must continue, hopefully at an accelerated pace. The many compromises that have been made in the prototype program, while necessary to avoid further delays, could ultimately delay for an unnecessarily long period the commercialization of oil shale.

Continued study of in situ gasification and retorting processes is warranted. The studies should focus on the economics of the process and the definition of technical advances that would be required to make this process competitive with other extraction techniques. At least one consortium of companies is prepared to undertake such a program with private funding, if an option can be obtained on a tract under terms and conditions similar to those arrived at in the prototype leasing program.

A demonstration plant of about 50,000 barrel/day capacity with a subsidy of about $1/barrel would cost about $15 million/year or less when the plant is in operation. The program should also include work on in situ processing at an annual funding level of $5 million, waste management at the $2 million annual level, and general system development, including mining, at the $4 million annual level.

Conversion of Biological Waste to Fuel

Continuation of pilot studies of advanced methods for utilizing solid waste as an energy source would require a funding level of about $5 million per year beyond the existing EPA program for the construction of demonstration plants by local government or private enterprise. This program also requires continued development of shredding and classification equipment to prepare the waste and separate metallic and glass waste for recycling purposes. Continued funding of demonstration projects where warranted is necessary. Program funding of 40 million dollars over the next 5 years should be provided for energy related activities. Further funding is probably justified in terms of solid waste disposal and material recovery benefits to be realized.

Underground Coal Mining

Innovations in underground coal mining are required to increase the safety and assure the production required in the years ahead. The program should be directed toward developing as fully an automated mine as is possible with advanced technology. The initial task would be a survey of alternative new concepts and the initiation of design studies for selected systems. It is estimated that a funding level of $10 million/year for 10 years will be required to develop and demonstrate advanced systems. The cost should be shared by industry with government providing approximately 2/3 of the support in the first 5 years and industry 2/3 in the latter 5 years.

The program to study in situ coal gasification should be continued. A 2 year study and program development phase should be funded at a 2 million dollar level. This study should address seriously the potential environmental impact of such a program. Subsequent funding would be determined upon completion of this effort. The possibility of in situ solvent extraction also warrants assessment.

A similar program for improving strip mining and reclamation technology should also be undertaken. A six month review and compilation of existing knowhow should be followed by a 1 year program formulation phase. Attention should be given to alternative land development approaches, methods for reclaiming arid lands and slopes as well as equipment and procedure development for immediately restoring top soil and vegetation. Two million dollars should be provided to accomplish this effort and initiate necessary projects in the interim.

Program Summary

Table III-1 presents a summary of the program elements discussed above including appropriate funding levels. More details and cost estimates for certain program areas are given in the panel report.[1]

IMPACT OF IMPLEMENTATION

Successful development of nuclear stimulation techniques would provide near-term benefits by increasing the domestic natural gas supply by one-half to one trillion cubic feet annually by the late 1970's.

Table III-1

Fossil Fuel Extraction Program

Improved Oil and Gas Recovery	First year costs $million	Long-term cost $million/yr
-Earth Fracture Studies	.5	22/11
-Fract. of Tight Gas Sands		
nuclear	5	90/7[1]
non-nuclear	2	10/5
-Adv. Oil Recovery	1	5/5
Oil Shale		
-Commitment to Commercial Prototype		100/10-200/10[2]
-General Systems Studies	4	40/10
-Waste Management	1	10/5
-*In situ* Retorting	2	40/8
R&D lease		no cost
In situ Processing of Coal	2	31/5
Energy Recovery from Organic Wastes	5	40/5
Coal Mining - high tech. mining systems	3	500/10
- strip mining reclamation	2	
	27.5	960-1060/10

[1] Primarily Federal expenditures for device development and safety analysis. Industry evaluation and field development will require additional funding.

[2] Assumed to be in form of subsidy of $.50-1.00/bbl from 50,000 bbls/day plant.

Further advancement of oil shale technology would enhance the position of this resource as a viable domestic alternative to imported fuel in the early 1980's. As such it would provide a credible ceiling on the price of crude oil in a non-competitive international environment.

The potential impact of the conversion of biological wastes is also large. It is estimated that about 170 million barrels of low-sulfur oil could be obtained from the conversion of wastes presently being collected. However, combustible wastes might better be used directly to fuel utility boilers in which case the energy recovery would be even greater. Such systems could be implemented on a large scale by the year 1980 if economical processes are developed.

An effective program for the development of an automated underground mine would enhance the position of coal in the energy market. Until further study and design work is performed it is uncertain whether underground coal could be made competitive with strip mined coal. In the longer run, of course, the vast underground coal deposits must be exploited in a safe and environmentally acceptable manner.

C. SOLAR ENERGY*

INTRODUCTION

Radiation from the sun represents the largest renewable energy resource on the earth. The flux of solar energy outside of the earth's atmosphere corresponds to a power of 130 watts/ft^2. By the time transmission through the atmosphere (and diurnal variation) are accounted for, this leads to an average power on the ground in the continental U.S. of 17 watts/ft^2. This is equivalent to an average daily (24 hour) energy supply of 410 thermal watt-hours/ft^2. This value distributed over the roof area of an average house is approximately twice the amount needed to heat and cool the house. Converting the 17 thermal watts/ft^2 into electricity at a 10% conversion efficiency would result in an average daily (24 hour) electric output of approximately 11,400,000 kilowatt-hours per square mile. Under that assumption of a 10% conversion efficiency and U.S. average solar incidence, the total electrical energy consumed in the U.S. in 1969 could have been supplied by the solar energy incident on 0.14% of the land area. Thus the resource base is large even compared to the rate of energy consumption in this country.**

Utilization of solar energy must recognize the major disadvantages of this energy source. It is intermittent; at night energy storage or alternative sources must be provided. It is diffuse; large land areas must be committed to collection of solar energy if it is to become a major source of energy. It is variable, seasonally and geographically, with solar energy much nearer to practical utilization in the South or Southwest than in other parts of the country.

CURRENT STATUS OF SOLAR ENERGY TECHNOLOGY

In discussing the current status of solar energy and recommendations regarding new R&D, three types of utilization will be considered: space

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* This section is based in large part on the NSF/NASA Solar Panel Report, "Solar Energy as a National Energy Resource," Reference 4.

** If this were not the case there would be significant climatic effects due to energy use. In some urban areas the density of energy use does exceed the solar incidence.

conditioning and water heating for buildings, electric power generation and the production of fuels using both direct and indirect solar energy.

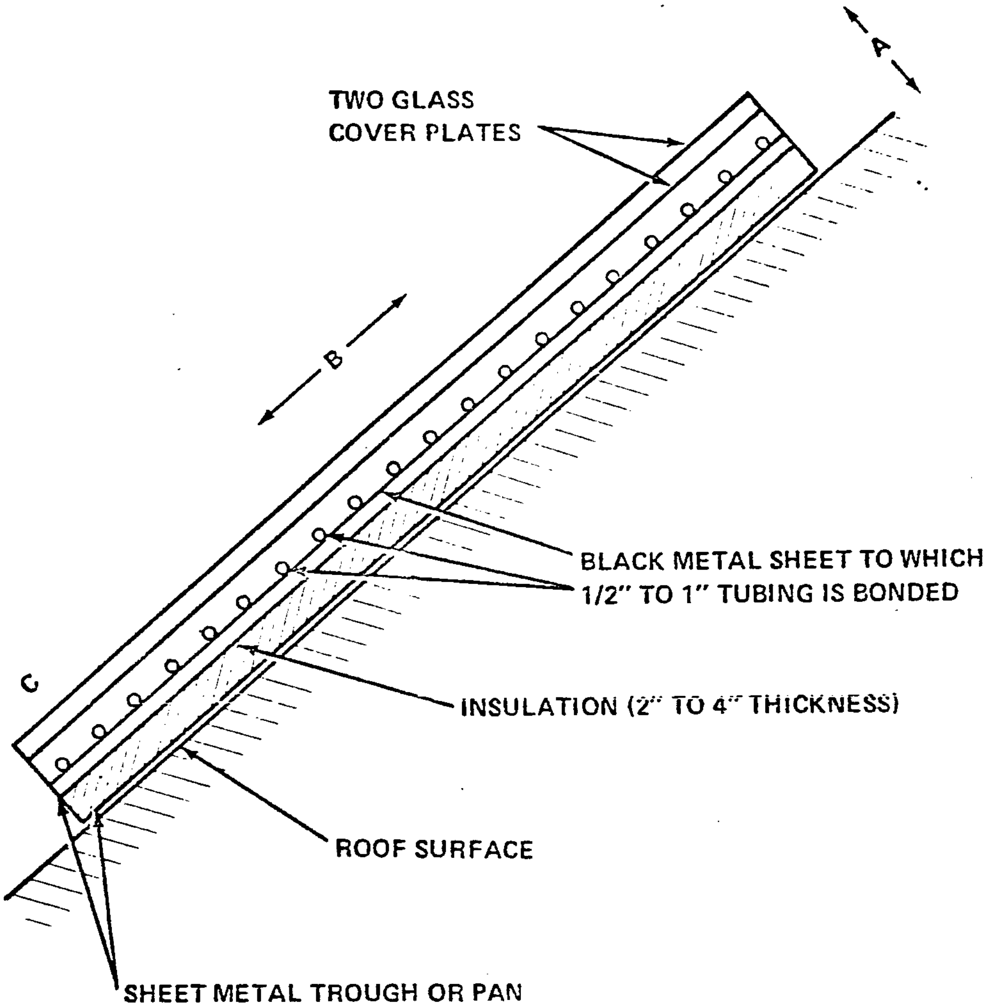
Space Conditioning and Water Heating for Buildings

Buildings may be heated and cooled with solar energy by the use of some type of solar receiver or collector in which a fluid, such as water or air is heated. The system includes an insulated storage tank and an auxiliary heat supply unit to supplement or substitute for the solar source when it is insufficient to meet the demand. A heat-operated air conditioner provides cooling when supplied with solar or auxiliary energy, and various pumps, controls, and facilities are used for circulating air from the conditioned space to either the heating or cooling unit. Figure III-1 is a schematic diagram of one system employing water as the heat collection fluid. As can be seen, hot water for household use may also be supplied by a system of this type. Numerous alternate designs are possible.

The solar collector is the most important, and probably the most expensive, element in the system. A sketch of one type is shown in Figure III-2. Solar radiation is transmitted by the glass covers and absorbed by the blackened metal sheet. This causes the temperature of the metal sheet to increase, so that water circulated through the tubes is heated. Water temperatures of 100 to 200^{o}F are commonly obtained, depending on conditions. Heat losses are minimized by insulation and the overlying glass covers.

A practical location, and suitable area, for the solar collector is the house roof. The collector should be facing south for maximum efficiency. In a temperate, sunny, central U.S. location, a 1,500 square foot house could be provided with about three-fourths of its heating and cooling needs with a 600 to 800 square foot collector and 2,000 gallons of hot water storage. By use of energy conserving house design, the heating and cooling requirements can be substantially lowered.

