (NCCS) technology offers the most efficient and least cost means of obtaining large volumes of low cost ice, slurries and chilled water from a natural source of cooling as is currently available. Ice ponds make ice by spraying atomized droplets of water into the cold winter air. The droplets cool and form ice crystals which fall into a basin in which very large ice piles can be accumulated over the course of a winter season. Experimental ice ponds were developed at Princeton University and commercial prototypes were developed by NOVA, Inc. and New York State ERDA. These systems have been developed for both building air conditioning and district cooling applications as well as for industrial process cooling and desalination. Ice ponds have demonstrated very high levels of energy efficiency and excellent potential for achieving very low costs for delivered energy in large size applications. Most of the R&D on ice ponds took place between 1979 and 1986.

In the early 1980s NYSERDA and NOVA investigated ice ponds for desalination and potable water production as well as for bulk ice production. In one of these projects an ice pond was coupled with a spray pond for pre-cooling water when ambient air temperatures were too high for ice production. This combined ice pond/spray pond or natural cycle cooling system was estimated to use less than 10% of the energy of conventional refrigeration systems in large scale commercial process cooling applications.

In addition to their high energy efficiency, ice ponds also exhibit several significant potential advantages for use in district cooling systems. By virtue of the fact that ice ponds produce ice they are an ideal candidate to use ice slurry district cooling distribution systems and would in the process eliminate the one major obstacle to the use of these systems--the high energy cost of ice production via conventional means. If an ice pond could incorporate a separate system for the production of very small individual ice crystals or pieces which could readily be pumped in an ice slurry district cooling system it could prove to be an unbeatable combination. For the same pipe size and mass flow rate, a 20% ice slurry with return water at 50F can provide 5 times the cooling obtained from a chilled water district cooling system with a supply temperature of 41F and a return temperature of 50F. Since the ice provides more than 10 times the cooling capacity of a chilled water store of the same volume it can permit an economical method of thermal storage at the point of end use thereby reducing the peak distribution capacity even further, as long as such technology can be developed. Pumping power can also be reduced because a 20% ice slurry carries about 5 times more cooling than water per pound circulated. (source: Tsai, Charley, "Advanced Fluid Cooling Systems", Sunwell Engineering, 180 Caster Ave., Woodbridge, Ontario, Canada 141 4X7)

If existing district cooling systems were to employ an NCCS/ice slurry system, those systems could expand services to areas adjacent existing loads using existing distribution system capacity. Whereas, new district cooling systems need only install distribution piping with a maximum of half of the diameter which would have to be installed with a conventional system. In addition, the cold supply temperatures which ice ponds can produce exhibit superior dehumidification characteristics when compared with conventional supply temperatures. Since latent heat loads can account for up to 30% of the total heat loads which need to be removed from buildings, this aspect of ice ponds can also prove significant for areas with high humidity. Thus, ice pond supplied ice slurry district cooling would appear to be an unbeatable combination.

The NCCS exhibits a 90% energy savings over an electric chiller supplying air conditioning at conventional temperatures. This efficiency advantage would be much greater when compared with an ice making chiller which must expend a significant amount of additional energy to make ice and low temperature chilled water for an ice slurry system. The high energy costs and low energy efficiency of the ice making chiller may well outweigh the considerable capital cost advantages of the ice making chiller when used in combination with an ice slurry distribution system. However, the NCCS with its extraordinarily high energy efficiency and high but tolerable capital cost would seem to be as close to an ideal match for the ice slurry district cooling system as can be devised. It clearly represents the ultimate in a highly energy efficient district cooling system.

Economic analyses of ice ponds done in the early to mid 1980s showed that these systems would cost about $500/ton vs conventional electric chillers at $350/ton. The 90% energy savings of these systems more than outweighed the higher capital costs. Paybacks for advanced ice pond designs were estimated to be able to deliver cooling with a payback of about 2 years. A DOE DHC feasibility study for Atlantic City, New Jersey conducted in the mid 1980s by Dr. Theodore Taylor, President of NOVA, Inc. and the inventor of ice ponds, showed that ice ponds could provide district cooling to existing buildings with a pay back of 3 years. The ice pond supplied the district cooling system with cooling at a cost of about $2-3.00/MMBtu. It is worth noting that this study assumed that ice ponds would supply low temperature chilled water at 33F rather than an ice slurry. If the additional capital and energy savings which ice slurry district cooling offers were incorporated into such a design the payback would very likely be much shorter.

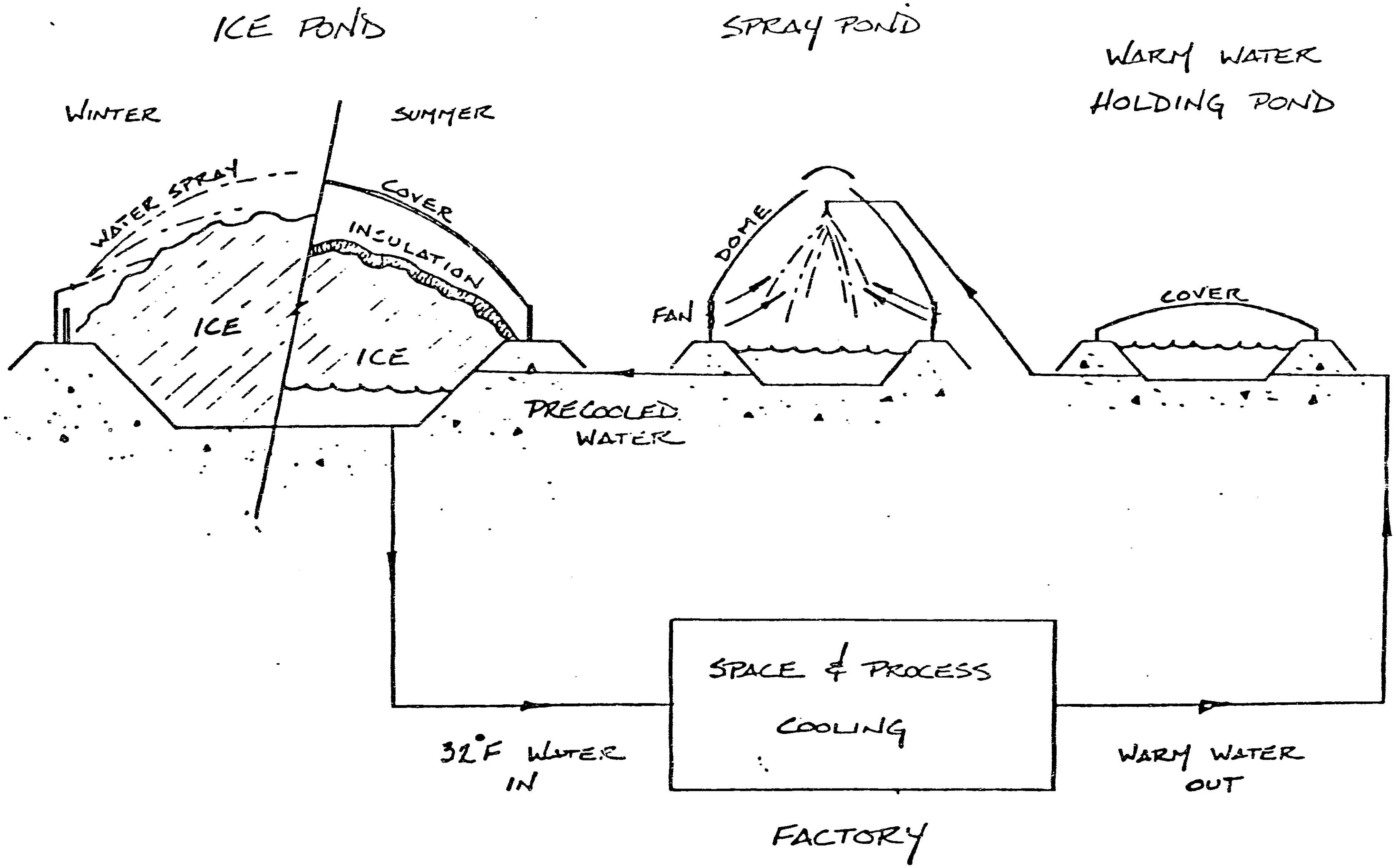
As the following chart indicates ice ponds exhibit very strong economies of scale. When ice ponds reach the scale of 10,000 tons of cooling capacity they begin to look competitive. In the case in which an ice pond competes with an electric chiller and $0.06/kwh electricity, the ice pond has a one-time capital cost advantage of $1,900,000 over a new chiller and an energy saving advantage of $800,000 per year. Thus, for a new system serving a building or buildings which do not yet have chiller capacity the advantage is clearly in favor of the ice pond. Since these calculations do not include the cost of developing a district cooling system, such costs would have to be factored into the equation before it would be apparent whether such a systems could be cost effective.

At $0.12/kwh and $1,600,000 in energy savings a 10,000 ton ice pond might be justified because energy savings of $533/yr/dwelling might be sufficient to pay for the development of a district cooling system serving an urban area comprised of attached houses. When ice ponds of 100,000 tons of cooling capacity are considered, the energy savings are so large relative to the capital cost of the system that the development of a district cooling system probably could be financed out of those savings in a reasonable amount of time as long as building and cooling loads were sufficiently dense and diverse.

These figures appear to indicate that because ice ponds have such strong economies of scale they should be added to a district cooling system only after loads have been built up sufficiently by other means such as mobile cogeneration/heat activated chilling/ammonia chilling/DHC systems. When a sufficient load of perhaps 100,000 tons of cooling capacity is interconnected via district cooling the NCCS could be constructed and immediately utilized to its maximum capacity. The mobile chillers could then be moved elsewhere to build up other loads for eventual connection to an NCCS.

One important consideration during the period when mobile cogenerators are being used to incrementally build up cooling loads and development of the district cooling system is on-going, is that the distribution system be designed to be an ice slurry system. This will require that the mobile cogenerators utilize vapor compression and heat activated chillers which can also produce ice. The reason for this is that ice slurries save so much in terms of capital that if ice slurries can be supplied from an NCCS then the combination of a very high efficiency source of ice and 33F water coupled with the low capital cost of the ice slurry distribution system would be an optimal combination and as close to an ultimate solution to long term urban air conditioning supply as can be envisioned.

There are several additional advantages of ice ponds which deserve mention. One application for ice ponds is the production of potable water from seawater via the freezing process in which only



NATURAL CYCLE COOLING SYSTEM

ICE PONDS FOR DISTRICT COOLING

	NOMINAL COOLING CAPACITY (TONS)			
	100	1,000	10,000	100,000
ANNUAL COOLING LOAD (TONS ICE EQUIV.)	5,000	50,000	500,000	5,000,000
ICE STORAGE CAPACITY (TONS)	5,700	49,000	450,000	4,300,000
NOMINAL # DWELLING UNITS SERVED	30	300	3,000	30,000
ICE POND AREA (ACRES)	0.32	1.3	5.9	27
CAPITAL COST OF ICE POND ($1,000's)	200	900	3,100	22,000
CAPITAL COST OF ELEC. CHILLER ($1,000's)	50	500	5,000	50,000
CAPITAL COST DIFFERENCE ($1,000's)	150	400	-1,900	-28,000
ANNUAL ENERGY COST SAVINGS WITH ICE POND (@ 6¢/kw hr.)	8	80	800	8,000
ANNUAL ENERGY COST SAVINGS WITH ICE POND (@ 12¢/kw hr.)	16	160	1,600	16,000

ASSUMPTIONS

ANNUAL COOLING LOAD = 50 X NOMINAL CAPACITY
NOMINAL COOLING CAPACITY/DWELLING UNIT = 3.3 TONS
COOLING WATER SUPPLY TEMP. = 33°F; RETURN WATER TEMP. = 58°F
ELECTRIC CHILLER COST = $500/TON; POWER/COOLING CAP. = 1.25 kw/ton
LAND COST NOT INCLUDED. WOULD ADD LESS THAN $50,000/ACRE

pure water is frozen, the highly concentrated unfrozen brine is washed off the ice as it melts and the brine is disposed of back into the sea. A demonstration of this application was conducted by NYSERDA in 1983-1984 on eastern Long Island, New York ("Investigation of Ice Pond Technology For Water Purification" Final Report, April, 1984, David Wolcott, Project Manager, NYSERDA & NOVA, Inc.) The results of this project indicated that ice pond spray freezing is a practical method for desalinating seawater to potable quality and is likely to be able to produce potable water at costs approaching $1.50 per 1,000 gallons. This cost is only slightly higher than the average cost of municipally supplied potable water in many locations. Ice ponds for desalination were determined to be viable anywhere there is land available near the sea and there are at least 600 hours per year of air temperature below 29F. If an ice pond were designed to simultaneously supply both district cooling and potable water the additional revenues from water supply could improve system economics even further.