Solar water heaters are commercially manufactured in Australia, Israel, Japan, USSR, and on a small scale in the U.S. The aggregate business of these enterprises is probably several million dollars per



NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING ON CONDITIONS

DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON WINTER-SUMMER LOAD COMPARISON

Figure III-2 SOLAR COLLECTOR FOR RESIDENTIAL HEATING AND COOLING
DIAGRAMATIC SKETCH OF ONE ALTERNATIVE
(elevation-section)

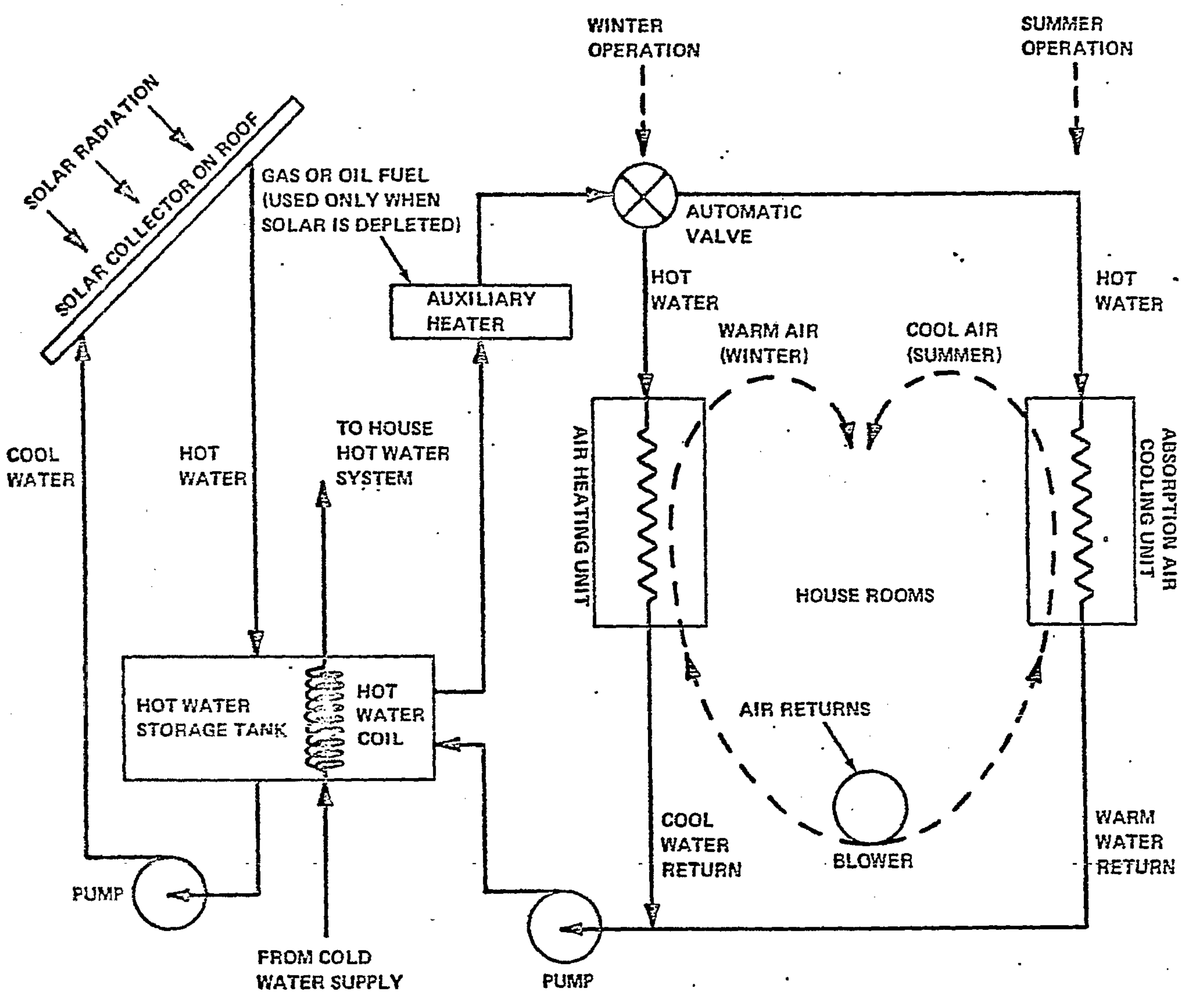


Figure III-3 RESIDENTIAL HEATING AND COOLING WITH SOLAR ENERGY: SCHEMATIC DIAGRAM OF ONE ALTERNATIVE year. Application in the U.S., once common in Florida but then diminished by the availability of natural gas, is now beginning to increase.

Approximately a dozen experimental solar heated structures have been designed, built and operated. While such systems have been shown to be less expensive than electric heat in a wide variety of U.S. climates, the system designs are far from optimized. Furthermore, solar collectors, energy storage units and heat transfer systems for these applications are still in an early stage of component development and engineering.

A few experiments have been conducted in the U.S. and abroad on the operation of absorption refrigeration systems by heat from solar collectors. These experiments show that the concept is promising, and no major technical barriers to successful development are seen. It is evident that there are numerous technological options to be explored; these include many types of cooling equipment and cycles, alternative methods of providing energy storage and auxiliary energy input, and combinations of these components in systems.

Although no experiments have yet been performed, the same major components, solar collectors and energy storage units can be used to supply hot water, space heating, and air conditioning. Economics of combined systems, with their higher use factor on capital intensive equipment, can be expected to be much better than that of either heating or cooling alone.

The principal factor limiting the adoption of solar heating in favorable sections of the U.S. is the lack of well-engineered and economically manufactured and distributed solar heat collectors. With the costs of fossil fuels and electricity expected to rise appreciably in the future, the difference in the cost of heat supplied by solar and by conventional sources will decrease and should make solar systems increasingly attractive in economic terms. However, marketing will require innovative concepts to achieve general acceptance by builders and home owners given the prevalent emphasis on initial rather than operating costs. The key problem impeding wide utilization of solar cooling and combined systems is the development of compact and reliable solar driven absorption refrigeration units. Improved collector, heat exchanger and storage devices are needed for cooling as well as heating applications. Several solar demonstration projects are underway including one (at the University of Delaware) in which a sheet of solar cells has been incorporated in the collector to supply a portion of the dwellings' electricity needs. The state of photovoltaic technology is discussed in the following section.

Electric Power Generation

A variety of approaches have been suggested for the use of solar radiation in electric power generation. It is useful to distinguish between direct collection of solar energy for power production and indirect collection. In direct collection solar radiation is converted to electricity by photovoltaic devices or by thermal-electric systems. Indirect collection utilizes energy from the wind, ocean thermal gradients or plants, all of which have been produced through the action of the sun.

If continuous power source is required an "integrating" element must be incorporated in the system. This might precede electric power generation, say by thermal energy storage, or it might follow electric generation either in some conventional storage mode or through the generation of a chemical fuel such as hydrogen. In the latter case the hydrogen could be used as an alternate energy transport medium as well as a storage medium and fuel. H_2 generation and transmission are discussed in the section on Synthetic Fuels.

Thermal-Electric Conversion Systems

Thermal conversion systems consist of solar collectors and thermal storage devices which deliver thermal energy to a reasonably conventional thermodynamic cycle. Through the use of high temperature selective solar absorber coatings recently developed for the space program, temperatures in the range of standard steam turbogenerators can be achieved with relatively low solar concentration--on the order of 10. This makes possible the use of relatively low precision optics for concentrating the solar radiation.

Several variations of this basic approach have been proposed. One scheme employs "linear" heat absorbers, e.g., absorbers extending primarily in one dimension thus permitting heat transfer through a pipe and concentrators with cylindrical symmetry. Estimates of conversion efficiencies (direct solar insolation to electrical power) in the range of 20 to 30% have been made. In the Southwestern part of the U.S. approximately 10 square miles are needed for a 1,000 megawatt power plant capable of operating on the average at 70% of capacity.

An alternate approach is to use reflecting surfaces with a control focus which concentrate the solar energy over a smaller surface area. Such systems are capable of producing extremely high temperatures within the absorber. Such systems would also reduce the amount of absorber surface area that must be coated and maintained. Higher temperature working fluids would also permit increased electrical generation per unit of cooling capacity required. Proposed systems of this type have utilized a tower at the center of the reflecting surface with the absorber at the top. Such systems are more esthetically offensive to some than the linear absorbers which, although they too occupy substantial land area, do not protrude on the horizon. In either case it is essential to maintain a clean reflective surface which can be adjusted to accomodate the sun's daily and seasonal positional changes.

The key problem in central electric power generation via solar thermal conversion is to find an engineering solution that is economically viable and that assures long-life operation with a minimum of maintenance. Specifically, the optical components, e.g., concentrator and absorber surfaces, have to maintain their performance for many years while exposed to the elements.

Photovoltaic Conversion Systems

Photovoltaic conversion systems are based on the utilization of the photovoltaic effect in solid state devices. In these devices, absorption of light generates free electrical charges which can be collected on contacts applied to the surfaces of the semiconductor. The theoretical limit to the efficiency of the conversion process is about 25% for a single-semiconductor device operating at room temperature. Photovoltaic devices made from silicon have supplied essentially all of the power used by the spacecraft of all nations. Their performance and reliability in space are well established. In addition, small quantities of solar cells have been made and applied utilizing other semiconducting materials. The average efficiency of present production silicon cells is near 11% for space and about 14% for terrestrial applications, with 16% for terrestrial applications reported on recent laboratory cells.

To make extensive application of silicon solar arrays for terrestrial consumption economically feasible, their price will have to be reduced by a factor of 100-1000 from present estimated ground system levels. A significant part of this may be gained through the required million-fold expansion of production rates and attendant automation. However, it is felt that new process approaches will have to be identified to provide for a continuous flow of operations from the raw material to the completed array, possibly similar to integrated circuit fabrication. A number of ideas have been advanced for individual process steps which could be important to the establishment of such integrated processing.

Cadmium sulfide solar cells have been developed, but efficiencies to date have been lower than those obtained for silicon. They have also proven to be less durable than silicon cells, but the reason for degradation of performance is not well understood at the present time. Their cost is substantially below the cost of silicon cells, however, and if the life of the cells could be extended, they could prove attractive even if further improvements in efficiency are not realized.

The various proposals for photovoltaic systems to supply large amounts of electrical power for terrestrial consumption can be classified into three types:

1. Photovoltaic systems on buildings, with the converters attached to or incorporated into the building structures, and supplying energy to activities connected with the buildings. The basic installation does not differ from that of solar thermal collectors. A particularly attractive

approach is to combine the photovoltaic array with a flat plate thermal collector. The absorber surface of the thermal collector is formed by the solar array which converts a portion of the incoming solar energy into electrical energy, and permits collection of about 50% of the remaining energy in the form of heat.

2. Ground central systems, with large contiguous or distributed, but connected photovoltaic collectors, serving either a distribution system or single large consumers.

Before commercial feasibility is achieved even for the terrestrial applications of photovoltaic systems, several problems must be solved. The cost of the photovoltaic and combined devices must be lowered by a factor of at least a 100 (to \$.50 - \$3.50/ft^2 for combined systems), the life of solar arrays must be increased (to 20-40 years) and economical energy storage devices must be developed.

3. Central systems in space, with power transmission to central ground stations and subsequent distribution. In this approach a satellite with photovoltaic panels would be place in synchronous orbit where it would receive solar energy for 24 hours a day, except for brief periods around the equinoxes. Transmission to earth would be by microwaves. This concept adds the significant technical difficulties of space systems development (the solar power system is 100,000 times larger than the proposed Manned Space Center) and major problems of transmission to the difficulties of photovoltaic system development characteristic of previously described systems. It now appears to be a significantly less viable approach than the others.

Wind Energy Conversion

It is calculated that the power potential in the winds over the continental U.S., the Aleutian arc and the Eastern seaboard is about 10^{11} kilowatts electric. There was a mature technology for windpower sixty years ago. In 1915, 100 Mw of electricity were being generated by windpower in Denmark. In the 1940's a 1.25 Mw machine was built and operated at Grandpa's Knob, Vermont, but was shut down by a materials failure of the blade. A conceptual design using aeroturbines to produce 160 billion kilowatt hours of electricity per year has recently been completed for the offshore New England region. This study indicates that the electrical power when used to produce hydrogen which is then piped onshore for consumption in power plants may be cost competitive with conventional methods of producing electrical power.

Power from Ocean Thermal Differences

The Gulf Stream carries about one billion cubic feet per second of near-tropical sea water through the Gulf of Florida. Within the stream the temperature difference between the surface and the depths ranges from 27.5°F to 39°F. That difference occurring at a surface temperature of 71.5°F, would permit a theoretical maximum conversion of heat to useful work of 5%. An overall efficiency of 2% can be attained with a practical engine. A collection system of units moored on one mile spacings along the length and across the breadth of the Gulf Stream (500 miles long x 20 miles wide) are thought capable of an annual energy production of 26 x 10^{12} kWh. In such a system, special thermodynamic cycles suited to low grade heat must be used. Such cycles are discussed in another section. One such cycle, the Claude cycle, was demonstrated in Cube in 1929 for this use and produced 22 kW of useful power. Two experimental units of 3,500 kW net output, each working in the Claude cycle were installed off the Ivory Coast in 1956 by the French. Due to mechanical failure and other problems the plants were abandoned after a short time. There is a small continuing French R&D effort in this field at the time and the NSF has just funded a feasibility study in the U.S.

Lunar Power

Although power may be extracted from the tides at certain unusual locations, such as at St. Malo in France or the Bay of Fundy, the total potential for this country is very small.

Production of Fuels

The natural conversion of solar energy into plant materials by photosynthesis and the further conversion of this stored energy into more concentrated forms such as natural gas, petroleum and coal is the basis of the world's fossil fuel supply. It is appealing to think of using the complex chemistry supplied by nature and to compress the natural time scale for fuel producing processes.

For land plants such as trees or grasses under intense cultivation the efficiency of solar energy conversion could range from 0.3% to 3%. This assumes an average heat of combustion of the dried plant material of 16×10^6 Btu/ton.

If, through advanced management practices involving plant genetics, plantations could be operated which produced continuous crops with 2 to 3% solar energy conversion, about 3% of the land area of the U.S would produce stored solar energy equivalent to the anticipated U.S. electric energy requirements for 1985. Analyses of tree farming indicate that a land area of 400-500 square miles would be required to produce fuel (costing \$1.50 to \$2.00/10^6 Btu) for a 1000 MWe power plant.

Extensive studies have been carried out over many years relating to the culture of specific algae strains as a potential high protein food source. Recent reports have indicated continuing yields of about 50 tons of dry material per acre per year with peak production at the rate of 70 tons per acre per year. Floating water plants, such as water hyacinth, presently are pest plants in many rivers and lakes in tropical and semitropical areas. The rate of growth is rapid and in nutrient-rich ponds net productivity of up to 85 tons of dry product per acre per year has been reported. A number of technical problems have been identified for aquatic sources of fuel but little development work has thus far been performed.

PROGRAM RECOMMENDATIONS

The general area of solar energy is fertile ground for new R&D. This follows from the general attributes of solar energy discussed in the introduction to this chapter, the wide variety of potential applications and the high potential return per incremental research dollar invested. The latter is due in part to the relative neglect of solar energy thus far in the nation's energy R&D policy. It is also due to the modular nature of the hardware used in many solar energy applications. Research on a space heating system on the scale of a household is inately cheaper (ceteris paribus) than research on a central station power system that must be developed at close to the 1000 Mwe scale.

In addition to the usual criteria applied in the setting of R&D priorities (areas of maximum feasibility, highest return per R&D dollar expended, etc.) two additional criteria applied to the choice among the many R&D options in solar energy:

1) Everything else being equal, preference should be given to those schemes which utilize as large a fraction of available solar flux as possible.
2) Everything else being equal, preference should be given to those schemes which have wide geographic applicability.

Specific program recommendations will be discussed in terms of the three areas distinguished in the previous section.

Thermal Energy for Buildings

The program in this area comprises three elements: water heating, space heating and space cooling. Although the technology for water heating is well advanced, the further development of low cost demonstration units requires additional support.

The short range goal of R&D effort in residential solar heating and cooling should be a fully workable prototype system suitable for test operation in favorably situated residences. This can likely be achieved within three years of the start of a program so oriented.

Component design and system design studies, optimization studies, cost analyses, and prototype construction and testing of components and the integrated system are the main elements of the three-year R&D program. The studies must involve solar collectors, heat storage units, heat exchangers, absorption refrigeration equipment, auxiliary heat supply facilities, control instruments, and various sub-assemblies and full assemblies of these components.

As specified in more detail in the solar panel report,[4] the estimated cost of an effective initial three-year R&D program will be about $16 million.

After initial performance testing of a functional unit, the residential solar heating and cooling system should be subjected to a rigorous program of improvement and optimization. Three interrelated objectives of the program beyond the third year are increased efficiency, reduced cost, and improved simplicity and practicability of application to general use. Most of the effort should be placed on concepts previously investigated, but there should be some work on promising alternatives, especially those involving cooling methods. As shown below, the funding level expected to be required from the fourth to the tenth year of development is an annual average of about $12 million, for an $84 million total.

Two specific milestones are designated at the 3-year, $15.8 million cumulative cost point and the 5-year, $42,6 million cumulative cost point. Effective national commitment should therefore be for $16 million initially, another $27 million on a contingency basis, and a final $55 million on a further contingency basis. If the total program is carried through approximately as outlined, it is fully expected that at its conclusion, residential heating and cooling with solar energy will be in general public use.

A closely related, and important area of R&D is architectual design to minimize heating and air conditioning needs. Such research is discussed in the chapter on urban energy use.

Thermal-Electric Conversion

The R&D effort aimed at electric power generation through thermal conversion should focus on the development of the various components of such a system with particular importance given to the total cost of the solar collector and concentrator. It is recommended that all promising alternatives for component elements be studies under various environmental and simulated operating conditions. Sub-assemblies should be prepared and tested for feasibility demonstrations.

Continued systems analysis should be carried out in parallel with the component studies to evaluate the potential performance and cost competitiveness of the subsystems under investigation. This should include alternative solar collector concepts. In addition, methods for best interfacing the solar-generated power with the existing electrical power grid should be studied.

When satisfactory components are in hand and when economic viability seems probable, a pilot plant of 10 to 25 megawatts should be constructed and operated. Based on the data from the pilot plant a size optimization study should be made and a full-scale demonstration plant should be considered.

The estimated cost of an initial seven-year program is $25 million. A small scale pilot plant is estimated to cost $100 million.

Photovoltaic Conversion

Regardless of the ultimate use, systems on buildings, central station generation or satellite-based systems, the main development required in the photovoltaic area is the production of very low cost, durable arrays. Work should be accelerated in materials, processing, and system design to make the manufacture of low cost solar arrays possible. During the first three years of the program some subsystem development and feasibility studies should be carried out. The development of low cost prototypes should await the early results of those studies. An initial annual expenditure of about $5 million in this area would be appropriate.

At this time work on the satellite solar systems should be confined to paper studies of the problems of probable reliability and safety of the concept. Until the land based system shows some evidence of commercial success no R&D expenditures seem warranted on the satellite solar system.

Wind and Ocean Thermal Gradients

Modest programs would be appropriate in the areas of wind power extraction and the use of ocean thermal gradients. These should be primarily feasibility studies including more realistic estimates of cost, total impact, and environmental effects. Note that programs recommended elsewhere on bottoming cycles are applicable to the problem of energy extraction from ocean thermal gradients. Programs in hydrogen production and the development of fuel cells are germane to both wind power and the use of ocean thermal gradients.

An annual effort of around $0.7 million would be appropriate in this area.

Production of Fuels

A serious difficulty with the various schemes for producing fuels through photosynthesis is low efficiency and thus the large land use required. These schemes may also turn out to be labor intensive and may also require extensive use of fertilizers. Nevertheless there is a need to know what is technologically possible in this area. Thus investigations of technological feasibility are required. An annual expenditure of $1 million should be adequate for this purpose.

Note that the related problem of using waste, animal and human, to produce fuels is discussed in the chapter on fuel extraction. The use of waste for this purpose is inately of more interest since the "resource" being consumed is a "bad" (waste) rather than a "good" (land).

Program Summary

Table III-2 presents a summary of the program elements discussed above including appropriate funding levels. More details are given on programming and on cost estimates in the panel report.[4]

IMPACT OF IMPLEMENTATION

Table III-3 represents the effect on resource consumption and on environmental effects of the energy system if solar energy is successfully developed and implemented. Degrees of implementation shown in that

Table III-2

Summary of Solar Energy Program

Program Element	Current R&D Objective	First Year Cost $ Million	Long Term Cost[a] $ Million/Years	Notes
Thermal Energy for Buildings			100/10	All systems should be commercially available at end of 10yrs.
Water Heating	Develop low cost demonstration units	0.6		
Space Heating	Component development and demonstration	2.3		
Space Cooling	Component development	0.6		
Electric Power Generation				
Thermal Conversion	Component development and analysis	2.5	125/10	Funding includes pilot plant. Demonstration plant (investment beginning in the 8th year) could cost about $1 billion and should be cost-shared with industry.
Photovoltaic Conversion	Lower cost of production of arrays	5.0	140/10	Primarily component development & evaluation. Additional expenditure for central station pilot plant could begin in yr 6.
Wind and Ocean Gradients	System studies	0.7	2/3	
Fuel Production	Feasibility analysis	1.0	3/3	Pilot plant development could start after 3 years.
TOTAL		12.7	370/10	

[a] More detailed recommendations for the break-down of these costs are given in the Panel report, Reference 4.

Table III-3

Impact of Solar Energy Implementation

Percent Change from Reference Energy System

	Thermal Energy for Buildings*		Misc. Electric for Residential & Commercial		Photovoltaic Central Station Electric		Thermal Central Station Electric	
	2000	2020	2000	2020	2000	2020	2000	2020
% of Sector or Category Replaced	10	35	5	50	1	10	1	5
Resources								
Nuclear	-0.7	-1.6	-	-6	-1	-10	-	-5
Coal	-0.5	-1.2	-	-4	-0.7	-7	-	-4
Oil	-0.5	-1.7	-	-0.5	-0.1	-0.9	-	-0.5
Natural Gas	-1	-3.9	-	-1	-0.2	-1.6	-	-0.8
Environmental Effects								
CO_2		-1		-2		-3		-1.5
CO		-		-0.1		-0.2		-0.1
SO_2		-1		-3.4		-5.7		-2.9
NO_x		-1		-3.1		-3.2		-1.6
Particulates		-		-0.8		-1.4		-0.7
Hydrocarbons		-		-0.2		-0.3		-0.2
Radioactive Materials		-2		-6		-10		-5
Land Use		-2		-6		+0.4		+4
Other Effects	Possibly lower costs, greater decentralization.		Decentralization					

* Assumes solar energy could provide an average of 80% of the heating and cooling requirements in 10% of new buildings (residential and commercial) built in 1985, 50% in 2000 and 85% in 2020.

table for each mode of use assume that the technology is more attractive--presumably from an economic point of view--than the technology used in the Reference Energy System. The perturbations on resource consumption and environmental effects are based on the Reference Energy System values given in Chapter II.

D. GEOTHERMAL ENERGY

INTRODUCTION - The Nature and Role of Geothermal Energy

Man is accustomed to seeking energy resources below the surface of the earth on which he lives. It is odd that he has paid so little attention to utilizing the heat that resides there as well as the fuels which ultimately must be converted to heat. The average distribution of heat flux under the surface of the earth discourages exploitation but, as with fuels, there is a large variation in that concentration and several kinds of potentially exploitable geothermal resources exist.

The significance of geothermal energy is that it represents an entirely independent energy source from those which will be pressed so severely in the near future. Furthermore, it is a form of energy which, through assertive R&D, can begin to contribute significantly in the relatively short term. Some exploitation of geothermal energy is already underway in California. Economics will dictate what fraction of the vast total geothermal resource base is exploitable in any practical sense.

Geothermal energy is not without its environmental problems. However, those problems appear no more severe than those associated with the near-term technologies with which it competes.

The Resource Base

Large variations exist in estimates of the geothermal resource base, particularly the portion of that resource base that can be converted to useful power. The differences reflect varying estimates of "how much is there," as well as differing estimates of the new technology needed to utilize it. Under assumptions of current technology, White[7] estimated that 5,000-10,000 Mw could be generated and maintained for at least 50 years. Technologically optimistic projections have indicated that a generating capacity of 400,000 Mw could be developed in the Western U.S. by 1995.[8]

Environmental Effects

Geothermal energy is often spoken of as being environmentally pure. It is true that many of the environmental effects of fossil and nuclear power plants do not exist for geothermal plants. No fuel mining is necessary; no particulate pollutants are produced; no radioactive wastes are produced and the accident potential is small. On the other hand, geothermal plants use more land than their competitors, and there are problems of contamination of ground and surface waters, noxious gas emission, noise, land subsidence and greater cooling water requirements. The possibility of increasing seismic frequency or intensity is also of consideration for some fields. These effects are strongly dependent on the particular type of resource being exploited and are all subject to amelioration through research and engineering design

CURRENT STATUS OF EXPLOITATION AND R&D IN GEOTHERMAL ENERGY

The normal vertical temperature gradients and heat fluxes near the surface of the earth are roughly 30°C per kilometer and 1.5 microcalories/cm^2-sec. Geothermal resources consist of the thermal energy and fluids found in regions with much higher temperatures than expected under more normal conditions. It is useful to divide geothermal resources into several categories. A convenient classification scheme is shown in Table III-4.

Vapor-Dominated Convective Hydrothermal Resources

Within the vapor-dominated geothermal reservoir, saturated steam and water coexist, with steam being the phase that controls the pressure. With decrease in pressure upon drilling and production, heat contained in the rocks dries the fluid first to saturated steam and then to supersaturated steam, with as much as 55°C superheat at a well-head pressure range of five to seven kilograms per square centimeter (70-100 psia). The steam may contain minor amounts of CO_2, H_2S, and NH_3.

TABLE III-4 CLASSIFICATION SYSTEM FOR GEOTHERMAL RESOURCES

A. Wet Formation

1. Convective hydrothermal resources

a. Vapor dominated
b. Liquid dominated

2. Geopressured resources

a. Liquid dominated

B. Dry Formations

1. Impermeable rock

2. Magma systems

C. Temperature Regimes

1. Superheated steam temperatures

2. Above 180°C

3. From 100°C to 200°C

4. Below 120°C

Source: W. J. Hickel, "Geothermal Energy," Report of the Geothermal Resources Research Conference, Seattle, September 1972.

Pressures larger than about 34 kilograms per square centimeter (483 psia) and temperatures above 240°C in vapor-dominated reservoirs are unlikely because of thermodynamic conditions and the flow dynamics of steam and water in porous media. Hot brine probably exists below the vapor-dominated reservoirs at depth but the reservoirs have not yet been drilled deep enough to confirm the presence of such brine. The steam reservoir may be a "cap" for the upflowing part of a major liquid-dominated convective hydrothermal system.

Liquid-Dominated Convective Hydrothermal Resources

These are thermally-driven convective systems of meteoric water in the upper part of the earth's crust which transfer heat from a deep igneous source to a depth sufficiently shallow to be tapped by drill holes. The exploration target is a reservoir located in the upflowing part of the convective system. The thermal energy is stored both in the solid rock and in the water and steam which fill the pores and fractures.