One potential problem with NCCS is that the scale of these facilities in district cooling applications will probably be quite large covering many acres with piles of ice reaching heights of up to 100´. The land intensity of these systems poses potential problems since to minimize thermal transmission costs it would be desirable to site NCCS as close to urban cooling loads as possible. However, since NCCS potentially can combine a number of functions, the location of these systems nearby urban areas could have several benefits which might offset the high land costs of siting these systems on expensive urban land. On the other hand, the urban heat island effect might significantly reduce the efficiency of an NCCS since rural urban temperature differences are normally in the range of 5-10F. All of these factors will have to be taken into consideration in the siting of NCCS.

Ice stored at 32F is capable of holding many more times the cooling capacity of cold water stored at 40F. An ice pond can store approximately 6 times the cooling capacity of 40F cold water. Since the vertical storage capacity of the ice pond can be at least twice that of a cold water store the ice pond can hold up to 13 times as much cooling capacity as the cold water store for an equivalent land area. If ice ponds are used to desalinate or purify and store potable water they may save land which would normally be required to store water in relatively shallow reservoirs since ice can economically be piled as high as 100´ whereas many reservoirs are only 20´ to 30´ deep. Ice ponds for combined potable water and cooling production also could conceivably be located at relatively great distances from potable water and district cooling loads as long as those loads are sufficiently large to capture the economies of scale of these systems and thereby justify the development of long distance ice slurry transmission systems.

Since ice pond and spray pond technologies are closely related, future research will have to identify those areas of the U.S. where each is most appropriate, either alone or in combination. It is most likely that stand alone spray ponds will prove most applicable in the southeast and southwest. However, in some of these areas, limited amounts of ice might be made but not efficiently stored in above ground piles over long periods. In such cases, meltwater from the ice could be stored along with cooled water from spray ponds in aquifers. From about mid-U.S. latitudes north, combined spray and ice ponds will probably be the most appropriate technology. However, future research will have to more precisely establish the markets for these systems.

If it is widely implemented, the impact of NCCS technology on the energy supply system of the U.S. might be nothing less than profound. Not only would the efficiency of air conditioning supply improve by 90% over present electric air conditioning systems but the remaining energy would be consumed for the most part during the winter months in the production of ice. Such a system would displace huge amounts of electric generating capacity, permitting the retirement of the most inefficient plants--those used for peak electricity supply in summer. In the process, air conditioning costs would plummet, significantly improving economic productivity.

The environmental impacts of the widespread use of NCCS based district cooling are even more impressive. A 90% energy efficiency improvement implies reductions in harmful emissions from power plants used to generate electricity for air conditioning of about the same amount. Moreover, these emissions reductions would take place during the summer months--the months which experience the greatest air pollution problems due to both the emissions attributable to electricity generation for air conditioning as well as photochemical effects. A drastic reduction in electricity generation during the summer months would also reduce the amount of heat emitted from power plants in and around urban areas which is considerable given the fact that much peak power is generated by relatively inefficient gas turbines which exhaust waste heat at very high temperatures which is then emitted into the atmosphere to contribute to the urban heat island effect. The shift away from such plants and toward ice ponds might result in a reduction in the ambient summer temperatures of many urban areas, thereby providing a further reduction in air conditioning requirements.

The fact that ice ponds substitute a naturally occurring refrigerant--cold winter air--for CFCs and their proposed environmentally problematic substitutes is yet another important attribute of these systems for which both economic and environmental credits could be taken.

The accumulated energy efficiency, economic and environmental advantages of ice ponds are so great that it is difficult to understand why the DOE and other private and public energy technology R&D institutions have virtually ignored these systems over the last decade. Ice ponds clearly have the potential to revolutionize not just the district cooling industry but also to positively effect an impressive array of environmental, energy and economic factors. NCCS have such a substantial array of energy efficiency advantages for district cooling and especially for use with ice slurry district cooling that the DOE DHC program and the American DHC industry should make the development of this technology the highest priority in future R&D programs.

Although ice ponds already appear very attractive for near term large scale district cooling applications, there are a number of opportunities available to improve the performance and further reduce the cost of ice ponds and ice pond-supplied district cooling. Research is needed in all phases of ice pond operation: ice making, ice keeping, ice crushing and ice melting. It should also include the use of ice ponds for potable water production and storage.

Radiative Cooling

Radiative cooling, a phenomenon which occurs at the earth's surface, is the only means by which the earth looses heat or cools itself. Infrared heat transfer as a result of radiation can be used as a source of natural cooling. This is especially true of arid areas with low humidity levels of 5-15%. In such areas of low humidity the effects of nocturnal infrared radiation are well known. The often extreme day to nighttime temperature swings experienced in desert areas are a dramatic illustration of the effects of nocturnal infrared radiation in a dry climate. The radiative cooling effect was harnessed for useful purposes by the ancient Persians who constructed tall masonry walls to shade shallow pools of water from the sun's heat. At night the water in these pools was cooled to freezing by radiative exposure to the sky, despite much higher ambient air temperatures. Given conditions such as shade and insulation from the sun's radiation and heat, low levels of humidity and clear skies, water can be frozen at ambient air temperatures as high as 9F/48F. Conversely, as humidity and cloud cover increase, infrared radiation emittance or, the cooling rate, is slowed. Although infrared radiation is most noticeable at night when it is not masked by daytime solar radiation, this process of radiative heat loss is in fact occurring all of the time. Thus, it has the potential to be tapped as a natural source of cooling both during the day and at night.

One of the most significant factors determining the effectiveness of radiative cooling is humidity. Research at Lawrence Berkeley Laboratory (LBL) in Berkeley, California and at Trinity University in San Antonio, Texas has shown that as atmospheric humidity increases the sky radiation intensity also increases. Thus, humidity causes the sky to radiate heat back at the earth's surface. As the humidity of the air increases, sky radiation back at the earth also increases and radiative cooling of the earth's surface decreases. Cloud cover also exhibits similar effects since the water droplets in clouds continuously emit radiation. Thus, radiative cooling is most effective in arid climates at night under clear sky atmospheric conditions.

The only type of radiative cooling technology which has been developed to date is the roof pond for individual building applications. Roof ponds have proven effective in supplying cooling in individual building applications. However, this technology could be significantly improved if new selective glazings and emittive materials with very high levels of reflectivity (80-90%) and transparency were developed. New selective glazings have the potential to increase the efficiency of radiative cooling using no glazings by about 3 times and to permit effective radiative cooling during the day as well as at night.

New radiative cooling systems using wavelength selective infrared radiation materials exhibit significant promise for increasing the efficiency of radiative processes. These materials include gases such as ammonia which has been able to furnish 25 W/m2 of cooling power at a temperature of 15C/27F below ambient temperatures under clear sky conditions. If such efficient technology could be developed it could prove very effective for supplying low cost cooling to communities located in desert areas which experience day to night temperature swings of 35-45F. It will be important not only to undertake the fundamental scientific R&D necessary to develop radiative cooling technology but also to research the ways in which this technology can be successfully scaled up for use as a source of district cooling. This appears to be necessary if this source of cooling is to be utilized to any great extent since radiative cooling processes appear to be land intensive and thus face spatial constraints in urban areas which can be overcome by removing these systems from densely developed areas to open land at the periphery of urban areas and piping the cold water to consumers using district cooling. If it is possible to solve the technical problems which confront high efficiency radiative cooling technology and then to scale up the systems which are developed to the community scale, then new district cooling systems in the arid southwestern U.S. might gain access to a very inexpensive and environmentally beneficial source of air conditioning.

It may be desirable to combine radiative cooling with other forms of precooling in order to be able to produce ice from radiative processes rather than merely cold water since ice can both be stored more efficiently and can be used in ice slurry distribution systems to great economic benefit. One such possibility is the use of direct solar thermal absorption chilling. Solar absorption chilling requires heat at about 230F which can be obtained from numerous types of relatively high efficiency and moderate temperature solar collectors. Such a system could produce chilled water at 45F during the day which could be stored until night when night sky radiation is at its maximum and the 45F water could be radiatively chilled producing ice.

The ice could either directly be used in an ice slurry district cooling system the next day or if produced during the winter, the ice could be accumulated into an ice pile for interseasonal storage and use during the cooling season. Such a multistaged renewable district cooling system would achieve very high levels of efficiency and would also produce a very high value added product, air conditioning, from low grade energy resources which are presently, for all intents and purposes, completely unutilized. A radiative cooling system might also be designed to produce significant amounts of potable water from the meltwater of an ice pile. Non-potable water sources could be used to make the ice resulting in the supply of yet another valuable product.

Solar Absorption Chilling

Solar absorption chilling was last investigated a decade ago for individual home and small commercial applications of 10 kw/3 tons and 35 kw/10 tons. These systems attained a COP of over 0.7 with a single effect air cooled chiller design using 230F solar heated water as the heat source. The design studies did conclude that with sufficient levels of production (several thousand per year) that the systems might be cost effective. Although the design studies concluded that the system was technically feasible the demise of the American solar energy industry made it economically infeasible.

Only one example of solar district cooling using absorption chillers is known. In Baghdad, Iraq, such a system was constructed in 1983 using 10,000 m3 of solar collectors supplying 60,00 m2 of residential buildings with chilled water for air conditioning. The electricity savings compared with a traditional system are about 85% leading to a payback of 8 to 10 years.

Other than these modest efforts direct solar district cooling has not received any other known attention. However, since the period of maximum solar radiation coincides strongly with the period of maximum cooling demand, this option would appear to deserve reconsideration. The solar absorption chilling option is particularly interesting in light of developments in moderate to high temperature solar collectors which have had their costs reduced and performance increased considerably over the last decade. This is particularly true of relatively large arrays of higher temperature collectors designed to produce process steam and electric power. These systems already exist at relatively large scale and thus, the technology can be transferred with very little adaptive R&D for use in driving absorption chillers. However, it will probably be necessary to integrate and adapt the technologies and to optimize designs if the resulting systems are to be economical and profitable. Since the temperatures required for single effect solar absorption chilling are not very high (230F) and economies of scale in both solar collectors and absorption chillers are well known, the direct solar district cooling option may indeed be one which deserves to be revisited.

Cold Surface Waters As A Source of District Cooling

Surface water bodies are yet another potential source of supply for district cooling systems. During the winter surface waters reach relatively low temperatures at points near shore which can be accessible to district cooling systems. Cold water from such sources can be obtained by merely installing cooling water intake piping at the shore, pumps to move the water and a heat exchanger to transfer the cold in the surface water to the water in the district cooling distribution system. A system such as this has been built in Hartford, Connecticut to supply district cooling to the downtown of that city. This system employs cold water from the Connecticut River at times when the temperature of the river water is below that of the send out temperature of the district cooling system (40F), a condition which is present for most of the winter. This system paid for itself in less than a year. Thus, this application can certainly be considered commercial and should be investigated by district cooling systems located near surface water bodies.

Since the temperature of bodies of water fluctuate at their surfaces on a seasonal basis, their use is limited to those times in the winter and spring when temperatures are sufficiently cold to be used either directly or indirectly for precooling. However, if inexpensive methods of long term storage such as appropriate aquifers are available it may be possible to collect the cold surface water, heat exchange it with aquifer water and store the cold water in the aquifer from winter until when it is needed during the spring, summer and fall. In principle, the same metnod could also be used to collect low temperature heat in summer for seasonal storage until winter when it can be employed by a heat pump to provide district heat.

It is also possible to use cold surface water as a source of precooling for district cooling return water before it reaches the chiller. However, a prerequisite for the use of water at variable temperature for precooling is the development of variable volume compressor technology which would ensure that the chiller can efficiently utilize cold water sources which are available even though they fluctuate in temperature.