This type of resource is commonly found in zones of young volcanism and mountain-building. Among geothermal systems discovered to date, hot liquid-dominated systems are perhaps twenty times as common as vapor-dominated systems.

Hot liquid geothermal systems contain water at temperatures that may exceed surface boiling temperatures substantially because of the effect of the higher pressure in elevating the boiling temperature.

Water in most hot liquid geothermal systems is a dilute aqueous solution (1,000 to 30,000 milligrams per liter) containing sodium, potassium, lithium, chloride, bicarbonate, sulfate, borate, and silica predominantly. The silica content and the ratio of potassium to sodium are dependent on the temperature of the geothermal reservoir, thus allowing prediction of subsurface temperatures from chemical analysis of hot fluids.

Geopressured Resources

Deep sedimentary basins filled with sand and clay or shale of Tertiary Age (less than 80 million years) are generally undercompacted below depths of 2 to 3 kilometers and, therefore, the interstitial fluid pressure carries a part of the overburden load. Such regions are said to be geopressured.

Geopressured geothermal systems occur in regions where the normal heat flow of the earth is trapped by insulating impermeable clay beds in a rapidly subsiding geosyncline or downward bend of the crust. Pressures at depth are significantly in excess of hydrostatic.

Aquifer systems within the geopressured section are compartmentalized by regional faults into blocks of horizontal extent ranging from tens to thousands of square miles. Aquifers a few thousand feet below the top of a geopressured zone commonly contain water having less than 10,000 milligrams per liter of dissolved solids. In some places the water is even potable (less than 1,000 milligrams per liter).

Because the solubility of hydrocarbon gases in water increases rapidly with decreasing dissolved solids, and because the high temperatures and pressures have resulted in a natural cracking of the petroleum hydrocarbons, the geopressured reservoir fluids commonly contain 10 to 30 standard cubic feet of natural gas per barrel of fluid. These dissolved hydrocarbon gases would be a valuable by-product of fluid production.

Temperatures of produced water would range from 150 to 180°C. Wellhead pressures would range from 4,000 to 6,000 pounds per square inch. Production rates could be several million gallons of fluid per day per well and possibly 1-10 million standard cubic feet of natural gas per day per well. This gas is relatively expensive to produce but might enter the marketplace in significant quantities if sold for $1.00 per thousand cubic feet. Development work is now being carried out by the private sector.

Geopressured deposits occur in continuous belts, are commonly bound by regional faults, and extend for hundreds of miles. The search for oil and gas has uncovered geopressured reservoirs in many countries of the world. In the United States, geopressures have been encountered in the Gulf Coast, California, and Wyoming. It may be that the geopressured geothermal resource, including its associated methane, will prove to be the most important of all geothermal resources in terms of its intermediate term impact. Although too little is presently known about them to make accurate projections the recoverable methane reserves associated with this geothermal resource are believed to be many times larger than all other U.S. methane reserves.[8]

Impermeable Dry Rock

Hot impermeable rock systems are those geothermal regions where the heat is contained almost entirely in impermeable rock of very low porosity. Interactions of the large plates of the earth's surface along the West coast of North America have resulted in volcanism, tectonic activity, and high heat flow affecting much or perhaps all of the Western United States. The heat generated by those interactions has been in part responsible for the presence of large, once-molten masses of granite forming the core of the Sierras and various other once-molten masses called batholiths. Areas such as Craters of the Moon, Idaho, are surface manifestations of the recent presence of similar ages of intrusive rocks. Thus the Western U.S. holds excellent prospects for finding enormous amounts of hot impermeable dry rock formations. Hot rock, however, underlies all of the U.S. and the question of the abundance and recoverability of this energy in the Eastern U.S. has not been investigated in sufficient detail to arrive at any valid assessment.

Magma Systems

Magma geothermal systems are those systems where the thermal energy is contained in liquid or near-liquid rock at temperatures ranging from $600^{\circ}C$ to perhaps $1,500^{\circ}C$. In the Hawaiian Islands a continuing history of magmatic activities presents some unique potentialities for recovering usable energy from volcanic areas. The other live volcanoes of the U.S., including Alaska, offer potential also. In some instances deep drilling may be required to reach these resources.

Current Utilization

The primary use of geothermal resources to date is for the generation of electricity. For this purpose, under existing technology, the geothermal reservoir must have a temperature of at least 180°C and preferably 200°C and lie at shallow enough depths (3 km or less) to be developed economically. In "dry-steam" fields, the steam is fed directly from well-head to turbine after removal of abrasive particles. In "wet-steam" fields, on the other hand, boiling of hot water at depth yields a mixture of steam and water at the surface. The steam and water are mechanically separated at the well-head and the steam fed to a turbine. In both types of fields the steam is at a much lower pressure compared to that used in fossil fuel or nuclear-powered generating plants, so that specially designed turbines are used to drive the conventional generators. World electrical capacity from geothermal energy in 1971 was approximately 800 megawatts, or about 0.08 percent of the total world electrical capacity.

Generation of electricity from natural steam in the United States is limited to The Geysers, California, which had an installed capacity of about 300 Mw in late 1972. The cost of power from these plants is less than that with either fossil fueled or nuclear power. Several hundred megawatts of additional capacity was under construction at that time. Industry estimates of the ultimate potential of this field exceed 2000 Mwe although the boundaries of the steam productive area have not been accurately defined.

Passage of the Geothermal Steam Act of 1970 gave the Secretary of the Interior the authority to issue leases for the development and utilization of geothermal steam and associated geothermal resources on Federal lands, where many of the most promising areas are located. Leasing the Federal land for geothermal exploration, however, has been delayed pending satisfaction of the requirements of the National Environmental Policy Act of 1969, as interpreted in recent court decisions.

Geothermal resources have other uses, but to date they have been minor. Geothermal waters as low as 40°C are used locally for space heating and horticulture in Oregon, Nevada, Idaho and California. Much of Reykavik, the capital of Iceland, is heated by geothermal water, as are parts of a number of other towns and cities. Geothermal steam is also used in paper manufacturing at Kawerau, New Zealand. Some geothermal waters contain potentially valuable by-products such as potassium, lithium, calcium, boron, zinc, and other chemicals.

Current Research and Development

Research and development programs in geothermal resources have been carried out in the United States by several Federal agencies, state agencies in most of the Western states and private industry. The Federal share of such research amounted to about $10 million in 1973.

The U.S. Geological Survey has conducted studies aimed primarily at geological mapping and geophysical and geochemical surveys. Some work has started recently on developing new geophysical techniques and modeling of geothermal areas. The Bureau of Reclamation, in conjunction with other groups, is studying the feasibility of multi-purpose development of electric power and desalted water from the geothermal resources of the Imperial Valley of California. A number of other agencies have small or preliminary programs in various aspects of geothermal energy. These are summarized in Reference (5).

The total current effort in geothermal R&D by private industry in the U.S. is not known, but it probably amounts to several tens of millions of dollars per year apart from costs of land purchase, production drilling and plant construction.

PROGRAM RECOMMENDATIONS

The pace of increased utilization of geothermal resources will depend on an expanded R&D program with broad coverage including resource appraisal, exploration methods, development and utilization techniques and environmental effects. The program should include both public and private efforts, with the latter concentrating on those resources that promise early development.

Federal programs in geothermal energy have been conducted by several agencies with no one agency having overall responsibility for program coordination and management. It is strongly recommended that a geothermal program office be set up within the governmental R&D structure to plan, evaluate and manage all elements of the geothermal program. This office would also liaison with private programs to see that duplication of effort is minimized and that all phases of the program are being pursued in a complementary fashion. Public-private cooperative efforts would also be arranged through this office.

Resource Appraisal

More precise estimates of the magnitude, quality and distribution of geothermal resources are essential to making Federal lands available for leasing under the National Environmental Policy Act of 1969 as well as for planning an intelligent strategy for the use of geothermal energy. An augmented program of regional studies, heat-flow measurements and research drilling is needed. The initial emphasis should be on potential geothermal areas deficient in power and/or water. Regional studies would include geologic mapping and synthesis, geochemical sampling and analysis and geophysical studies including both ground and airborne methods.

The appraisal should specifically include the geopressured resources of the Gulf Coast and impermeable dry rock regions. Industrial interest in dry steam and high temperature ($220^{\circ}C$) hot water will lead to substantial private support of these resources. Government must maintain a program sufficient to manage these resources in the public interest. The need for an accelerated leasing program seems obvious in view of the interest already demonstrated by industry and the preliminary assessment that most of the highest quality geothermal resources underlying public lands. A ten year program estimated to cost 142 million dollars with a first year cost of 6 million dollars is recommended.

Exploration Methods

Development of geothermal resources and evaluation of their magnitude are handicapped by the relatively primitive nature of exploration techniques currently in use, by the absence of an adequate understanding of the factors that characterize geothermal systems, by the lack of inexpensive techniques for drilling, and by the need for better borehole logging and sampling techniques.

Research on drilling methods should include the development of high temperature components for drilling equipment, analysis of drill failure and advanced concepts such as the melt drill. The well logging program should include the development of high temperature (350°C) components. A ten year program totalling 25 million dollars is recommended with 2.5 million dollars committed in the first year. Industry should be involved in both the funding and execution of this program element.

Reservoir Development and Production

Although reservoir studies of dry steam fields are currently being made by private industry, less attention is being devoted to hot water, wet steam and geopressured fields. Reservoirs of these types are going to be of major importance for geothermal fields used for desalination purposes. Reinjection techniques need further development for these purposes.

Hot rock reservoir studies are also of importance. These should include tests of hydrofracturing methods followed by thermal shrinkage fracturing studies. The possibility of using explosives for fracturing hot rock geothermal wells should also be investigated. The hot rock resource, while likely to be available over a wider geographical area, represents the most challenging form of geothermal energy to extract. A major effort in fracturing should be accompanied by a more thorough assessment of the magnitude and location of the resource and the development of utilization technology for hot water systems. The latter will also be needed in converting energy from the hot rock resource.

The water value of steam and hot water geothermal resources should not be ignored. Studies may utlimately conclude that geothermal energy in these sources is most efficiently used for desalination purposes, particularly in water deficient regions of the country. Systems studies using the experience of earlier Office of Saline Water programs should be undertaken to determine the technical and economic feasibility of using geothermal resources in this manner.

A 10-year program of \$125 million for hot water resources and \$71 million for hot rock is recommended. The latter should be reviewed at several points to make certain the ultimate payoff justifies continuation of the effort. First years funding of \$2.5 million and \$2.3 million for hot water and hot rock reservoir development and production is required.

Utilization Technology and Economics

This area of research has the greatest potential for short term impact in the geothermal area. Adequate techniques for generating power from dry steam fields and from certain wet steam fields such as Cerro Prieto are well developed. A priority program is required on the utilization of other geothermal resources for power production, desalination of brines and commercial recovery of chemicals. Possibly 70 to 80% of the geothermal reservoirs susceptible to development within the next decade or so contain hot water at temperatures of less than $180^{\circ}C$ ($356^{\circ}F$) or have dissolved chemicals of such a nature or abundance that they cause problems in power generation.

Major emphasis should be placed on a technology demonstration program supported by studies of the physical chemistry of known geothermal brine systems. Key hardware components need to be developed, preferably by a joint government-private industry effort. Examples of critical components are down hole water pumps and high tenacity, high temperature rubber. Applied research is also needed on scaling phenomena and means of prevention; corrosion; heat exchange concepts; low temperature vapor cycles using freon , isobutane and other fluids; improved steam-water separators; alternative devices to conventional turbines such as screw expanders, rotary vane machines, and other previously untested devices. The high pressure potential of geopressured resources can also be used for power production or to return waste water to the reservoir. These resources frequently contain commercial quantities of dissolved methane which must be recovered. These two potentially valuable energy sources should be considered in R&D programs to utilize this type of resource.

Preliminary hot rock utilization studies should also be pursued. Systems for converting the low temperature energy extracted by the fluids circulating through hot rock formations will likely be similar to those used for the hot water resource. Thus, the highest priority should be given to the development of these systems in connection with the abundant hot water resources initially. These systems could also be used as bottoming cycles on conventional steam power plants. As fuel costs rise and the need to lessen thermal discharge increases, such systems will likely become more attractive economically.

Program funding for hot water and mixed steam water systems is estimated at $143 million over the next ten years. This would permit the development and demonstration of one or two low temperature cycles for use with geothermal sources or as bottoming cycles on conventional plants. A first year commitment of 4 million dollars should be made. Hot rock utilization technology will build on the above program and will require modest funding in early years. Half a million dollars is recommended in the first year to begin analysis of the types of utilization technology best adapted to hot rock systems. Over 10 years an estimated 54 million dollars could be needed if other phases of the hot rock program progress satisfactorily.

Environmental Effects

Environmental problems arising with geothermal developments are of major importance and need to be evaluated and kept within manageable proportions. Six activities can be identified as important; 1) a water quality monitoring program, 2) development of hydrogen sulfide and ammonia removal processes, 3) development of noise abatement technology, 4) a subsidence monitoring program, 5) a seismic monitoring program, and 6) preparation of environmental impact studies of sites made available for competitive lease sales. A ten year program totalling $35 million is recommended with $2.5 million in the first year. It should be advanced as rapidly as possible to permit incorporation of the findings in other phases of the geothermal program.

Institutional Factors

Funding should be provided to study the institutional and legal factors limiting geothermal development. A five million dollar over 10 years continuing program is deemed adequate.

Program Summary

Table III-5 summarizes these program elements and gives suggested FY 1974 and long-term funding levels. If adequately funded from this point forward, funding for exploration and resource appraisal should peak in the FY'76-'77 period and reservoir development and production about FY'81. At the end of an aggressive ten year program the annual Federal R&D funding level in geothermal energy should be on the descent. Industry can reasonably be expected to pick up an increasing share of the load as the size of the economically recoverable geothermal resource becomes evident.

IMPACT OF IMPLEMENTATION

TableIII-6 presents the impact on resource consumption and environmental effects of the implementation of geothermal energy. The levels of implementation given in those tables are very uncertain due to the lack of knowledge of resources and the immature state of technological development. These estimates assume the successful completion of all major elements of the program outlined above.

Table III-5

SUMMARY OF GEOTHERMAL ENERGY PROGRAM

Program Element	Current R&D Objective	First Year Cost $ Million	Ten Year Cost $ Million
Resource Appraisal	More precise estimates of magnitude, quality and distribution of resources.	6	142
Exploration Methods	New geophysical exploration methods, high temperature drilling & logging technology.	2.5	25
Reservoir Development and Production			
Hot water	Develop desalination and reinjection	2.5	125
Dry hot rock	Develop fracturing techniques	2.3	71
Utilization Technology and Economics	Materials and component evaluation. New devices, cycles for energy extraction.		
Hot water-wet steam		4.0	143
Dry hot rock		0.5	54
Environmental Effects	Gas removal technology, noise control, subsidence and seismicity monitoring.	2.5	35
Institutional & Legal		0.5	5
	Totals	$ 20.8 million	$600 million/10 yr

IMPACT OF IMPLEMENTATION OF GEOTHERMAL ENERGY[a]

	Year 1985	Year 2000
% of Installed Electric Generating Capacity	3.2	25
Resources[b] (Percent change from Reference Energy System)		
Nuclear	-3	-25
Coal	-1.9	-17
Oil	-0.3	-2
Gas	-0.4	-4
Environmental Effects		
CO_2	-0.9	-7.6
CO	-	-0.5
SO_2	-1.5	-14
NO_x	-0.9	-8
Particulates	-0.9	-3.5
Hydrocarbons	-	-0.8
Radioactive materials	-3	-25
Land Use	c	c
Other	Increased H_2S, CH_4 and noise, possibility of subsidence and increased earthquake inciden[illegible]	
Power Costs	Possibility that lower power costs, characteristic of current dry steam systems will prevail for other systems as technology develops.	

[a] Impact based on replacement of central station electric component of Reference Energy Systems.

[b] For 1985 these figures omit both the dissolved gas in the geopressured water and electricity that could be produced from associated thermal and hydraulic energy. Although very little is known of the practicality of large scale development of this resource, it could contribute significantly to gas supply. See discussion in text.

[c] Land use at power plants would decrease, but total use (including mining, waste disposal) would decrease.

E. CLEAN FUELS FROM COAL

INTRODUCTION

As one of the nation's most abundant energy resources, coal can play a major role in meeting future energy needs. Methods must be developed for utilizing coal for direct firing to produce electric power in a more environmentally acceptable manner as well as for the conversion of coal into liquid and gaseous fuels to serve both electric and non-electric energy demands. The successful development of reliable and economically viable processes for controlling sulfur dioxide emissions from coal-burning power plants, either during the combustion process by stack gas scrubbing, or by removal of sulfur from the fuel before combustion could help to reverse the existing trend away from coal as a boiler fuel and provide environmental benefits in the near term.

It is important, at the same time, to address technological and environmental problems in the coal extraction area in order to resolve any constraints that they may place on the supply of this fuel. Technological opportunities in this area are discussed in the section on Fossil Fuel Extraction (III-B). Advanced power cycles which can increase the efficiency with which coal is used in the generation of electricity are also discussed in a separate section (III-F).

The implementation of technologies for the conversion of coal into liquid and gaseous fuels to supplement, and in the longer term replace, oil and natural gas would contribute significantly to national self-sufficiency for energy resources. Clean fuels, low in ash and sulfur content, obtained from coal may also be burned as boiler fuels providing another path for the use of coal to produce electricity in an environmentally acceptable manner. Numerous processes are under development for the production of methane, fuel oil, and a clean solid boiler fuel from coal.

Two major R&D initiatives in the area of clean fuels from coal were identified in the President's Energy Message of June 1971. These initiatives involved work on processes for the removal of sulfur dioxide from stack gases and for the conversion of coal to methane. Expanded programs in these areas are already underway and should be continued. Industry has made substantial commitments to testing stack gas cleaning systems and government programs should concentrate on more advanced processes which minimize or eliminate the solid waste disposal problem.

Industry is also prepared to build commercial coal gasification plants using Lurgi* fixed bed systems to gasify the coal. Methanation of this gas is required to increase the energy content to that of natural gas. Industry efforts to improve this technology are underway with promising results having been obtained recently. The Federal program on advanced gasifiers includes four pilot plant projects, three of which are jointly funded with the American Gas Association. The fourth project is being pursued by the Bureau of Mines using its Synthane process. Construction of a demonstration plant will presumably commence in 1976 if one of the four processes looks sufficiently attractive. Industry would share in funding such a plant which should be operative by about 1980.

CURRENT STATUS OF COAL TECHNOLOGY

The coal technologies will be discussed in two general categories: coal combustion processes where coal may receive some pretreatment for sulfur removal, but is burned as a solid fuel for power generation, and conversion processes in which the coal is converted to a liquid or gaseous fuel.

Coal Combustion Processes

Processes for the removal of sulfur during and after combustion include fluidized bed combustion and stack gas scrubbing. They are reviewed here as processes which relate to the combustion of coal directly. These technologies serve primarily to reduce emissions from

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* A well established technology licensed by Lurgi Gesellschaft für Mineraloltechnic, Germany.

coal-fired central station electric plants. They are methods which capture sulfur oxides after they are formed. The question of whether sulfur and sulfur compounds are best removed from the fuel before combustion, during combustion, or from flue gases after combustion is still an open one. The ultimate choice will depend on development progress and the economics of the various options. At the present time only the stack gas cleaning development programs are far enough along to possibly have any impact on meeting sulfur emissions by 1977. Stack gas cleaning impact by 1977 will likely be minimal because of the lingering technical problems plaguing most processes and the lead time required to design and construct these facilities once the technology is fully developed and demonstrated.

Coal Cleaning for Sulfur Removal

A variety of mechanical, physical washing and chemical cleaning processes may be employed to reduce both the ash content and the sulfur content of coal. These processes are effective in removing the pyritic sulfur in coal, which typically accounts for about half of the total sulfur content, but leave the organic sulfur virtually untouched. About 60% of the coal mined in the U.S. is cleaned mechanically by crushing and washing. The pyrites, largely iron sulfide, are heavier than the coal and are removed by various techniques that take into account this density difference. From 10 to 50% of the total sulfur content can be removed by washing techniques. Thus, the reduction in sulfur for the large portion of U.S. coal reserves with a sulfur content above about 1% is not satisfactory, if SO_2 emission standards now promulgated are to be met. If the pyrites are finely dispersed it is necessary to crush the coal to a fine particle size, resulting in a greater loss of coal with the rejected pyrite fraction.

A chemical cleaning process, in which coal is contacted with a ferric salt solution at about 100^oC, is under development by the Environmental Protection Agency and TRW, Inc. The ferric ion oxidizes sulfides to sulfate and facilitates their removal. It too removes primarily pyritic sulfur, but may be more effective than physical separation processes. The design of a pilot plant using this process for the removal of pyritic sulfur is being considered based on bench scale experiments performed to date. Other solvents, such as nitrobenzene and p-cresol have been considered for the removal of organic sulfur. Organic sulfur may also be removed effectively by the conversion of coal to liquid or gaseous fuels.

Fluidized Bed Combustion

The development effort in advanced combustion techniques has concentrated on fluidized bed boilers. The fluidized bed combustion process may be carried out at atmospheric pressure or at some higher pressure in which case the installation is more compact and the possibility of utilizing combined cycle systems exists. Limestone may be added to the bed, to react with any SO_2 that is produced to form calcium sulfate. The ash and sulfate are drawn off, the sulfur is extracted, and the limestone is recycled to the boiler. The lower combustion temperatures associated with fluidized bed combustion will result in less NO_x production from atmospheric nitrogen. However, it appears that nitrogen in the fuel will still be converted to nitrogen oxides. The heat transfer rate to the tubes is enhanced by immersing the boiler tubes in the fluidized bed. Such a system would also reduce the temperature of the combustion gases which would be expanded in the gas turbine and thus yield less of an improvement in overall plant efficiency than might be expected with the low Btu gasification-combined cycle system ultimately.

The Office of Coal Research (OCR) has supported atmospheric pressure work at Pope, Evans & Robbins which has led to the 30-Mw atmospheric pressure unit presently being installed. Elevated pressure fluidized bed combustion research is also being conducted by the National Coal Board in Britain under contract to the OCR and by Exxon with EPA support. It is estimated that the atmospheric and pressurized units could be commercially available between 1977 and 1980 if current programs are successfully completed and prove economically attractive relative to other options for using coal.

Stack Gas Treatment

Numerous processes are under development for the removal of sulfur dioxide from the stack gases at central station power plants. The lime or limestone scrubbing process is considered to be the closest to commercial availability although problems still remain to be solved before prudent investments in the systems can be justified. Other processes, such as the double alkali, magnesium oxide, and catalytic oxidation systems, are also being tested on coal fired boilers. While some of these options avoid the problems of lime-limestone systems, they have other problems which still must be eliminated.

In the lime-limestone scrubbing process, the flue gas is contacted with a wet slurry. The SO_2 is captured and fly ash removed in the scrubbing liquor. The solid product is removed in settling ponds. The liquor is recycled to the scrubber circuit with makeup absorbent. About 70 to 90% of the SO_2 in the gas stream may be removed. By-products are $CaSO_3$ and $CaSO_4$ in the form of a wet sludge which creates a disposal problem. Several demonstration installations are in operation on units of up to 175 MWe capacity and nearly 7000 MWe of scrubbing capacity has tentatively been ordered by utilities. Cost estimates for these systems are currently $40-$70/kW for new plants and about $80/kW for retrofit installations. However, costs vary considerably from plant to plant. Operational problems that have arisen with this process include the buildup of solids in equipment, plugging of the demister at the top of the scrubber, chemical scaling, corrosion, erosion and blending of the reactant lime.

Tests have been conducted on a dry limestone injection process where the material is injected directly into the boiler. The limestone is calcined and reacts with SO_3 to form calcium sulfate which is removed along with the fly ash either by mechanical collectors and electrostatic precipitators or by wet scrubbing. Boiler tube fouling was encountered in addition to several other problems that arose in the wet scrubbing process. Work on this system has declined with the increasing interest in the lime-limestone wet scrubbing process.

Another slurry scrubbing process uses a mixture of magnesium oxide magnesium sulfite, and magnesium sulfate. The flue gases are first cleaned of all particulates and then contacted with the slurry in a venturi absorber. A bleed from the absorber is centrifuged and the liquor is returned to the scrubber with MgO makeup. The separated solids are dried and calcined to regenerate the MgO. A stream containing about 15% SO_2 is taken off for further processing to produce either sulfuric acid or sulfur. The SO_2 removal efficiency is in the 80 to 90% range. Pilot plant tests have been conducted and a demonstration unit of 150 MWe capacity is in operation on a plant burning fuel oil with 2.5% S content. Some difficulties in the regeneration step have been experienced, but the process appears to be one of the more promising. A demonstration effort on a coal-fired plant is presently underway.

To avoid the scaling, plugging, and erosion problems that arise with slurry scrubbing, the double alkali process has been proposed. The flue gases are scrubbed with a soluble alkali, usually sodium or ammonium sulfite. The sulfite ion in an aqueous system effectively removes SO_2 by forming the bisulfite ion. The solution may be treated with an insoluble alkali, such as lime or limestone, to regenerate the sulfite ion and to react with any sodium or ammonium sulfate formed to produce a calcium sulfite or sulfate sludge. Pilot plant scale tests have been performed on this process with encouraging results. Other solution scrubbing processes that are under test use sodium and ammonium sulfite with different chemical processing techniques or use other solutions such as sodium hydroxide. This process does not avoid the "solid waste" problems associated with lime-limestone processes.