Although surface waters near shore may warm with the onset of summer, eventually becoming too warm to use in cooling to any great effect, some water bodies are sufficiently deep that they contain very cold water throughout the year. This is the case with certain parts of the Great Lakes, the Atlantic and Pacific coasts and islands such as Hawaii and Puerto Rico. DOE studies a dozen years ago indicated technical as well as economic feasibility for many such projects. For example, one DOE study showed that the option of running an undersea cold water intake pipeline off Miami to recover cold water at a depth of 700′ for supplying district cooling to that city appeared economical at the time (1977). Preliminary studies of using Lake Michigan water at a depth of over 100′ and several miles offshore to provide district cooling for Chicago was also technically and economically feasible. A study undertaken for the Canada Mortgage and Housing Corporation of Toronto, "The Freecool Project", also concluded that this source of cooling was both technically and economically feasible to tap as a source of district cooling.

A key finding of the American studies was that when a sufficient quantity of naturally occurring cold water at about 40F is available relatively close to areas of high air conditioning demand, 70 to 80% of the electric energy used for air conditioning can be saved by converting urban areas to this district cooling supply option. This energy savings is the result of the elimination of compressors and condensing units which are the largest energy users in conventional systems. In a natural cold water district cooling system, energy is used for pumping the water from its source, circulating it through the district system and circulating air in buildings. Since this option was studied about 15 years ago and it was determined to be technically and economically feasible at that time, it is very possible that it is also feasible today.

A fresh look at this option was taken recently for the Waikiki Beach area of Honolulu, Hawaii in a recent DOE sponsored District Cooling Technology Assessment Program. This project found that the use of deep, cold ocean waters for district cooling is both technically and economically feasible today. Cold water at about 45F is available at a depth of 1680′ three miles off Waikiki on the island of Oahu. The availability of this very cold water source so close to shore is due to the shape of the Hawaiian Islands which, because of their volcanic origin, descend at a very steep slope to the ocean floor resulting in comparatively great depths and cold water located in close proximity to the shore. The Waikiki District Cooling Assessment Project studied the feasibility of laying a pipe on the ocean floor and conveying the cold seawater to a battery of heat exchangers located in a central pumphouse near the beach. From this point, chilled fresh water would be circulated through a district cooling system to buildings. It was found that the system could save over 50 MW of electric power generating capacity which is presently used to supply electricity for the air conditioning of the buildings in and around Waikiki Beach. The energy value alone of this power at $0.065/kwh was calculated to be $2,276,00/month not including demand charges. Assuming that the project would save 75% of the electric power presently used for air conditioning, savings could amount to about $2 million per month. The cost of the 3 mile undersea cold water intake pipeline was $9.5 million and the project was deemed to be marginally profitable at current energy prices. However, the energy security benefit to Hawaii, a state almost totally dependent upon imported oil, was thought to be a sufficient concern to tip the scales in favor of this project. Whether or not the Waikiki seawater district cooling project is built or not, the DOE should revisit this option and evaluate anew the potential for using deep surface waters as a source of district cooling.

Bibliography

Task 3

Renewable Energy Technologies For DHC Supply

Part 1:

Renewable Sources of District Cooling

Clark, Gene *, "Passive/Hybrid Comfort Cooling By Thermal Radiation",(*Dept. of Physics, Trinity university, San Antonio, TX.)

Darrow-Sawyer & Associates, Inc.*, "Waikiki District Cooling Utility: Project Report", (Report to USDOE, DHC Program), Honolulu, Hawaii, Feb., 1990.

Davison, R.R., et. al.*, "Storage of Cold Water In Aquifers", "Fundamentals and Applications of Solar Energy", American Institute of Chemical Engineers, (* Texas A&M University, College Station, Texas), 1980.

Kirkpatrick, D.L., et. al., "The Ice Pond: Production and Seasonal Storage of Ice For Cooling", Princeton University, Center for Energy and Environmental Studies, PU/CEES Report No. 149, August, 1982

Martin, Marlo *, "Radiative Cooling", (*Lawrence Berkeley Laboratory, University of California, Berkeley, California).

Masoero, Marco, "Annual Storage of Naturally-Frozen Ice For Building Air-Conditioning", Center For Energy and Environmental Studies, PU/CEES Report No. 127, December, 1981.

Nova, Inc., "Investigation of Ice Pond Technology For Water Purification", Final Report, NYSERDA, Report NR-201-1, April, 1984.

Nova, Inc., "Ice Ponds for Process Cooling, Air Conditioning and Desalination", 1984.

Taylor, Theodore, B.*, Personal Communications 1983-1986 Concerning Natural Cycle Air Conditioning Systems, (*: President, Nova, Inc., Gaithersburg, MD).

Tracor JITCO, "Feasibility Of A District Cooling System Using Natural Cold Water", Argonne National Laboratory, ANL/ICES-TM-10, USDOE, 1977.

Wankat, Philip C.*, "Use of Natural Cooling As An Energy Source: Literature Review" (*Purdue University), 1976.

TASK 3

Renewable Energy Technologies for DHC Supply

Part II: Renewable Sources of District Heat Supply

Table of Contents

Solar District Heating: A Solution To The Problem Of Heating Urban Areas With Solar Energy

The problem of how to achieve very high levels of penetration of solar energy for space heating and domestic hot water production for buildings is one which cannot be successfully resolved with individual building solar energy systems. Although the use of combinations of energy conservation, passive solar and active solar technologies can achieve very high solar energy supply fractions in new buildings, the retrofit of individual building active solar systems onto existing buildings has proven to be very problematic both technically and economically. This is due to a number of factors.

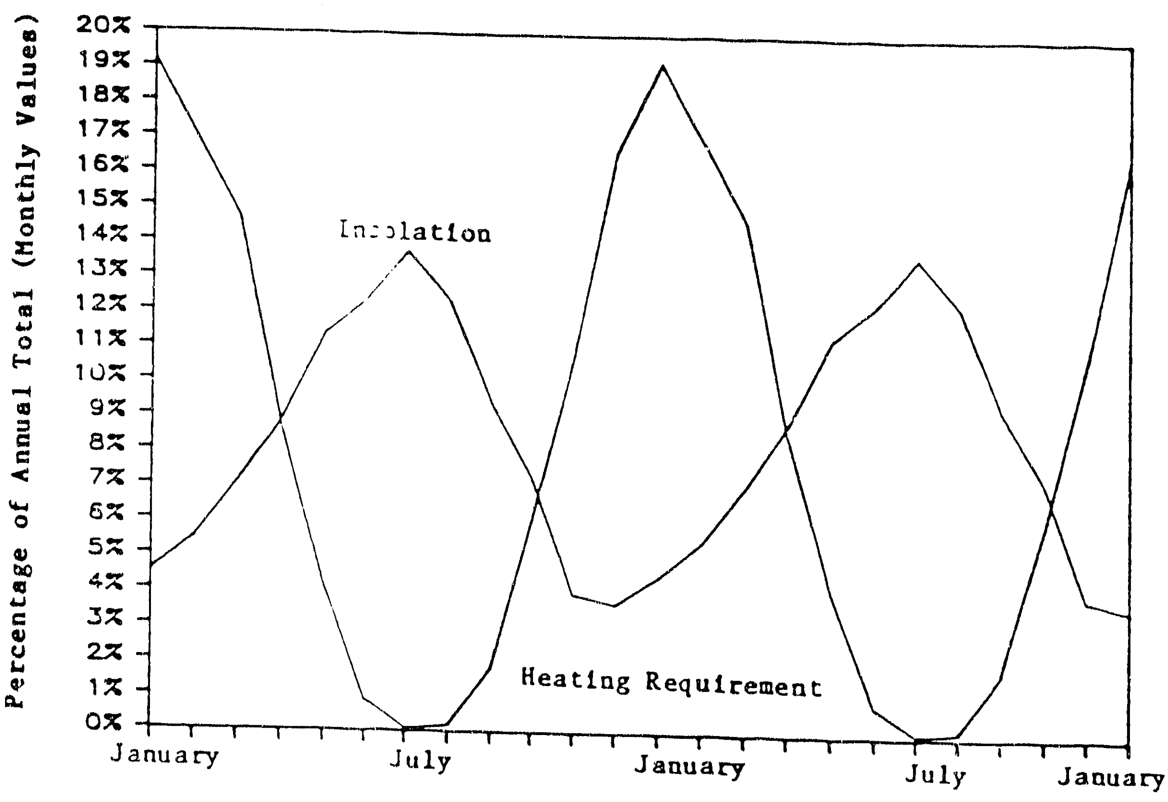
Firstly, there is the problem of solar access in existing cities which were not designed or planned with building solar access in mind. Hence, buildings located in established urban areas seldom have adequate, unimpeeded access to the solar resource. In fact, the reverse is often the case since numerous factors such as street orientation, topography, architectural and building code requirements, land use density, vegetation, building density patterns and the prospect of future intrusive development often conspires to make economical individual building solar heating nearly impossible to achieve.

Secondly, there is a seasonal mismatch between the availability of solar energy and the demand for space heat. The extent to which demand and supply are out of phase can be seen in the following graph (source: International Energy Agency, Solar Heating and Cooling Programme, Task VII, "Central Solar Heating Plants With Seasonal Storage: Summary Report Phases I and II, May 1986). Therefore, there is a need to collect solar heat in the summer, when it is most available, and store it for use in the winter when it is most in need. The economics of long term storage are such that it is more economical and more efficient to employ very large scale thermal storage systems than small ones. The economies of scale in thermal storage can only be exploited on the community level if the storage volumes required by numerous buildings are, in effect, pooled into a single system.

Thirdly, there is a need to maximize the contribution of the solar fraction and also to supply building air conditioning so that the renewable energy supply system minimizes the need to maintain expensive backup and parallel energy supply systems.

Fourthly, there is a need to locate large scale centralized solar collector arrays, renewable cooling production systems and seasonal thermal storage capacity on open land which is removed from the city center but at the same time not so far removed that it is economically inaccessible to thermal transmission systems. Such systems are relatively intensive in their land use requirements and inexpensive land is usually not located in close proximity to high levels of dense urban development.

Seasonal Mismatch Between Heating Requirement and Solar Insolation for a Northern Climate

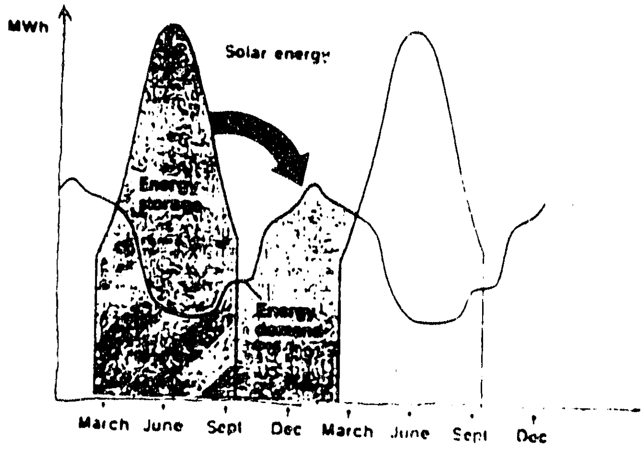


These requirements collectively seem to indicate that if existing cities are to be supplied in large part from renewable energy sources, and especially the direct solar thermal source, such supply systems will have to employ district heating and cooling since the renewable heat and cold production and storage systems will very likely need to be located at some distance from the load. Recent R&D in solar district heating has revealed that the thermal distribution system design is critical to the economic viability of the system. Since solar energy is most economically collected and stored at low temperatures, the distribution and end use systems must be designed to utilize this low temperature source as efficiently and economically as possible.

Initial Swedish Solar District Heating and Seasonal Heat Storage R&D

The idea that district heating may hold the key to the supply of the heating needs of existing cities via solar energy initially began to be forged into viable technologies during the late 1970s in Sweden. Sweden was faced with several factors which pushed it in the direction of solar district heating. Given the extreme northern latitude of Sweden it was quite obvious that if solar energy was ever to have an impact on energy supply, seasonal heat storage would have to be employed since most of the solar insolation at high latitudes occurs during the summer months while the winter sees very little sun while imposing very high space heating requirements. Moreover, political pressures for a more environmentally sound Swedish energy policy resulted in a national commitment to not build any additional new nuclear plants, to shut down any operating nuclear plants by 2010 and to also reduce dependency on imported fossil fuels. Domestic renewable energy sources were practically the only source which was not precluded by these requirements. In addition, the extensive Swedish experience with the development and implementation of district heating and a variety of large scale underground oil and coal storage techniques which could be used as the basis of solar heat storage strongly indicated that this combination of technologies held the key to realizing the very stringent demands of Swedish citizens for environmentally acceptable sources of energy in general and space heating in particular.