The catalytic oxidation process uses a vanadium pentoxide catalyst to convert SO_2 to SO_3 after the particulates have been removed in an electrostatic precipitator. The SO_3 is passed through a packed bed absorber where it is converted to sulfuric acid. The SO_2 removal with this process is 85 to 90% efficient. A 100 MW system has been operated intermittently. Catalyst life, corrosion and disposal of dilute acid are among the problems which must be solved.

Numerous variations of these processes have been considered and some of them tested on utility systems. Other processes which utilize different scrubbing solution chemistry are also under development. Technical reviews of these processes have been conducted by several organizations, including the National Academy of Engineering, Hittman Associates[11] and Chem Systems.[12] An interagency government panel, the Sulfur Oxide Technology Assessment Panel (SOCTAP), also reviewed all available stack gas treatment systems, including the Japanese plants. While these reports provide a review of the process chemistry, they quickly become dated as to the status of any particular one because of the intensity of the development and testing programs in this area. As of mid-1973, it was the general consensus of all such reviews, that none of the processes being tested on a commercial scale had yet been proved sufficiently reliable to permit widescale utility acceptance.

Coal Conversion Processes

The commercial application of methods for converting U.S. high sulfur caking coals and abundant non-caking western coals to clean fuels is of high priority.

Coal can be converted into three gaseous products that are categorized by their heat content as follows:

* Low Btu Gas of less than 250 Btu/SCF heat content
* Intermediate Btu Gas having a heating value of 250-600 Btu/SCF, and
* High Btu Gas having a heating value of 800 to 1100 Btu/SCF.

Clean Low Btu gas from coal at pressure is of high interest to the power industry. Its manufacture avoids the use of tonnage oxygen plants for its production and is produced in relatively simple process schemes.

Low Btu gas is as much as 40% lower in cost than High Btu gas from the same coal. However, it cannot be economically transported very far and must be utilized within a short distance, or at the plant. If produced at moderate pressures, its utilization in combined cycle power generation schemes promises low-cost electric power, without emission of sulfur oxides, nitrogen oxides, or particulates.

Utilization of Low Btu gas as a replacement for natural gas currently used for generating electric power in existing power stations, causes a serious derating of the quantity of power that can be produced from already installed gas-fired electric generating equipment. Intermediate Btu gas from coal can be used as fuel in existing gas-fired equipment, without serious derating of the equipment electric generating capacity. Its manufacture avoids the shift and catalytic methanation step which involves the conversion of carbon monoxide to methane with hydrogen. It can be transported further from the plant site than Low Btu gas.

High Btu gas or synthetic natural gas (SNG) will be used to supplement a dwindling supply of natural gas. It is essentially methane with other minor constituents present. Because of health requirements, it contains essentially no carbon monoxide. The latter gas is a poison and can cause death. Synthetic natural gas or High Btu gas is transmitted by high pressure inter-state pipelines and distributed within cities by an extensive pipeline network. This gaseous fuel product is of interest for the gas industry. A generalized processing scheme for producing SNG from coal is shown in Figure III-3.

Clean liquid fuels and synthetic crude oils can be produced from coal by hydrogenation techniques at pressure that may or may not use modern catalysts. Liquids from coal may also be produced by rejecting carbon. The latter technique is designated a pyrolysis which involves the processing of coal with heat in the absence of air. The products from pyrolysis are gases, liquids and char.

Low Btu Gasification - The production of Low Btu gas for power generation was practiced in the nineteenth century. Louis Mond, the famous nineteenth century chemist, designated such gaseous fuel as power gas.* In the 1920's, fluid beds gasifying coal were used in Germany to produce clean gaseous fuel for combustion by the historic Winkler process. Fixed bed gas processes were operated using air. These older processes

* Power gas - low Btu gas used for generating electric power.

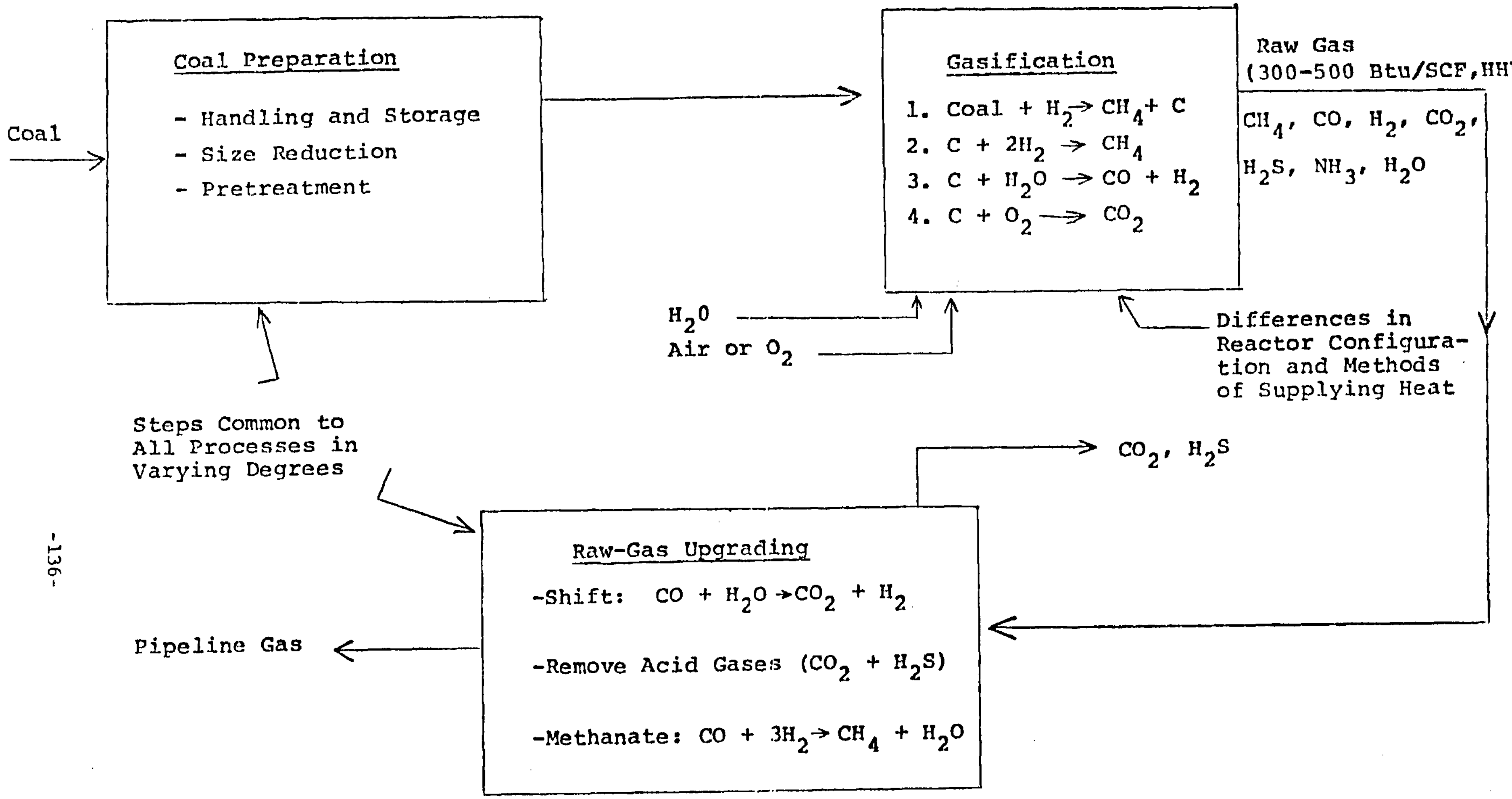

Figure III-3

GENERAL PROCESS SCHEME FOR PRODUCING SNG FROM COAL

(after Siegel and Kalina, Mechanical Engineering 95 (5)) cannot be adapted to handle eastern caking coal, and are not suitable to operate at other than essentially atmospheric pressure.

The Lurgi process has been operated at pressures of up to 450 psig at a commercial scale in Europe and Asia to produce town gas* and synthesis gas† for ammonia production. The Lurgi gasifier is a downward moving bed of lump coal that is converted by a series of chemical reactions to produce gaseous fuel of intermediate heating value. Lurgi operation carried out commercially uses oxygen. It has been in operation for almost thirty years in Europe and Asia.

The Lurgi process has the following limitations with regard to U.S. needs:

... It cannot handle caking coals without modification.

... It is of relatively low capacity so that a large plant uses many gasifiers.

... Fines produced from mining operations cannot be used unless briquetted.

... It has not been operated to demonstrate its application to produce the gaseous fuel products of high interest in the U.S., i.e., Low and High Btu gas.

... It is a relatively high cost method and new methods promise considerable cost reductions.

Several programs are proceeding in the U.S. and Europe to overcome these deficiencies with fixed bed gasifiers:

... The gas industry is operating a series of tests at Westfield, Scotland that utilizes U.S. coals that range from non-caking to caking coals. In order to handle run-of-mine caking coal (that contains fines) the gasifier uses a mechanical device. The tests will be conducted using oxygen to produce intermediate Btu gas that can be upgraded to pipeline gas.

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* Town gas - intermediate Btu gas of a specific composition that provides controlled combustion characteristics.

† Synthesis gas - a mixture of carbon monoxide and hydrogen in the proper molal ratio that is used to produce ammonia.

... The U.S. Bureau of Mines has developed and operated a 3½ ft. diameter, stirred, fixed bed gasifier that successfully handles run-of-mine caking coal. Its throughput is 1000 pounds/hour and it has been operated at pressures up to 200 psig.

... The Commonwealth Edison Company, with the support of the Electric Power Research Institute will construct and test a 70 MW Lurgi gas producer that will utilize an array of U.S. coals to produce Low Btu gas using air. The development work will include combustion tests in large-scale equipment, advanced purification processes, as well as control systems for turning the plant capacity up and down over short times. Ultimately a combined cycle power system will be demonstrated.

... The Lurgi Company is testing an integrated airblown gasification process using a combined cycle generating system in Lunen, Germany on low sulfur non-caking coal. It has a capacity of 165 Megawatts of power.

The only commercially proven gasification process that handles caking coals is the Koppers-Totzek process. This process is used to generate synthesis gas, i.e., carbon monoxide and hydrogen for the production of ammonia. Some fifteen plants are in operation in Europe and Asia on petroleum feedstocks and coal and new plants have been commissioned in India.

The Koppers-Totzek gasifier is an entrained gasifier that utilizes oxygen to partially combust fine-sized coal at essentially atmospheric pressure. It features a flexibility to switch from solid to liquid feedstocks. The gasifier operates at high temperatures (ca. 3000^{o}F) and ash is slagged, i.e., melted, in the process. It suffers from several deficiencies:

... It has not been operated with air and its adaption to airborn operation is probably impractical since it requires cumbersome and costly air preheaters.

... Its capacity is limited and a multiplicity of gasifiers are required for large-scale plants.

... It requires the use of a large oxygen plant.

... It has not been operated at elevated pressure. Modification to permit high pressure operation is being considered.

... The Koppers-Totzek process produces a higher cost gaseous fuel than Lurgi, but has other advantages.

Table III-7 summarizes a number of advanced Low Btu gasification systems. Unfortunately, the status of the new methods for gasifying coal to produce Low Btu gas is poor. Only small-scale tests have been carried out and large-scale test programs are just now being considered. Relative to the cost of Low Btu gas from a pressurized Lurgi system, newer methods promise to save about 15 cents/million Btu and produce gas with fewer environmental control problems. The monetary savings alone, if realized from new developments, are significant and justify large expenditures. For example, at 15¢/MM Btu cost saving, total fuel cost savings at only one 1,000 MW power plant would be about $250 million dollars over the plant's lifetime. Based on available development schedules and on assumed level of funding, these new methods would be commercialized in the early 1980's.

Sulfur removal can occur either in the bed if limestone or dolomite is fed with the coal or after the gasification occurs. If the latter approach is used it is advantageous in terms of energy efficiency to utilize a hot gas cleanup process which eliminates energy losses inherent if the Low Btu gas must be cooled for cleaning purposes and then fired to the combustor. Work on these processes should continue at the bench scale and use bleed streams from early gasifiers, either fixed bed or moving bed. The gas should also have the particulate content reduced to a level so that it is suitable for use with combined cycle systems.

The advanced systems have been proposed to overcome deficiencies of available process technologies. These systems use:

Table III-7

Major Programs for New Process Technology for Low Btu Gas

Developer	Type of Gasifier	Status
Institute of Gas Technology	Fluid Bed	Lab Tests
Foster Wheeler Corp.	Entrained Bed	Design
Combustion Engineering Corp.	Entrained Bed	Conceptual
Westinghouse Electric Co.	Fluid Bed	Small pilot unit being constructed
M. W. Kellogg Co., Atomics International	Molten Salt	Lab Tests
Consolidation Coal Co.	Fluid Bed	Lab Tests

... Fluid beds,

... Entrained beds, and

... Molten baths.

These new methods, when coupled with gas turbine,steam cycle systems of advanced design, promise to increase overall efficiency of power generation from about 35% that is achieved in pulverized coal combustion to an indicated efficiency in excess of 50%. Thus, if successful, the cost of electric power may decrease substantially.

The opportunity for the power industry is to utilize non-polluting gaseous fuel from coal conversion methods that have flexibility in handling caking and non-caking coal. Substantial savings can be realized from using air as an oxidant instead of oxygen and the development of high capacity gasification processes. These represent the principal advantages of the new methods. In addition, the rapid evolution of gas turbine technology represents a large opportunity to generate low cost power using a variety of combined gas turbine-steam cycle systems.

High Btu Gasification - Improved methods that promise high capacity, an ability to handle caking coals, improved efficiency and lower cost gas for supplementary natural gas supply from coal are under development. These methods utilize a variety of techniques, described below. The primary national effort is under the sponsorship of the Office of Coal Research and the American Gas Association who are cooperating in large-scale test programs to prove out new methods. The Bureau of Mines is funding a test program at a large-scale with its process technology designated as the Synthane process. The economic promise of these new technologies is to decrease the required selling price of High Btu gas by about 20 cents/million Btu, as compared with selling price of High Btu gas from the Lurgi process. These new methods overcome limitations of the Lurgi and Koppers-Totzek processes that are discussed above.

The gas industry has proposed the construction of large scale Lurgi plants that utilize western caking coal to produce synthetic pipeline gas. The only step not yet completely demonstrated, methanation, is undergoing intensive development in a number of programs.

The Federal Power Commission estimated that 25 plants using new methods will be constructed in the U.S. to gasify coal to produce a supplemental supply of pipeline gas by 1985. Taking into account the promised savings and the estimated production of about 2 trillion cubic feet of gas per year, a large effort to develop these new methods is justified. At this time, it is not possible to select which of the new methods should be commercialized. It is anticipated that based on the current program and funding, enough information will be available to select one or more of the new methods for commercial scale demonstration by 1976.

Table III-8 summarizes a selected number of programs in the development phase under Federal and private industry sponsorship.

The HYGAS process developed by IGT with OCR-AGA support uses a series of fluidized beds. A pretreatment step is used when operating on caking coal. The coal passes through a series of fluid beds against a rising stream of hydrogen and steam at 1000 to 1500 psig and 1200 to 1800^{o}F. Under these conditions a high yield of methane is achieved (about 2/3 of the final methane yield). IGT has proposed to provide the thermal energy for this endothermic reaction by burning char in oxygen, by electric resistance heating of coal char which is reacted with steam to produce a mixture of hydrogen-rich gas and steam, or by indirect means with the steam-iron process. A pilot plant using this process has been constructed to produce 1.5×10^6 SCF/day from 75 tons of coal feed.

The CO_2-acceptor process supported by OCR-AGA utilizes a series of fluidized beds through which calcined dolomite, char, and coal are circulated. In one bed, char is reacted with steam in the presence of calcined dolomite and the product gas is transported to a devolatilizer where, along with steam, it is contacted with coal and calcined dolomite at 300 to 400 psig. In both the char gasifier and the devolatizer, dolomite combines with carbon dioxide (in the gas stream) to form calcium carbonate. This exothermic reaction provides the heat needed to sustain endothermic chemical reactions. Dolomite and char are

TABLE III-8

MAJOR PROGRAMS FOR NEW PROCESS TECHNOLOGY

FOR HIGH Btu GAS

PROCESS	DEVELOPER	TYPE OF GASIFIER	SIZE OF PLANT
HY-GAS	Institute of Gas Technology	Fluid Bed	75 tons/day
BI-GAS	Bituminous Coal Research	Entrained Bed	120 tons/day
CO_2-Acceptor	Consolidation Coal Company	Fluid Bed	40 tons/day
Synthane	Bureau of Mines	Fluid Bed	70 tons/day
AT-GAS	Applied Technology Corporation	Molten Iron	1 ton /day
Agglomerating Ash	Battelle Memorial Institute - Union Carbide Corporation	Fluid Bed	1 ton /day
Molten Salt	M.W. Kellogg Co.	Molten Salt	Benchscale
GE-GAS	General Electric Co.	Fixed Bed	Benchscale
NU-GAS	Hydrocarbon Research Inc.	Fluid Bed	Conceptual
Flash Pyrolysis	Garret R&D	Entrained Bed	Benchscale
CO-GAS	FMC	---	Benchscale

withdrawn from the char gasifier and fed to a fluidized regenerator, where char combustion with air provides heat for dolomite calcination. The CO_2-acceptor process does not require a coal pretreatment step because it is used only with sub-bituminous coals and lignite which generally are non-caking. A 40-ton/day pilot plant has been constructed and is now undergoing shakedown tests.

The BI-GAS process (OCR-AGA supported) features a two-stage oxygen blown gasification system operating at 1000 to 1500 psig. Coal is fed to the gasifier and is entrained in a stream of steam and hot gas--CO_2, H_2 and CO. Residual char is swept from the gasifier in the gas stream, separated from the gas, and recycled to the lower section of the gasifier where it is completely gasified under ash slagging conditions (2500 to 3000^{o}F) by reaction with oxygen and steam, thereby producing the hot gas stream previously mentioned. It is expected that the BI-GAS process will have the capability of handling caking coals without pretreatment. A BI-GAS pilot plant is currently under construction.

The Synthane process (BOM) includes a pretreatment step which permits the use of coals having caking properties. The coal is gasified in a fluid bed at about 1,000 psig pressure with oxygen and steam; the gas is purified, shifted, and finally methanated. A 70 ton/day pilot plant is currently under construction after a smaller pilot operation at Hydrocarbon Research, Inc. was successfully carried out.

Other processes that are being studied include a molten salt gasifier and a coal solution gasifier. Industrial organizations are also carrying out gasification development that seem to offer promise. However, these new processes have not yet been tested at a large-scale even though they represent viable technological options.

Coal Liquefaction - The production of synthetic liquid fuels and hydrocarbons from coal has been attempted by direct hydrogenation in the presence of catalysts, by the solution of coal in a hydrogen system that avoids using catalysts; by means of a hydrogen containing solvent; and pyrolysis of coal at essentially atmospheric pressure. With a minimum of hydrogenation it seems possible to produce a clean heavy fuel oil, that is useable as a boiler fuel. With more severe hydrogenation sulfur levels can be reduced even further and a light fuel oil, gasoline or other distillates produced. The overall product from severe hydrogenation is similar to crude oil. Although coal requires greater hydrogen addition to produce acceptable crude oil fractions than does oil shale, it is more abundant, more uniformly distributed over the country and less damaging environmentally to mine and process. Coal derived liquids are presently estimated to have a higher cost than shale oil, but substantially less development work has been done on the coal technology than on shale.

Liquefaction research and development programs have been carried on by the Bureau of Mines' laboratories and in industry. Several of the recent efforts have received support from the Office of Coal Research. Included among these are the CRESAP, H-Coal, COED and Solvent Refined Coal programs, all of which have advanced to the pilot scale. In the case of H-Coal the OCR support has been small relative to the more recent level of industry support.

The CRESAP project, conducted by Consolidation Coal, had as its initial objective the production of gasoline from coal. Although difficulties related to separation of mineral matter from the product was never adequately resolved, gasoline was produced, but at a cost far above the market price at the time. Subsequent efforts were directed at producing a fuel oil with the process, but this effort was terminated before a complete evaluation of the approach could be made. The experience of the investigators at CRESAP and, perhaps, some of the facilities still remaining at the West Virginia site should be utilized in the ongoing program.

The COED 36T/day pilot plant at Princeton, New Jersey, has been operated successfully by FMC, producing liquid and gas product streams as well as a char product. The process uses a multibed pyrolysis approach which recovers the higher grade hydrocarbons contained in the coal. The char which remains amounts to about 50% of the plant output and contains essentially all of the ash and sulfur that was present in the coal feed. For the process to become commercial a means of utilizing the char must be developed. The COGAS process, which is being developed with private funds, is designed to utilize char to produce a high Btu gas. Other efforts are exploring the possibility of burning the char to produce power.

Hydrocarbon Research, Inc. and a consortium of oil companies have developed a catalytic hydrogenation process using an ebullating bed reactor, similar to the one used in the commercial H-Oil process. H-Coal, as the process is known, hydrogenates a coal slurry over the ebullating catalyst bed at 1000 to 3000 psig. Bench scale results appear encouraging. However, a reliable means for removal of solids from the product stream is needed and remains an unsolved problem. This problem is under study along with improved catalysts in an industry sponsored program. HRI has recently proposed the construction of a demonstration plant in which they project yields of 3.5 bbl oil/ton coal at a cost of $6.00-$7.00/bbl for coal costs of $6.00-$7.00/ton.

The Solvent Refined Coal process is based on the solution of pulverized coal in a coal-derived solvent boiling in the 450 to 850^{O}F temperature range. The process uses a moderate amount of hydrogen and operates at about 1000 psig. The dissolved coal-char product is passed through a filter or suitable device which removes the solids, consisting of ash and any undissolved coal.

The product has a heating value of 16,000 Btu/lb and a sulfur content of 0.5-0.8%. At temperatures above 200-300^{O}F the fuel is liquid and can be used much as a residual fuel oil. At lower temperatures the product is solid and can be shipped in railroad cars or slurry pipelines and fed like pulverized coal to combustion equipment. Additional hydrogenation of the above product produces a synthetic crude with a lower sulfur content.

The principal unsolved problem in this process, as in all liquefaction processes, relates to the solids separation. Two pilot plants are currently under construction. One being built by Southern Services should be operative in early 1974 and will test several approaches to solids separation. A second, funded by OCR and managed by Pittsburg and Midway Coal Company, is being built at Tacoma, Washington. Its completion is expected in 1974.

All of the liquefaction processes require a source of hydrogen. While pilot plant testing can utilize hydrogen derived from natural gas, it will be necessary to develop an independent hydrogen source before any process can be commercialized. Synthesis gas from gasification of coal may provide such a hydrogen source. The Koppers-Totzek entrained gasifier utilizes oxygen to produce a synthesis gas with a relatively high hydrogen concentration. These gasifiers are commercially available today and their applicability to this need should be determined in future efforts.

High temperature gas cooled nuclear reactors could conceivably provide hydrogen at their peak operating temperatures by thermally decomposing water. Considerable work remains to be done on both the chemistry of the cycle and the reactor development before such an option could be available. An economical solution to this problem will be important to the future of coal liquefaction.

PROGRAM RECOMMENDATIONS

Coal research in the United States has lagged far behind the efforts of Britain, Germany and the Eastern European countries due to the apparent adequacy in the past of oil and gas reserves and the past insensitivity to the environmental consequences of coal useage. Consequently, an integrated across the board effort, from basic research to demonstration plants, must be programmed on an accelerated basis if coal is to contribute significantly to meeting U.S. energy needs over the next several decades. Universities, industry and government must unite in a well coordinated effort to bring the nation's technical resources to bear on the many problems that remain. Government must assume a central role in this effort, particularly in the planning and funding areas.

Universities must supply technically trained manpower to engineer the many plants needed over this period and also contribute to an improved understanding of coal and sulfur chemistry, fluidized gas-solid reactors, high temperature liquid-solid separation, and other unit operations. Industrial participation is essential for much of the existing and related large scale technological expertise resides there. Industry must ultimately develop and implement the advanced processes and systems.

From an R&D perspective, the coal area is particularly complex since it spans the energy system from extraction to final use. The balance of an R&D program in coal must be arrived at through consideration of the total coal system. Any such analysis of the coal system would clearly identify the extraction phase as one of the major constraints on expansion. It is for this reason that R&D on coal extraction, and attendant environmental impacts were emphasized in the resource extraction section (III-B) above. These characteristics also imply a need for continuing integrative assessment of coal R&D and vigilant coordination of R&D programs.

The coal R&D program, summarized in Table III-9, represents a balanced approach in which all of the more promising SO_2 control techniques as well as liquefaction and gasification processes are pursued. The various control technologies and conversion processes have not yet been engineered and demonstrated to the point that any are clearly more promising than others. The program elements emphasize pilot and demonstration plant construction and operation so that engineering, reliability, and economic factors may be assessed in as short a time as possible. The R&D program elements are discussed below.