For these reasons, Sweden was the first country to recognize the importance of solar district heating and to initiate a long term R&D program to turn the concept into technically and economically viable energy supply systems. The Swedish program initially focused on making the concept of seasonal storage feasible since this was the most critical element in solar heat supply systems serving communities located at high northern latitudes. The concept of seasonal storage is simply to store energy that is collected in summer until it is needed in winter. It is illustrated in the following graph (source International Energy Agency, Solar Heating and Cooling Programme, Task VII, Central Solar Heating Plants With Seasonal Storage, Proceeding of the Workshop, "Toward Better Cost-Effectiveness", Workshop Held At the International Solar Energy Society World Congress, September 15, 1987, Hamburg, Federal Republic of Germany, May 1988).



Correcting the Solar-Load Mismatch with Seasonal Storage.

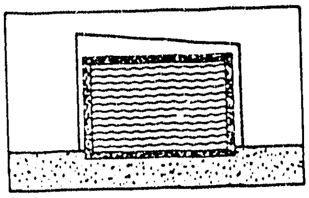
The solar energy systems designed to incorporate seasonal heat storage are in principle no different from those designed for diurnal service except for the fact that the components of the system are much larger than would be required by single buildings. A key feature of the seasonal heat store is that it must be large enough to absorb most of the summer output of the solar collectors without overheating. Thus, the ratio of storage volume to collector area is much larger in a system designed for seasonal storage than one designed for daily storage. In addition, in order to achieve a high level of efficiency in heat storage, i.e. to minimize losses, and to achieve acceptable levels of cost effectiveness through the exploitation of economies of scale, it is necessary that seasonal storage systems be quite large. The performance and economy of seasonal storage technologies are very cost sensitive to large scale construction techniques rather than large scale manufacturing techniques.

Seasonal heat storage options include heat storage in aquifers, earth coils, rock caverns, boreholes in rock, boreholes in clay, water pits and tanks. These various types of seasonal storage concepts are depicted in the following illustrations. (source: International Energy Agency,Solar Heating and Cooling Programme, Task VII, "Central Solar Heating plants With Seasonal Storage: Summary Report, Phases 1 and 2", May 1986) The essential element which all of these techniques have in common is that they become more cost-effective as the storage volume increases. The efficiency of storage increases with volume because the capacity of the system is proportional to the volume while the losses are proportional to the surface area. Thus, larger heat stores have a greater storage volume to surface ratio than smaller heat stores. So, in this particular case bigger is more efficient and also more economical. The unit cost of heat storage decreases as systems become larger because of the economies of scale which are possible to exploit in large scale construction projects. Systems which can use heat pumps can reduce the size of the heat store. The major benefit of seasonal storage for a solar heating system is that it allows the collector subsystem to operate at or near its peak efficiency throughout the year. (source: International Energy Agency, Solar Heating and Cooling Programme, Task VII, Central Solar Plants With Seasonal Storage, Proceedings of the Workshop: "Toward Better Cost Effectiveness", Workshop Held At The International Solar Energy Society World Congress, September 15, 1987, Hamburg, Federal Republic of Germany, May, 1988)

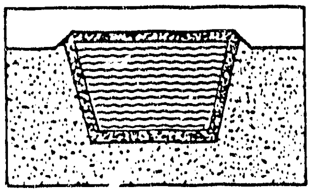
As a result of being able to operate at peak efficiency throughout the year, collectors in seasonal storage systems can deliver two or even three times as much heat as those in diurnal systems. This is primarily due to the fact that summer heat is not lost by shutting down the collector array when there is no heating load and also because operating collectors in the summer when the difference between the collector temperature and the ambient temperature is small, is more efficient than winter operation.

Sweden constructed 6 seasonal solar heat storage and/or solar district heating projects in the late 1970s and early 1980s. These systems employed a wide variety of seasonal heat storage, solar

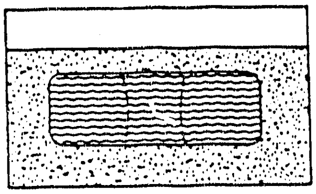
Storage Types



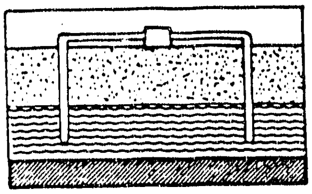
Water Tank



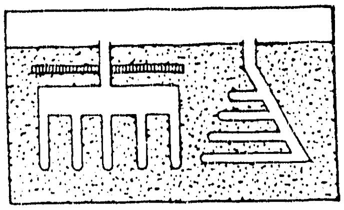
Water Pit



Water Cavern in Rock

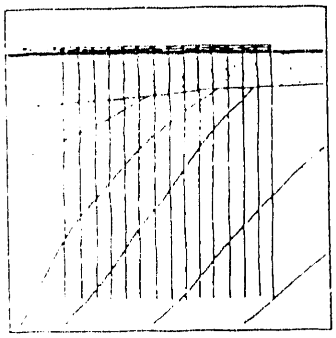


Aquifer



Earth with horizontal ducts, excavated

Earth with vertical ducts, drilled



Rock with ducts

collection and district heating supply technologies. The storage techniques which were investigated included above ground concrete and steel tanks, heat storage in an earth bermed, plastic lined and insulated pits, large underground rock caverns and boreholes in clay. The solar collectors which were used ran the gamut from parabolic troughs, flat plates, compound parabolic collectors and unglazed low temperature collectors. Most of the systems employed very low temperature hot water district heating supply systems with supply temperatures ranging from a low of 30C to a high of 100C. In addition to these projects Sweden evaluated a number of other heat storage techniques which did not involve solar heat supply. The total number of seasonal heat storage projects in Sweden to date number over two dozen. The variation of the cost of 9 different types of seasonal storage techniques with scale is illustrated in the following graph which reflects the experience of a number of countries and projects. (source: International Energy Agency, Solar Heating and Cooling Programme, Task VII, "Central Solar Heating Plants With Seasonal Storage", Summary Report of Phases I and II, May, 1986, p. 38)

IEA Project On Central Solar Heating Plants With Seasonal Storage

Although the early projects were not nearly cost effective much was learned and much interest in the concept was stimulated. As a result, in the early 1980s the International Energy Agency initiated an international collaborative R&D program in "central solar heating plants with seasonal storage" (CSHPSS) which was led by Sweden and involved the participation of another 8 countries including the U.S. In addition to the 6 Swedish projects the CSHPSS Program stimulated the design and/or construction of another 11 projects. Numerous variations on the above systems were investigated including a number of projects which employed heat pumps.

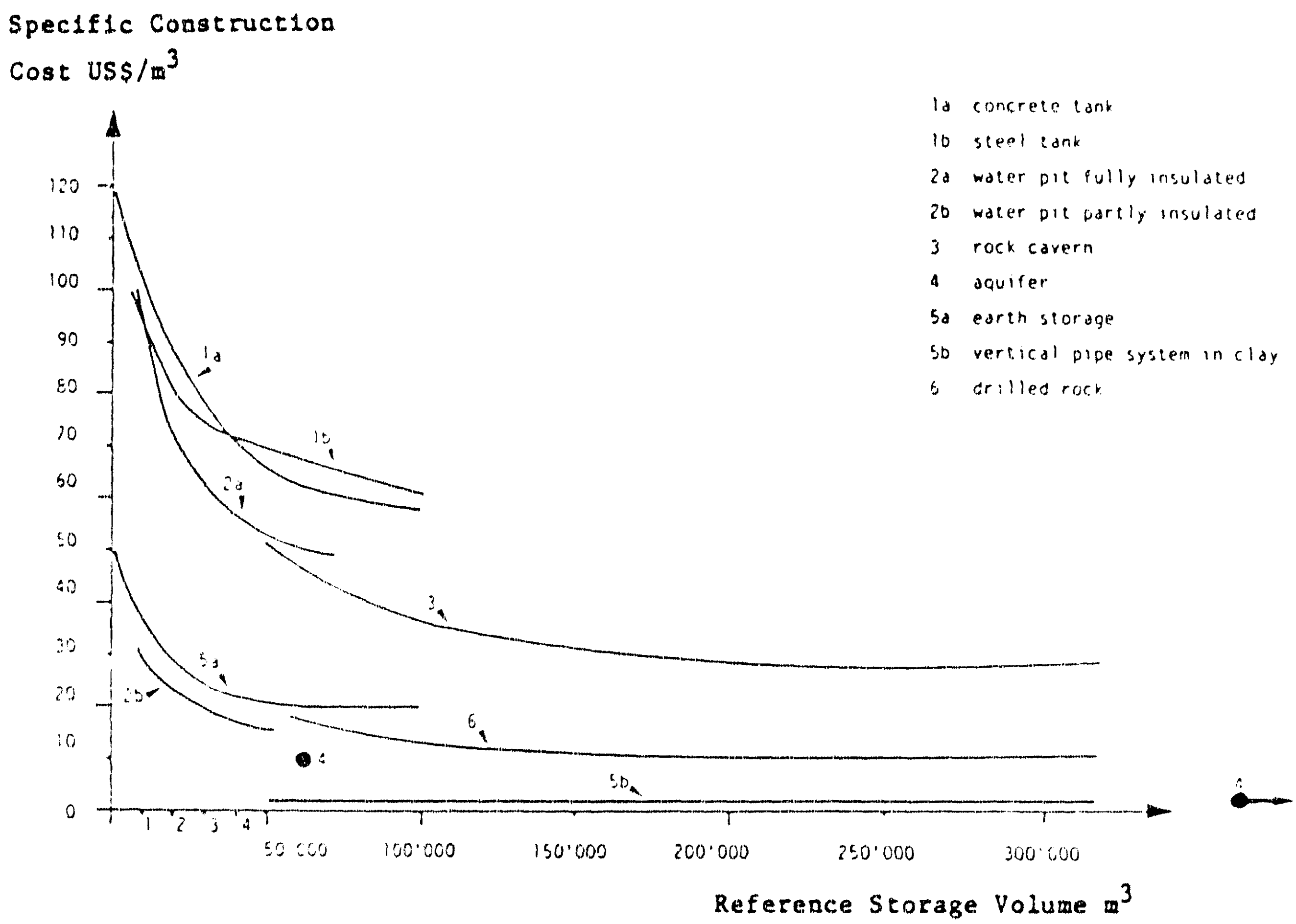
The most significant area of investigation and progress in the IEA CSHPSS Program was in the field of seasonal heat storage. A summary of the findings of this program in the fields of seasonal heat storage is contained in the following table.

Summary of Characteristics of Seasonal Thermal Storage Technologies

Storage Type	Temperature (degrees C)	Size Range (m3)	Efficiency (%)
Steel Tanks	<100	1-500,000	70-80
Earth Pits	<100	100-10,000	60-80
Rock Caverns	>100	0.01-10M	70-90
Boreholes In Rock	≤100	0.5-10M	60-90
Ducts In Earth	≤70	0.01-10M	50-80
Aquifers	15-150	as required	50-90

(source: Bankston, Charles A., "The Status and Potential of Central Solar Heating Plants With Seasonal Storage: An International Report" in "Advances In Solar Energy", Vol 4, ed. by Karl W. Boer, Plenum 1990, p.421)

Characteristic Storage Costs using Assumed Cost Parameter Values



The seasonal storage cost of energy stored for a single annual cycle which was developed during the course of the CSHPSS program is illustrated in the following figure. (Source: Bankston, Charles A., "Ibid", p.424)

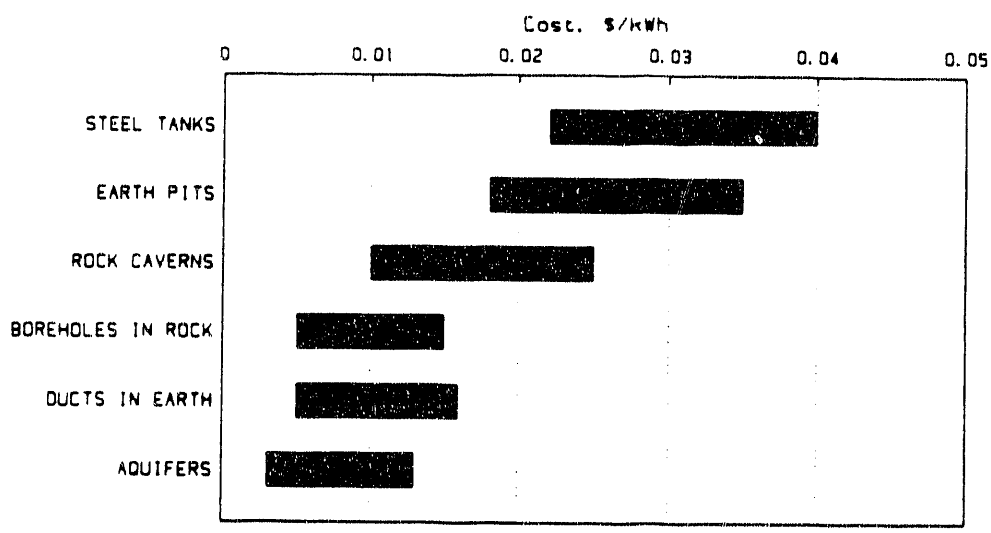
The experience of the IEA CSHPSS Program showed that water pits with polymer liners can be operated at temperatures between 30 and 80C for long periods without serious degradation or leaking. Pits in soft clay or unconsolidated earth must be built with shallow side slopes to meet building requirements and construction safety standards. Such pits have poor surface-to-volume ratios and large upper surface areas which must be insulated. More favorable geometries may be constructed in rock or hard ground but the excavation cost is higher and there may be extra cost installing insulation and lining a pit excavated in rock because of the rough surfaces. The top of the pit may float on the water or have a separate support structure. Filling the pit with gravel reduces the structural requirements for the lid. Stratification in pits is more easily achieved in deep pits than in shallow ones.

Duct storage, i.e., in-ground heat exchangers using drilled holes, pipes or ducts in rock or earth can be very inexpensive in areas where the geological conditions are favorable. Favorable conditions for low and high temperature storage are found in both very soft clays (<70C) that can be penetrated easily by vibrating lances or pile driving techniques or in competent bedrock formations (>100C) where the holes can be drilled and heat can be extracted without casings or linings. Loose soil or mixed soil and rock are more difficult. Thermal energy storage in low temperature aquifers is now established technology. Storage of high temperature water (>180C) in deep aquifers is under investigation in at least two countries. (source: Bankston, Charles A. "Central Solar Heating Plants With Seasonal Storage: An International Review", CBY Associates, Inc., Washington, D.C., p. 6)

CSHPSS experiments used glazed and unglazed flat plate collectors, evacuated collectors and parabolic troughs. System studies have indicated that in some climates and system applications, solar ponds or central receivers may be viable. The primary determinant of collector technology is the supply temperature required by the load or the maximum temperature in the storage system.

In low temperature systems, especially those using heat pumps, the temperature and temperature swing of the storage volume is low and unglazed collectors or wind convectors operate efficiently. Natural solar collectors such as the surfaces of rivers, lakes, parking lots and buildings may also be used in low temperature systems with heat pumps.

When the delivery temperature is between 50-70C flat plate collectors may be the best choice. In Sweden the development of large area, high efficiency flat plate collectors especially for CSHPSS applications has greatly improved cost the effectiveness of the flat plate systems. For temperatures above 90C evacuated or tracking



Seasonal storage cost of energy stored per annual cycle in Sweden—1985.

supply 75% of the space heating for 350,000 m2 of residential, commercial and service space (the size of about 2,000 residences) with the remainder supplied by oil fired boilers. The total heating requirement of this space is 56 GWh/yr. The supply temperature of the district heating system will be a maximum of 100C with a return of 60C. The collectors will require a land area of 28 hectares, 35% of the services area. The cost of the collectors represents about 50% of the heating cost. The solar collector component will employ special large area collectors designed especially for use with large scale solar district heating systems. These collectors are available in sizes of over 12 m2 or more per unit, a factor which minimizes plumbing costs, heat losses and installation costs. The collectors are equipped with convection barriers to enable them to produce hot water at over 90C.

The heat store consists of a 30m high, 153m long and 110m wide water-filled cavern in rock with 6 unexcavated rock columns, all of which is located 70m underground. Although the Kungalv cavern will be a very large thermal energy storage unit, it is not a large cavern system by Swedish standards. Oil storage caverns have been constructed in Sweden with volumes of 10,000,000 m3. The configuration of this entire system can be seen in the following illustration.

The cost of delivered energy from the Kungalv plant is expected to be $0.067/kWh with a solar fraction of 75%. However, in the future it is expected that the cost of the special large area flat plate solar collectors developed specially for Swedish CSHPSS systems will decline by about 30% due to a variety of improvements and that the cost of conventional energy sources will also increase. The project was based on a real interest rate of 4%. A decline in interest rates of 1% would reduce the cost of heat from the solar source by 10%. Also a 10% increase in oil prices will result in the project becoming that much more competitive. Based on the results of the Kungalv design it has been estimated that Sweden could find up to 150 applications for similar systems. By constructing several such systems in the early 1990s Sweden could be in a position to obtain a very significant portion of its space heating demand from solar district heating technology of this as well as other types within a decade.

Using the data from Kungalv, CBY Associates of Washington, D.C. has essentially relocated a modified Kungalv plant from Sweden to Denver. Performance and cost data used for granite rock storage are similar to those used in Sweden. Data on large scale parabolic trough arrays from Luz, International, Ltd. or large flat plate collectors from the IEA CSHPSS program were used. Reoptimization of the plant for Denver revealed that the same size community (2000 residences) could be supplied with 100% of its heating needs from solar energy at a cost of $0.028/kWh. With projected future installed costs for the Luz solar arrays of $135/m2 and Swedish rock cavern storage holding 150C hot water it has been estimated that these costs could be reduced to $0.02/kWh. The IEA CSHPSS Program has adopted the cost goal for delivered energy from these systems of $0.03/kWh. Costs for delivered collectors are likely to be most economical. Tracking collectors may be suitable for bright sunny climates and where sun angles cover a wide range. In many northern climates, however, the insolation is diffuse and collectors with a wide acceptance angle may be preferred. For large systems, the evacuated collector arrays must be carefully designed to minimize night losses and pumping power.

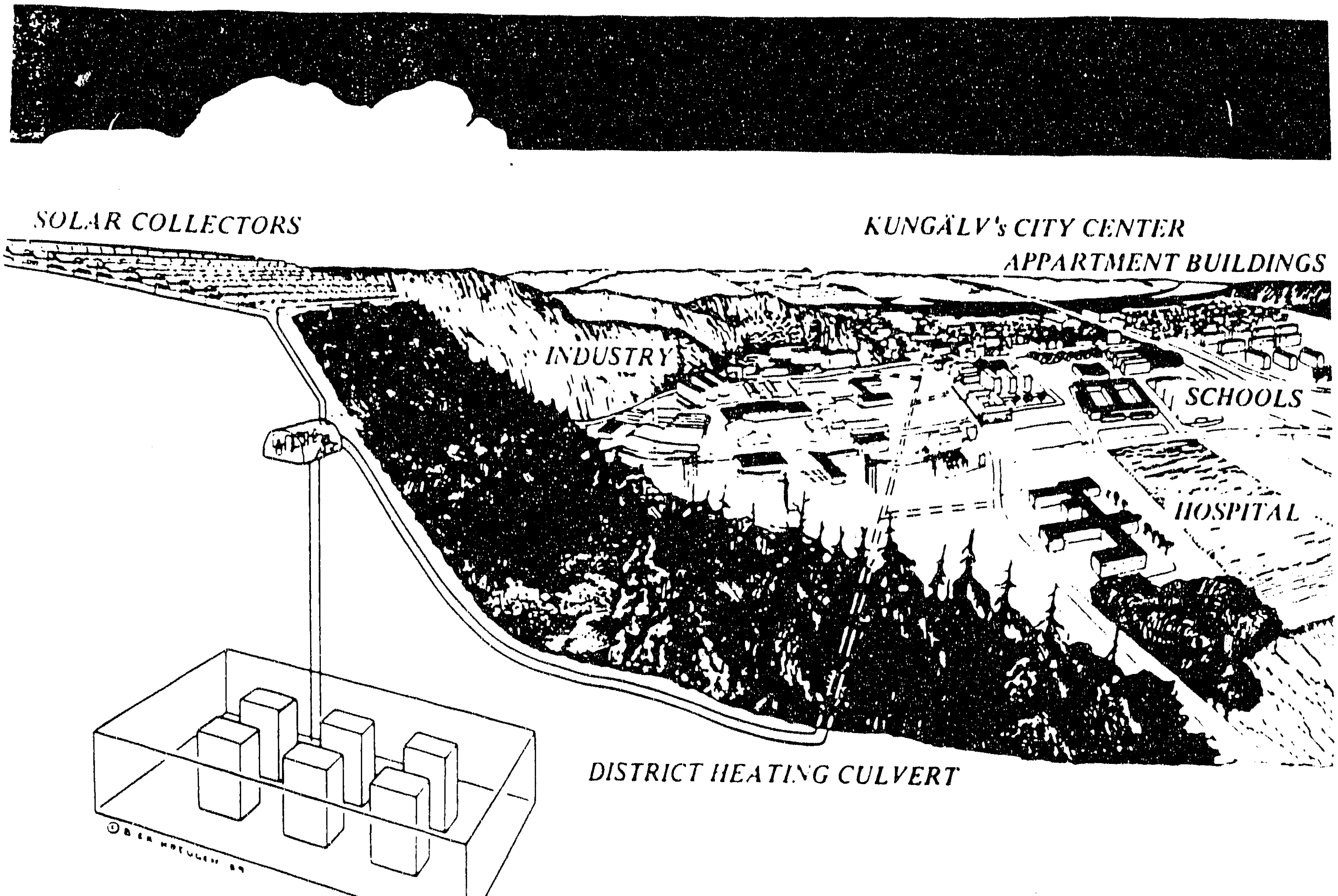
One of the more controversial system design issues concerns the use of heat pumps in conjunction with CSHPSS. Economic analyses show that with current collector costs, heat pump systems deliver lower cost heat than direct systems. The least expensive heat pump systems generally achieve solar fractions of only 60-70% while most of the balance comes from power input to the heat pump. However, if the heat pump is electric, and if electrical energy requires an expenditure of three times as much primary energy, such heat pump systems may represent no net displacement of primary energy. It may also be argued that the low temperature energy required for heat pump systems may frequently be obtained more cheaply from such naturally occurring sources as surface waters from rivers, lakes, large scale wind convectors, ground collectors and various waste heat sources than from manufactured solar collectors. Direct solar systems, in which the entire load or most of it is met directly from stored solar heat, displace the maximum primary energy but generally cost more than heat pump systems at current cost and performance levels.

The economic viability of CSHPSS is very sensitive to supply and return temperatures. These temperatures determine the size and efficiency of the collector and storage subsystems as well as the cost of the distribution network and end use delivery equipment. The trend in modern district heating systems is to reduce the delivery temperature so that less expensive materials and simpler installation techniques may be used. District heating systems are now designed to use hot water at temperatures as low as 50C. (source: Bankston, Charles A., "Ibid", p.7)

The most impressive solar district heating project developed to date has been the Lyckebo Project in Uppsala, Sweden which employes a large rock cavern seasonal heat store supplied with heat from solar collectors and cheap off-peak electricity for providing 100% of the space heating needs for 500 houses. Although this project is not competitive with other alternatives, economic analyses indicated that if the systems were to be rebuilt using more recent and cost effective solar collector designs which would supply 100% of the heat load and if the cavern were to be doubled in size to supply twice the number of houses that the resulting costs would be competitive with Sweden's alternatives.

Recent Designs and Analyses of Advanced CSHPSS System Projects

Based on this analysis a much larger solar district heating system design employing a rock cavern seasonal heat store was proposed for the town of Kungalv, Sweden. This system will be designed to employ 120,000 m2 of high efficiency flat plate collectors supplying heat to a rock cavern seasonal heat store of 400,000 m3. It will


SOLAR COLLECTORS
KUNGÄLV's CITY CENTER
APPARTMENT BUILDINGS
INDUSTRY
SCHOOLS
HOSPITAL
DISTRICT HEATING CULVERT

solar energy of $0.02 to $0.03 or about $6.00 to $9.00/MMBtu are as close to commercial as has been achieved by any active solar space heating system in the U.S. without the benefit of tax credits or other subsidies.

Conclusions and Recommendations of the IEA CSHPSS Program

There are a number of noteworthy conclusions from the IEA CSHPSS Program.

1. Rankings of system configurations on the basis of cost depend primarily on the distribution temperature and on the cost of auxiliary power and are less sensitive to the climate, total load and DHW fraction.

2. For low temperature distribution, these rankings favor systems including unglazed solar collectors and heat pumps, and for high temperature distribution, systems including evacuated collectors without heat pumps are favored.

3. Low temperature distribution, together with systems with heat pumps offer the lowest solar unit costs -- as low as $20/MWh when a suitable aquifer is available -- and can meet about 75% of the load from solar.

4. Low temperature distribution, together with systems without heat pumps are more costly -- about 60-70 $/MWh -- but can meet 100% of the load from solar.

5. The most cost effective plants for use with high temperature distribution systems employ temperature stratification on the storage volume and use evacuated collectors. The minimum solar cost of these systems is 90-100 $/MWh.

6. All systems show economies of scale because of diminishing unit storage costs and heat losses with scale and show improved cost effectiveness for increasing domestic hot water (DHW) fractions because of higher load in summer. Rock cavern systems exhibit the greatest size dependence and duct systems the least.

7. Collector costs dominate all but the low solar fraction, low temperature systems with heat pumps. The collector sub-system cost is often twice as large as the storage sub-system cost.

Site-specific studies were carried out in a number of the countries participating in the CSHPSS program. Some of the most important findings from these studies are described below.

The Netherlands

Duct storage systems were studied. Systems with heat pumps, especially gas driven heat pumps, were found to be the most cost effective. It was found that the cost for a system with heat pumps including heat pump fuel cost was not much greater than conventional energy cost and was not very sensitive to collector unit cost; for the system without heat pumps, however, the system cost is very sensitive to the collector unit cost.

Sweden

Results in Sweden show that the development of thermal energy storage in water and of collector technology has reached a level at which systems without heat pumps are competitive with heat pump systems for all solar fractions. These systems are already nearly competitive with conventional energy sources.

United States of America

The performance and cost of the optimized drilled rock storage systems analyzed in the U.S. were not much different from those of the reference studies or other national evaluations. Because of the high cost of oil and electricity in New England, however, CSHPSS systems have costs that are already attractive. The U.S. study showed that even without tax incentives the system unit energy costs for optimized CSHPSS systems are below electricity prices and on a par with oil.

The major conclusions of the IEA CSHPSS Program are as follows.

-- CSHPSS can meet a large fraction of the space and water heating load for buildings even in harsh northern climates and they are already cost effective in some locations.

-- Solar costs as low as 20 $/MWh are possible where appropriate aquifers are available if a heat pump and low temperature distribution system can be used.

-- Large solar fractions, more than 80%, can be achieved by systems without heat pumps using stratified energy storage and high performance collectors. Costs for these systems are about 60-70 $/MWh for low temperature distribution systems and 90-100 $/MWh for high temperature distribution systems. (source: IEA, Solar Heating and Cooling Programme, Task VII, "Central Solar Heating Plants With Seasonal Storage: Summary Report of Phases I and II", May, 1986, pp.65-66)

Although Phases I and II of the IEA CSHPSS Program has been completed, a number of countries are currently engaged in discussions to define a follow-on project. This new phase has been designated as Task 15: "Advanced Central Solar Heating Plants With Seasonal Storage". It has been recommended that this program contain some of the following elements.

-- Continued international review and evaluation of new and planned projects.
-- National R&D with common technical and economic goals to improve the competitiveness of pit, duct and aquifer storage subsystems in CSHPSS. For CSHPSS without heat pumps, the appropriate goal for the

storage subsystem is to allow a temperature high enough to meet the peak temperature demand without augmentation and do so at a cost equivalent to 20 $/m3.

-- Improvement of both detailed modeling capabilities for design and performance analysis and analytical or empirical methods for predesign and optimization.

-- Analytical studies of promising system configurations and control strategies that have not been analyzed including:

- -- combined heating and cooling systems with and without heat pumps;
- -- Heating systems with distributed and/or interconnected collectors, storage and loads and with hybrid storage systems or collector arrays;
- -- Optimal and adaptive control strategies using long term and short term weather projections; and
- -- Multi-year predictive and stochastic control strategies.

-- Organize joint workshops with IEA or other programs on topics of common interest such as:

- -- A workshop to evaluate the economics and performance of ground mounted and building-integrated solar collectors for large CSHPSS arrays;
- -- A workshop to compare the economics and performance of low and normal temperature water heat distribution for buildings;
- -- A symposium on the application of high technology developments in CSHPS, e.g. rock melting or laser drilling, underground radar or micro-seismology for geotechnical site evaluations.

(source: CBY Associates, Inc. "Final Report On IEA Task VII: Central Solar Heating Plants With Seasonal Storage" for USDOE, August, 1990, p. 18-19)

Despite the modest financial requirements for participating in this program the U.S. DOE has not yet decided to support American participation in this next phase of the IEA program. This is despite the fact that U.S. participation in the Phase VII CSHPSS Program was purchased for the very modest sum of $75,000/yr. The U.S. stands to gain much more than it would be contributing to such an effort due to the substantial commitments which other countries such as Sweden are making to their domestic R&D programs in this area, the fact that this experience will be made available to the participants in Task 15 and the fact that many other countries will also be participating and contributing their experiences. Thus, any funds spent on American participation would be very highly leveraged.

If the DOE solar program declines to fund U.S. participation in this IEA program, the DOE DHC program should consider it since it could just as easily be considered an element of the DOE DHC Program as an element of the DOE Solar Thermal Program. Moreover, since CSHPSS will clearly be a technology which will be implemented by utilities of one sort or another, it is only logical that the DOE Utilities Division, within which the DHC Program is located, take this project under its wing. This is all the more reasonable when one reflects on the fact that one of the most important driving forces behind district heating and cooling is its environmental benefits. The ability of DHC to supply communities and eventually entire cities with heating and cooling supplies almost completely from renewable energy sources such as solar could provide the DHC industry with a very powerful vehicle with which to penetrate the market for building heating and cooling services at a time when the environmental and energy efficiency aspects of energy supply are of paramount concern to American citizens.

If the U.S. does decide to participate in this program there are several additional technologies which deserve to be included. In the area of solar collection technology the metallic foil and polymer thin film collector developed by BNL should be the subject of a study to determine if this collector can achieve economies of scale as have the very large flat plates which have been developed for the purpose of solar district heating in Sweden. The BNL foil/thin film collector weighs 1/10th and costs at most 1/3 of the installed cost of a conventional flat plate. Consideration also ought to be given to combining this collector with a modified solar pond such as has been suggested by Taylor. This design also incorporated a plastic film and metallic foil collector which was laid flat on insulation floating atop an excavated and bermed hot water storage pond. An initial technical and economic study of this option indicated that it could be developed to supply solar heat at the community scale via low temperature district heating at about $1/MMBtu.

Another consideration is the use of heat pumps. CSHPSS systems with electric heat pumps were viable only in those countries which have very low electricity costs such as Sweden. In countries which have high electricity costs electric heat pumps will only be viable if these systems can have access to large amounts of very low cost low temperature heat. Where this is not possible it may be necessary to opt in favor of the higher temperature solar collection and storage alternative. However, the Dutch experience in the CSHPSS program needs to be highlighted since they found that the use of gas-fired heat pumps could be very beneficial to the overall efficiency and economy of the CSHPSS system. This experience may be applicable to the U.S. where gas is plentiful and relatively inexpensive and where a fuel fired heat pump can also be utilized as a chiller to supply district cooling. The use of this technology would be enhanced thermodynamically if cost effective heat activated chillers for small cogeneration systems were developed and if ammonia vapor compression systems were to be used as the heat pump/chiller rather than a CFC based system. These options should be investigated in a future U.S. CSHPSS project.

In addition to less costly collectors and the use of fuel fired heat pumps, the other area of greatest interest is with renewable district cooling production technologies. In the U.S. air conditioning is a much more valuable commodity than space or domestic hot water. Therefore, it is anticipated that district cooling will be more important than district heating in the future and that district cooling will lead district heating into the marketplace. There are a number of renewable cooling production systems which could be developed and combined with CSHPSS systems. If high temperature solar collectors are employed then it would be only logical to use the high temperature hot water to drive a single or multiple effect absorption chiller or some other heat activated chiller such as a jet refrigeration system or organic Rankine cycle turbine. Alternatively, the high temperature solar thermal collectors could generate electricity which could power a vapor compression chiller. If a low temperature solar thermal source was selected the best options for district cooling production might be ice ponds, spray ponds, radiative cooling or some combination thereof.

Biomass Sources of Renewable Energy For District Heating

There are numerous sources of biomass which can be used for the production of district heating. However, this section will confine that discussion to those new technologies which are being developed to convert biomass energy sources into useful supplies of district heat. Although in principle, these same sources and conversion technologies can be used for the production of district cooling, most have not been considered in this context by the European researchers developing the new systems.

The development of new technologies for the conversion of biomass and particularly biomass wastes has reached its most advanced stage in Denmark where numerous techniques for converting biomass waste fuels into useful supplies of heat and power have been the subject of R&D for over a decade. Although Denmark has assumed the lead in this area, several other countries, most notably Finland and Sweden, are also engaged in developing biomass energy conversion systems for the production of district heating. In recent years a number of new technologies have reached the commercial stage and are increasingly being applied in the production of district heating. The fuels which have been the subject of most of the R&D include wood waste and straw, animal manure, the organic fraction of municipal solid waste and sewage effluent.

One energy source which has attracted much attention in Denmark is the use of straw as an energy source. Previous to its being used as a fuel straw left in the fields after a harvest was burned causing significant air pollution problems in the autumn. The extensive use of straw for conversion into district heat effectively converts a source of waste and pollution into a useful energy source and in the process minimizes the emissions which result from combustion due to the efficiency of the conversion process and the use of environmental controls. Currently, Denmark extensively uses straw combustion for district heat production. Over 20 plants are already in place which use 100,000 tons of straw per year. Another 20 to 25 plants are planned for the near term which will increase straw consumption to 200-240,00 tons/year. The capacity of these plants varies from 1.8 to 9.5 MW. In some plants straw bales are burned directly in a furnace while in others the straw is first broken up before combustion. The straw is delivered to the plants in the form of bales of 500 kg. A plant usually has about one week's consumption stored for future use.

Denmark also maintains an R&D program in the field of straw and waste wood combustion and handling systems. Many of the plants of the future as well as those currently operating are designed for the supply of district heat. Fluidized bed systems will probably be employed in the new generation of plants which are now planned. These plants will be designed to serve as local cogeneration plants supplying district heating. It has been estimated that Denmark could obtain 3-4% of its space heating needs from straw combustion.

Another area in which Danish technology has excelled is the development of biogas production plants using animal manure. These plants usually take the form of relatively large "communal" plants serving a rural area in which numerous dairy and pig farms are located and to which they contribute their manure. The manure is collected by special trucks and brought to a central processing plant where it is converted into "biogas" which contains about 50% methane. The processed waste is then returned to the farms from whence it came to be spread on the fields as a fertilizer. The biogas plants are usually located close to a district heating supply line at the outskirts of a small town or city. This allows them to employ biogas-fired diesel engines in a cogeneration mode, supplying electricity to the grid and heat to the district heating system.

The largest such plant is in Fangel, Denmark and it handles 160 tonnes of liquid manure daily in addition to much industrial waste. It produces biogas equal to one million litres of oil per year. Even larger plants are planned for the future and 15-20 plants the size of Fangel or larger may eventually be constructed. Denmark is also undertaking extensive R&D in the refinement of biogas production systems for use not only in the conversion of animal wastes to biogas but also for the conversion of human wastes and municipal solid wastes into biogas. These new systems are intended to employ biogas in local cogeneration plants producing electricity for the grid and heat for district heating.

In addition to the development and use of animal wastes for biogas production there are numerous R&D programs and projects in many countries focused on the use of human wastes and the organic fraction of municipal solid wastes as waste feedstocks for biogas production. In Finland this technology appears to have reached an advanced stage and commercial plants have recently been constructed and are currently operating. The new Finnish plants utilize a mixture of the organic fraction of MSW and undigested sewage sludge as the feedstock into the anaerobic digestion process. The plants employ a relatively high solids content and are designed for high levels of efficiency in the production of biogas for use in gas-fired cogeneration systems. The cogenerated electricity is sold to the electric utility while the heat is sold to the district heating utility. The process has reached the commercial stage for plants of intermediate scale with a capacity to digest about 55 tons/day of which 55% is comprised of the organic fraction of MSW and 45% is undigested sewage sludge. The amount of total solids digested in each batch is 20%. Many such commercial plants are planned for construction in Finland given the success of the initial commercial plants and many of these can be expected to produce biogas for cogeneration and district heating supply. (source:Pesonen, Herkko, "The Wabio Biogas Process For Treatment of municipal Solid Waste And Sewage Sludge", DN Bioprocessing Ltd., Lakkisepankuja, 7, SF-00620, Helsinki, Finland)

Sewage Water Source Heat Pumps For District Heating

The relative level of warmth in sewage water, sewer mains and sewage treatment plants can also be used as a source of low temperature heat for heat pumps which can be sued to supply district heat. This option is especially popular in Sweden which has over 120 heat pumps supplying heat to district heating systems. Twenty-nine of these systems are larger than 1 MW and 52% use sewage water as a heat source. Swedish sewage water heat source temperatures vary between 7C/44F to 20C/68F, while district heating water temperatures vary between 45C/158F and 85C/185F. The average COP of heat pump plants using sewage water as a heat source is 3.0. Some of Sweden's heat pump installations which use sewage water for the production of district heating are quite large, up to 13 MW per unit. The City of Uppsala has one of the largest installations of this type, combining 3 x 13 MW units into a plant of 39 MW using sewage heat as a heat source to produce district heating.

The reason why these plants are so popular in Sweden is that electricity prices are very low (about $0.01/kWh) due to low cost hydro and nuclear generation plants. Since these conditions are not duplicated in most parts of the U.S. where electricity prices are usually many times higher, it is only logical to expect that such systems would find scant possibilities for application. However, if these systems were to be driven by gas fired or biogas fired cogenerating engines the economics might be more in line with U.S. economic realities. The additional efficiency boost which is obtained by both the high electric conversion efficiency of some small to intermediate scale gas fired engines (40%+) coupled with the waste heat which is captured from these systems (50%) could further increase the efficiency and economy of sewage water source heat pumps. The COP of a gas fired cogenerating engine driven heat pump could reach 1.7, while the effective COP of an electric heat pump with a COP of 3.0 is actually about 1.0 if the efficiency of the overall electricity supply system is taken into account. Thus, the gas fired option would be 42% more efficient than the electric heat pump option.

Another modification which might be made in this equipment to make it more applicable for U.S. conditions would be to use the sewage water heat pump as a chiller for district cooling production. Although summertime U.S. sewage water temperatures might be much higher than winter temperatures, there are probably some parts of urban areas in which temperatures might be about the same the year round due to the extensive use of air conditioning which, in the process of cooling an entire building also cools the water used for washing and toilet flushing to about 70F. In the middle of summer during the middle of the day waste water at this temperature might yield a very substantial efficiency advantage if used for precooling a chiller producing district cooling as compared with the use of cooling towers using ambient temperatures. The energy savings might be about 40% under such conditions. By using the heat pump as a chiller for district cooling as well as district heating production the capacity factor of the systems and the economics is also improved.

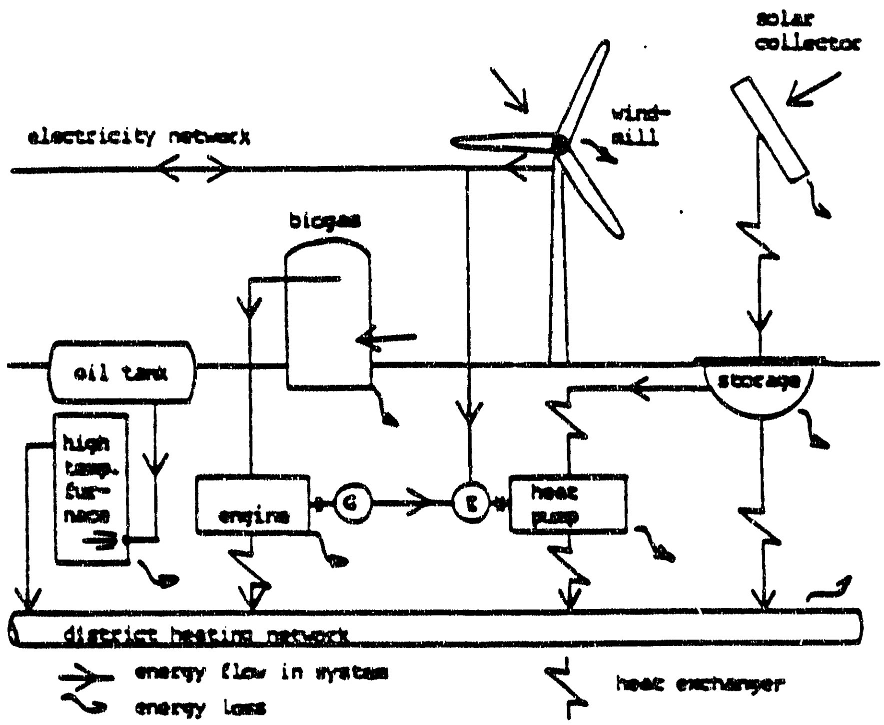
Another modification in this technology which is required is to convert these systems to an alternative refrigerant other than CFCs. Sweden is currently considering the use of ammonia refrigeration technology for this purpose.

Putting It Altogether: Integrated Renewable Energy Systems For District Heating

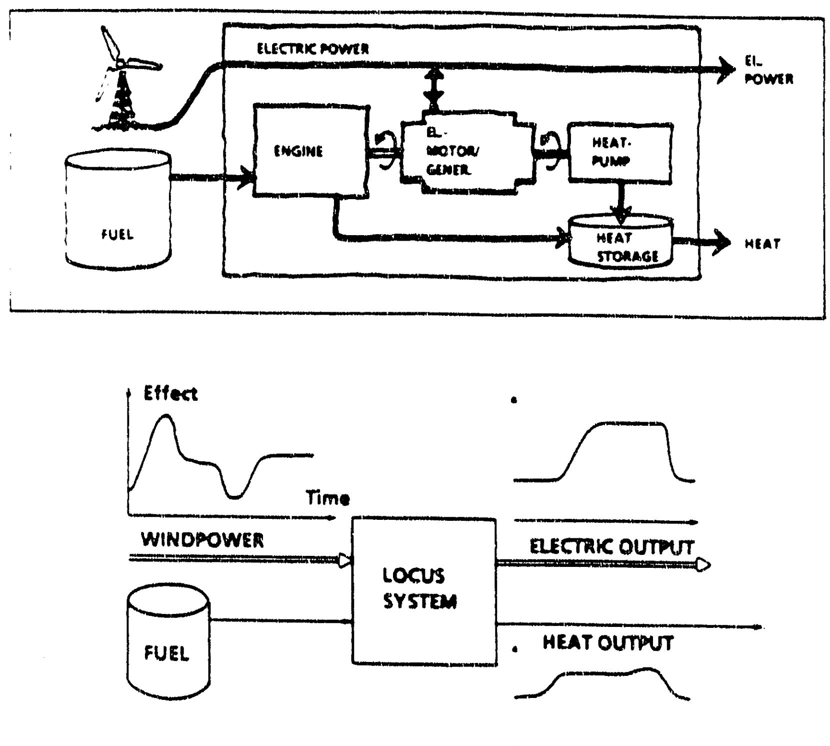
There are numerous thermodynamic and economic advantages in combining various renewable energy sources and technologies in integrated systems supplying district heating. For example, solar energy availability is significantly out of phase with space heating demand. Although interseasonal storage of solar heat solves this problem to a certain extent, the water temperatures in interseasonal heat stores can decline to very low unusable levels after undergoing a number of months of heat extraction. However, solar systems need not stand alone, providing all the requirements of a district heating system when there are other renewable energy sources available at different times to complement the solar resource. One such complementary renewable energy resource is wind energy which is available in abundance in many parts of North America during the winter months and can be used to produce either electricity or mechanical power to drive heat pumps to boost interseasonally stored solar heat to useful levels. Similarly, biomass and methane gas from wastes can be stored and used as backup.

A small district heating system designed for a rural Danish village exemplifies this integrated approach. The "multicomponent renewable energy system" designed for the village of Baring-Asperup in rural Jutland, combines building energy efficiency improvements with a renewable thermal supply system to provide 78% of the low temperature district heat required by 267 houses. The district heating system was designed to be supplied from the following combination of renewable energy sources and conversion technologies: solar collectors with seasonal storage, a wind driven heat pump, a biogas-fired internal combustion engine cogeneration unit, a biomass-fired boiler and a back up oil-fired boiler. This combination of technologies can be seen in the following figure.

Recently, Danish energy supply system planners have taken the principle of the integrated, multicomponent energy supply system and developed analytical procedures and controls which enable these systems to be integrated into many different electricity and heat supply situations which are typically found in Denmark. The resulting system has been dubbed "LOCUS" for LOcal Cogeneration Utility System. There is a distinction which must be made between LOCUS plants and LOCUS systems. A LOCUS plant is a cogeneration plant that may consist of engines, heat pumps, boilers and heat storage tanks. The following diagram shows the main components of such a plant. A LOCUS system may



Multi-Renewable Energy Source
District Heating System Design



LOCUS-plant, principle. A LOCUS-plant composed of an engine, an electric motor/generator and a heatpump and equipped with the necessary heat-storagetanks provides enhanced possibilities for regulation of simultaneous thermal and electric output-effects.

consist of several LOCUS plants sited in various towns and villages within a certain region. The plants within such a system are assumed to be interconnected through the electric grid and the regulation of the power generation of each plant is assumed to be subject to rules designed to optimize the performance of the system. These rules constitute a hierarchical structure of LOCUS systems by which electric power production can be regulated.

The LOCUS plant concept has primarily been developed to facilitate the optimally efficient and economical utilization of windpower in combination with natural gas, biogas and other renewable or non renewable fuels through the regulation of the simultaneous electric and thermal outputs which are determined by the actual variations in heat demand and the desired variations in electricity generation from the plant. For example, if the LOCUS plant incorporates windmills at times it may be necessary to use part of the electricity output from the windmills to drive the LOCUS plant´s heat pumps to supply district heating. This is done by increasing the power input to the heat pump when the electric output from the windmill exceeds a certain value. Thermal storage is also incorporated into the design of a LOCUS plant to provide a buffer between demand and supply of electricity as well as heat. The system is programmed to deliver electricity in certain amounts to the grid at certain times. Both thermal storage and a back up boiler facilitate the discharge of this task without compromising the plant´s responsibility to supply district heating.

The system incorporates thermal storage capacity at a variety of temperature levels. Separate heat storage tanks are provided for supplying the heat pump and the engine cogeneration system incorporates thermal storage at various temperatures for heat output from the exhaust gases, water jacket and lube oil, each of which is employed in a different stage in the process of producing district heat. The system can also be designed to use an absorption heat pump operating off the exhaust gas and solar collectors with seasonal storage capacity.

LOCUS plant technology is considered to be a commercially available system today in Denmark. Five engine driven heat pump plants supplying district heating are currently operating in Denmark and many more have been operational in Germany for some time. Biogas-fired, cogeneration engine driven heat pump plants with attached windmills for district heating and electricity production were built in three villages in Northern Jutland, Denmark from 1984-1987.

The hardware and software required for controlling more complex systems involving wind and solar inputs is being developed for both the individual LOCUS plants as well as the system of regulating many such plants within large regional electricity supply systems and city-scale district heating systems. A primary function of LOCUS systems in the context of the Danish national electricity grid as well as regional electric networks will be to serve as peaking plants. This is possible for such a system due to its extensive thermal storage, inherent flexibility and the ability of software to predict thermal and electric demand. LOCUS technology is considered to be the most efficient, flexible energy supply system which is commercially available for use in supplying district heating to small and medium sized towns in temperate regions where the heat demand from district heating systems in the cold season is relatively large in proportion to the power demand.

There are several similar R,D&D projects sited in Danish villages which have had as their objective the integration of other renewable energy sources and technologies such as straw fired furnaces, heat pumps using ground coil and solar absorber heat, biogas fired cogenerating diesel engines and windmills. One such project also incorporates a pulsing district heating system in which DHW supply is the highest temperature required for a group of 97 buildings which otherwise require only very low temperature hot water for heating. A pulse of water at a sufficient temperature to supply DHW to the storage tanks of the buildings is sent out several times per day over the district heating network but at other times the system operates at the much lower temperature required for space heating supply.

Although these integrated renewably energized district heating systems are currently operational only at the relatively small scale of several hundred houses, there is no reason why such systems cannot be scaled up considerably first to supply small towns and later entire cities. The R,D&D in this area in Denmark appears to be proceeding in the direction of integrating numerous renewable energy sources for heating and electricity supply into regional electricity supply systems and large urban district heating systems. There is no reason why the work currently going on in Denmark could not be applied to American conditions. Although application of such systems in the U.S. would encounter many different energy supply and economic conditions, the basic approach seems to be valid no matter where a particular application might be sited.

LOCUS-type systems developed for U.S. conditions would have to incorporate district cooling as well as district heating production capability. However, other than this single additional component and the variations in software which would be required due to different production requirements, the system as it is presently being developed is as close to ideal as can be envisioned for a near term renewably energized DHC system for a U.S. city. The extensive use of thermal storage at various temperatures in order to ensure maximum flexibility in electricity generation is of particular importance for such a system operating in the U.S. since it is very important for it to obtain the maximum amount of revenue from electricity sales as is possible. This is likely to require it to be dispatched by the electric utility during periods of peak demand without compromising thermal supply reliability.

Swedish Land Use Planning For Solar District Heating Supply

One of the primary reasons for considering solar or other renewable forms of district heating and/or district cooling supply is that there is insufficient space of the right type available at a low enough cost for the location of production and storage facilities. The economies of scale in both heat and cold collection and storage are such that very large areas of inexpensive open land will be required to site these facilities. Open land simply cannot be spared or afforded in most densely populated urban areas. Therefore, it will be necessary to locate such facilities at the periphery of such cities or at least outside of the center city.

Land use planning studies for the siting of solar district heating production and seasonal heat storage facilities have been undertaken for several Swedish cities to determine the optimal location of solar collector arrays and daily and seasonal heat storage facilities. In the case of the largest city studied, Linkoping, sites were examined within a 3 km radius from the city center. The mean transport distance from these sites to suitable connection points on the networks was determined to be 1.1 km. Sites within 3 km of the center of the city could provide 44% of the projected heat demand of the entire district heating system which serves the entire city of 80,000 inhabitants. By increasing the distance from the city center to 5 km, sites suitable for 75% of the annual heating demand could be found within a mean transport distance of 2.1 km of the district heating system. Adequate space was rarely found within the built up areas of the city on which to locate large solar collector fields or under which to locate large heat storage facilities. One limiting factor is that large collector fields and large seasonal heat stores need to be located in relatively close proximity in order to achieve necessary efficiencies and economies.

Some of the types of land which met the criteria of low economic value which in part determined the location of the solar production and storage facilities included the following:

Low Value Land For Siting Solar Collection and Storage Facilities
(Lowest Value Land Given Highest Priority)

1. Cut off land, e.g. by highways;
2. Old sand or clay pits or gravel quarries;
3. Municipal waste deposit sites;
4. Noise corridors around highways;
5. Protection zones near air fields and shooting fields;
6. Currently unused land held by industry for possible future use;
7. Large roofs of industrial buildings;
8. Recreational area with low frequency use;
9. Military training area with low frequency use;
10. Forests;
11. Rock outcroppings; and
12. High productivity agricultural land.

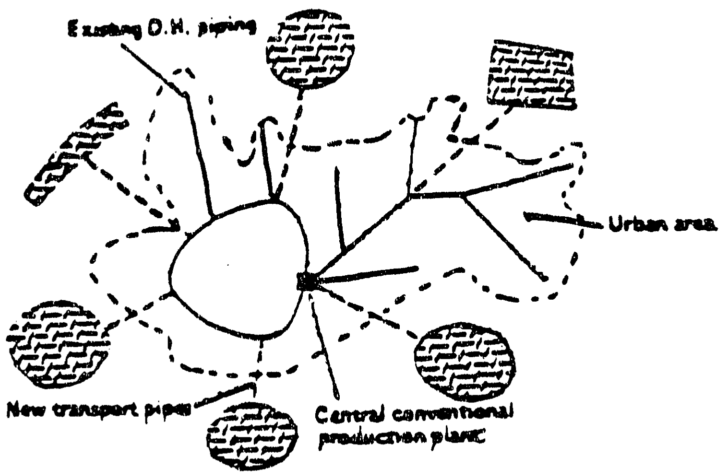
The use of land of these types at the periphery of a central city leads to a renewable energy land use pattern such as that depicted in the following figure which was developed for a Swedish city. (source: Margen, Peter, et. al., "The Prospects of Solar Heat In District Heating Schemes: An Analysis of Economic, City Planning and Geotechnical Factors", in D.O. Hall and June Morton, (eds) "Solar Technology For the Eighties: Solar World Forum", Pergamon Press, Oxford and New York, 1982.)

It should be evident from the foregoing description of activities in renewable district heating and cooling that numerous possibilities exist for combining a wide variety of types of renewable energy technologies for the heating and cooling of entire cities. In the process it is possible to achieve extraordinarily high levels of energy efficiency, economy and environmental amenity. Optimal combinations of systems can be expected to vary considerably from region to region throughout the U.S. Applications studies will have to be conducted regarding the various climates, regions, building stocks, urban densities, thermal transmission systems and combinations with other renewable and fossil thermal supply technologies before it will be apparent which combinations and scales of technology will be viable in any particular region or city. However, the absence of any meaningful R&D by the DOE in any of these areas is the surest way to thwart the development of renewable district heating and cooling systems.

The DOE needs to make a 180 degree turn in its policy toward community thermal energy supply systems R&D in general and renewable district heating and cooling in particular if anything is to happen with these technologies in the foreseeable future since at present there are virtually no resources being allocated to these R&D tasks. This is all the more imperative in light of the global environmental crises which currently threaten human civilization and the very basis of life on earth--global warming and stratospheric ozone depletion.

In order to stabilize the global climate it will be necessary to reduce our emissions of greenhouse gases by 80% within about 50 years. It is also necessary to achieve a nearly immediate curtailment in the production and emission of CFCs. One of the surest ways to achieve both goals is to focus on the buildings sector which accounts for over 1/3 of all U.S. energy consumption. Advanced, high energy efficiency and renewable district heating and cooling supply systems have the potential to reduce the consumption of fossil fuels for building heating and cooling in urban areas in which over 75% of all of our buildings are located by 80 to 90%. It is difficult to envision another technology which evidences similar capability that is also acceptable environmentally to the citizenry of the U.S.

The potential which this technology offers is clearly in line with the long term need for higher levels of energy efficiency and the much greater use of non polluting renewable energy sources. In order to tap this potential the DOE needs to initiate a well funded R, D and D program in renewable energy production systems for DHC which has as its goal the development of technically and economically feasible



Schematic of a City District
Heating System Supplied Largely By Solar
Collector Fields Outside the Urban Area

systems for each region of the U.S. within the shortest time possible. An R,D&D program funded at the level of about $10m/yr for a decade should result in the development and commercialization of technologies which are up to the task at hand and an indigenous industry which is capable of implementing the technology to the extent that both market and environmental conditions permit. A program such as this should be undertaken in a coordinated manner with other countries such as Sweden, Denmark, Finland, Germany and the Netherlands which have evidenced a very high level of interest and commitment to the development of renewable energy systems for DHC.

Bibliography

Task 3:

Renewable Energy Technologies For DHC Supply

Part II:

Renewable Sources of District Heat Supply

Bankston, Charles A., "The Status and Potential of Central Solar Heating Plants With Seasonal Storage: An international Report", Chapter 5 in "Advanced In Solar Energy", Vol 4, Karl W. Boer (ed), Plenum Publishing Corp., 1989.

Bankston, Charles A.*, "Central solar Heating Plants With Seasonal Storage: An International Review" (*: CBY Associates, Inc., Washington, D.C.).

Bankston, Charles A., "Central Solar Heating Plants With Seasonal Storage: Evaluation of Concepts", for International Energy Agency, Solar Heating and Cooling Task VII, Nov. 1986.

Breger, Dwayne S.*, "A Central Solar Heating Plant With Seasonal Storage For the Tri-County Regional Vocational Technical School, Franklin, Massachusetts", (* Dep't. of Mech. Eng., Univ. of Mass., Amhearst, MA., July, 1990.

Breger, Dwayne S., et. al., "Central Solar Plants With Seasonal Storage: A First U.S. Project Under Development at the University of Massachusetts, Amhearst", ASHRAE Journal, July, 1991.

Breger, D.S., et. al., "Preliminary Design Development of a Central Solar Heating Plant With Seasonal Storage at the University of Massachusetts, Amhearst", 1991 Solar World Congress, International Solar Energy Society, Denver, Colorado, August, 1991.

Bruce, Tomas and Jan Nilsson, et. al., "Solar Heating Plant With Seasonal Storage For 500 Apartments in Sodertuna: Predesign for IEA SHC Task VII/le" Swedish Council for Building Research, Stockholm, Sweden, 1985.

CBY Associates, Inc.(*), "Final Report on IEA Task VII Central Solar Heating Plants With Seasonal Storage" (*: Washington, D.C.) for USDOE, August, 1990.

Claesson, Tommy, et. al., "Seasonal Storage of Solar Heat in Kungalv", Swedish Council for Building Research, 1988.

Fisch, Dr. M.N. (ed), "Central Solar Heating Plants With Seasonal Storage: Proceedings of the Workshop: Toward Better Cost Effectiveness", held at the International Solar Energy Society World Congress, Hamburg, Federal Republic of Germany, September, 1987

Illum, K.(*), "Integrated Multi-Task Energy Systems" (*: Institute of Development and Planning, Aalborg University Center, P.O. Box 159, 9000 Aalborg, Denmark.

Illum, Klaus, (*), "LOCUS-Systems and Plants", (*: Institute of Development and Planning , Aalborg University, Fibigerstraede 11, DK-9220, Aalborg, Denmark), in "Advanced District Heating Production Technologies", Ove C. Mork and Thomas Pedersen (eds), IEA DH R,D&D Programme, Novem, 1989.

Jilar, Torbjorn, (*), "Central Solar Heating Plants With Seasonal Storage", (*: Dept. of Building Services Engineering, Chalmers university of Technology, S-412 96, Goteborg, Sweden, in "Advanced District Heating Production Technologies", Ove C. Mork and Thomas Pedersen, (eds), IEA DH R,D&D Programme, Novem, 1989.

Leijendeckers, P.H.H. (*), "The combination of Total-Energy and Solar Assisted Heat Pumps At The Project 'De Achtse Barrier' At Eindhoven", (*: Van Heugten, Rotterdam, the Netherlands.

Mahler, Allan, (*), "Geothermal Demonstration Plant In Thisted With An Absorption Heat Pump", (*Dansk Olie og Naturgas A/S, Slotsmarken 16, DK-2970, Horsholm, Denmark) in "Advanced District Heating Production Technologies", Ove C. Mork and Thomas Pedersen, (eds), IEA DH R,D&D Programme, Novem, 1989.

Pedersen, Peder Vejsig, (*), "Insulated Storage in the Ground for Seasonal Storage of Heat", in "Advanced District Heating Production Technologies", Ove C. Morck and Thomas Pedersen, (eds), IEA DH R,D&D Programme, Novem, 1989.

Peltola, Seppo, (*), "Central Solar Heating Plants With Seasonal Storage" (Helsinki University of Technology, Dept. of Technical Physics, Rakentajanaukio 2 C, SF-02150, Espoo, Finland, in "Advanced District Heating Production Technologies", Ove C. Mork and Thomas Pedersen (eds), IEA DH R,D&D Programme, Novem, 1989.

Rasmussen, H.C. and J. Jensen (*), "Multicomponent Renewable Energy Supply For Low Temperature District Heating Systems" (*: Energy Research Laboratory, Odense University, Campusvej 55, DK-5230 Odense, M, Denmark.

Swedish Council for Building Research, "Plant: Kungalv: Proposed Solar Group Heating Plant With Seasonal Storage", Stockholm, Sweden, 1988.

Timmerman, R.W. and Associates(*), "Report of Design Study: Solar Rennovation and Ground Coupled Heat Pump For Tri-County Regional Vocational Technical High School", Boston, MA, July, 1990.

END

DATE FILMED

9/30/92