Coal Desulfurization

Coal desulfurization by mechanical and chemical methods, if not too costly and limited in its applications to U.S. coals, offers a most attractive means of meeting sulfur dioxide emission standards, particularly for existing plants. Continued effort is justified on both physical and chemical coal cleaning methods, although greater promise

TABLE III-9

SUMMARY OF CLEAN FUELS FROM COAL PROGRAM

Program Element	Current R&D Objective	First Year Cost $ Million	Long Term Cost $ Million/Yrs.	Notes
Coal Desulfurization	Increased sulfur removal.	2	30/8	Ferric salt extraction most advanced; effective on pyrites only.
Stack Gas Cleaning	Regenerative process with readily disposable product; reliable performance on utility systems.	30[3]	100/5[3]	Nearest to commercialization; appears less attractive in longer term.
Fluidized Bed Combustion	Sulfur removal; system design and performance assessment.	5	200/8[1]	30 MW atmospheric pressure plant; ESSO miniplant; OCR British pressurized R&D.
Low Btu Gasification	Retrofit assessment; fuel for combined cycles;	20	200/5	BOM fixed bed gasifier + fluidized & entrained, molten bath gasifier development.
Gasifier Development	Hot gas cleanup R&D			
Demonstration Projects	Demonstrate 2 processes		500/8	
High Btu Gasification	Pilot Plants	40	100/3	4 processes.
Demonstration	2 processes		700/8[1,2]	2 from among all candidate programs.
Liquefaction				
Pilot Plant Studies	4 processes	40	250/5	
Demonstration	3 processes	5	900/8[1]	1 SRC and 1 catalytic to be included.
Coal Chemistry and Predevelopment R&D		20	250/10	
TOTALS		162	3230/8	

1) Demonstration projects to commence as soon as possible; projects to be selected from among all candidate systems (public and private).

2) In addition to industry-funded Lurgi plants to be started as soon as possible.

3) Government funding only; industry expenditures for development and testing should be larger.

is judged to exist for the latter. A larger scale test of the TRW process using a ferric salt solution should be pursued. Continued EPA support of this project seems warranted, particularly the study to extend the sulfur removal to organic as well as inorganic sulfur. Another approach which utilizes fluids, such as methanol, which permeate the coal structure preferentially along the seams of inorganic material thus exposing the pyrites and facilitating their removal seems worthy of exploration. This area is ideally suited for academic research programs where a solid base in coal and sulfur chemistry exists. Other processes under study should be evaluated before the program reaches the demonstration stage.

Funding of 30 million dollars over an eight year period would permit the study of several additional processes at the bench scale, the construction of small pilot plants and the design of a commercial prototype facility, if justified. While efforts in this area should not be constrained by funding, it would appear that 2 million dollars is sufficient to fund the more promising approaches in the first year of such a program. If successful, this technology would permit utilities and other industrial users of coal to meet environmental standards with a minimum perturbation to their present systems, while still utilizing transportation and coal handling facilities in place.

Stack Gas Cleaning

Stack gas cleaning by virtue of the sizeable government and industry investment to date is the most technically advanced of the sulfur removal options. Stack gas cleaning will undoubtedly be used widely in the 1970's to achieve emission control of SO_2 on plants where other control schemes are unacceptable, if technical and economic problems can be solved. It has become increasingly obvious to most utilities, as well as many developers of these processes, that stack gas cleaning does not appear to provide the best long range solutions to SO_2 control. Costs have risen; the disposal problem looks more serious for most processes; and, reliable operation over a sufficiently long period of time is proving more difficult to achieve than had been expected.

With these factors in mind a program with the following objectives is recommended: 1) Elimination of the solid waste disposal problems associated with lime/limestone and double alkali scrubbing system with an easily disposable or marketable sulfur product; 2) Reliable operation for a sufficiently long period of time to insure that the incremental environmental improvements achievable justifies the cost which consumers will be required to pay; 3) Continued testing by utilities of systems which offer promise of providing cost effective sulfur oxide control.

The private sector, in response to EPA's new source performance standards, has invested many millions of dollars in the development of these processes. Additional investment will be required. Future government support in this area (beyond completion of its present commitments) should emphasize advanced processes which promise significant improvements in the technology now being tested, and then only if such processes promise to be more economic and environmentally acceptable than other clean fuel from coal programs discussed below.

Such a recommendation is not seen as inconsistent with the earlier Presidential decision to intensify efforts in this area. Present funding levels are about 48 million dollars, including 18 million dollars for a TVA flue gas cleaning system. A continued program by industry with a government contribution totalling 100 million dollars over the next five years should be sufficient. Continued funding in the next year of 30 million dollars from Federal sources is needed with the level gradually reduced over the next five years.

This recommendation to scale down the Federal support for stack gas cleaning over the next five years presupposes that industry will continue to make the necessary investments. Thus the national effort, which includes both the development of advanced processes and the testing on utility systems of the more promising processes, should continue to expand until such time as a clearly superior means of providing clean fuels and power from coal is demonstrated. A cost/benefit analysis is needed in making such a determination which should properly reflect the feasibility of using tall stacks and intermittent control to extend and best use the presently available clean fuels. It is strongly recommended that such an analysis be made by an impartial organization, sufficiently knowledgeable in all relevant disciplines.

Fluidized Bed Combustion

Fluidized bed combustion systems could offer an attractive alternative in both economic and environmental terms for new coal fired capacity. Such systems would seem to have limited applications for retrofit purposes, but this possibility should not be ruled out prematurely. Program objectives should include: 1) Early determination of the relative advantages of the atmospheric vs pressurized systems for use in a variety of industrial applications; 2) Determination of the startup and turndown characteristics of these systems; 3) Determination of the coupling characteristics of these systems with the generation equipment when used on utility systems; 4) Development of effective inbed sulfur removal and absorbent regeneration or disposal; 5) Assessment of utilization with combined cycle systems; 6) Determination of the degree of NO_x control achievable with these systems; and 7) Determination of the optimum system configuration with respect to heat transfer surface within/or outside of the fluid bed.

To achieve these objectives it is recommended that the present program, which includes the 30 MW atmospheric pressure system (OCR supported); the Esso-EPA pressurized miniplant and the OCR funded development in Britain, be carried forward. Each of these programs provide sufficiently independent information so that all will be needed before a decision can be made as to which approach is most likely to become of commercial interest.

The funding level of 200 million dollars recommended allows for the testing of several system pressures and configurations in addition to full scale industrial demonstrations of the most promising systems over an eight year period. It is possible that a commercially attractive system could be demonstrated within five years if a serious industrial commitment is sustained. A substantial portion (at least half) of the recommended funding should come from industry, particularly if the results of the present experimental efforts appear promising. The first year funding should be a minimum of 5 million dollars.

Low Btu Gas

Oxygen blown gas producers operating on coal have been used in many parts of Europe, but electrical utilities have had little experience in using these gasifiers for electrical generation where load following capability is an important requirement. This technology also requires on-site oxygen plants and has been operated only with non-caking coals. If it is to become an attractive option to U.S. electric utilities, it must be capable of using the high sulfur caking coals of the east and midwest and utilize air rather than oxygen as the oxidizing agent. The most attractive aspect of low Btu gas relates to its use with the potentially more efficient combined cycle systems. Thus the gas must be sufficiently free of particulate material to avoid erosion of gas turbines and have a sufficiently low sulfur content so that post combustion sulfur removal is unnecessary.

With these points in mind the objectives of the low Btu gasification R&D program include the following: 1) Determination of the combustion characteristics of Low Btu gas so that its value as a retrofit fuel for fossil fuel fired boilers and its potential for combined cycle use can be assessed; 2) Development of gasifiers which will gasify most U.S. caking coals using air rather than oxygen; 3) Determination of the dynamics of gasifiers when coupled with power producing systems; 4) Development of adequate sulfur and particulate removal systems for the applications envisioned; and 5) Improved economics of gasifier and power producing systems.

Lurgi gasifier technology is judged to be the most advanced at the present time and could be used to provide utility testing of Low Btu gas as a fuel, with or without the combined cycle system. An industry commitment to such a plant has recently been made by Commonwealth Edison and the Electric Power Research Institute. This plan, which will incorporate improvements based on Lurgi's recent Westfield, Scotland

and Lunen programs, should provide a basis for comparing the economics, operating reliability and flexibility of the advanced gasifier concepts under development. It should also test the modifications which have been incorporated to accomodate caking coals and fines on Lurgi systems.

The Bureau of Mines has operated a 3½ foot fixed bed air blown gasifier at pressures up to 200 psig feeding 1000 pounds of coal per hour. The gasifier employs a rotating arm which also vertically moves through the bed. It has operated successfully with caking coals using run-of-the-mine coal crushed to a nominal 2" size. Scale-up of this process should be given serious consideration as an alternative to Lurgi gasifiers. Difficulties have been experienced in scale-up of gasifiers by European firms and thus an increase in size much beyond 10-15 feet in diameter would seem quite risky as a next step, particularly with the mechanical complexities introduced by the stirring arm. Such a unit could be used on a utility system for firing a boiler or fueling a combined cycle system.

TVA is currently studying the technical and economic feasibility of such a gasifier under contract with the Electric Power Research Institute. Should the Lurgi modifications to accomodate caking coals prove unsuccessful, this program would take on added importance to the utility industry.

A longer range program to develop advanced gasifiers for use with combined cycles should be pursued vigorously. In addition to the fixed bed projects, it is recommended that development continue on advanced gasifiers and that two or three of the more attractive approaches be tested at the pilot scale over the next four years.

This program should include the evaluation of existing gas cleanup technology for application to low Btu gas and the development of advanced high temperature processes which will eliminate the need to cool the gas for cleanup purposes. Attention must be given to particulate removal as well as sulfur so that the gas can be used to fuel gas turbines without damage to the blades. The program should include the following elements:

1) Production of low Btu gas on a utility system (probably using Lurgi technology) for testing purposes as soon as possible.

2) Development of high temperature sulfur and particulate removal systems for incorporation into a low Btu gasifier - combined cycle system.

3) Development of advanced air blown gasifier concepts for utilizing caking coals with improved economics and testing of the two or three most promising at the pilot scale. Fixed bed, fluid bed, entrained bed and molten bath gasifiers should be considered. Wherever possible, information obtained from the more advanced high Btu gasification program should be utilized.

This program will require 200 million dollars over the next four years. At least 20 million dollars are needed in the first year with substantial increases in the following three years. The major portion of these funds should come from the Federal government with some industry sharing. The Lurgi test plant is expected to be privately funded.

The demonstration phase of this program should commence as soon as practicable. The Lurgi test represents the first phase and if successful, could lead to rapid commercialization. Assuming that the anticipated performance and economics of advanced gasifiers are realized in the pilot plant phase of the program, design and construction of the first of two demonstration plants might commence within three to four years. These plants should incorporate the most advanced combined cycle systems available at the time of construction. The cost of the program over the next eight years is estimated to be 500 million dollars, most of it required in the last four years. Industry would be expected to share substantially in this phase of the program. If reasonable progress is realized in the gasifier development portion of the program defined above and the combined cycle portion described in III-E, the utility industry should have the option of ordering advanced plants by the early 1980's with the distinct possibility that first generation fixed bed gasifier and combined cycle plants will be commercially available by 1977-78.

High Btu Coal Gasification

The High Btu gasification program recommendations parallel those for the Low Btu program in that it includes the immediate construction of a Lurgi demonstration plant while work on advanced gasifiers continues. Lurgi technology is sufficiently well established to permit gasification of certain U.S. coals and the testing of methanation process on a commercial scale. Such a plant would provide a reference base for evaluating possible process improvements and cost reductions realizeable with advanced gasifier systems.

The gas industry has announced plans to build several 250 million ft^3/day plants in the southwest if FPC regulatory policy with regard to SNG pricing justifies the investment. Plant costs are currently projected to be about $400 million per plant for producing 250×10^6 standard cubic feet per day of SNG. Gas from these plants will likely cost $1.25/1000 ft^3, substantially higher than current wellhead prices and early LNG contract prices. However, the escalation of construction costs will likely outpace cost reductions which appear possible with advanced gasifiers and thus a delay in the construction of gasification plants until advanced systems are developed does not seem justified.

The present program to develop advanced gasifier systems is intended to increase the capacity of gasifiers, utilize a wider range of U.S. coal as well as accomodate fines, and lower costs. Advanced systems result in a projected 15-20% reduction in gas price relative to the Lurgi system. Four intensive pilot plant projects are included in the Federal program and an effort to develop a rabble arm device that would permit fixed bed gasifiers to operate with caking coals. Industry is supporting additional gasifier concepts at levels ranging from bench scale to pilot plants. The AGA-OCR program which is funded at about the $30 million level in 1974 ($20MM OCR - $10MM AGA) anticipates operation of three pilot plants by 1976. Other processes, including the Bureau of Mines Synthane process, should be sufficiently well advanced by that time so a decision can be made on which of the processes should be advanced to the demonstration plant level. This schedule would likely lead to the construction of one or two demonstration plants by the late seventies and the introduction of advanced gasifiers on a commercial scale by the early 1980's. Demonstration plant funding should be provided largely by the gas industry if the process development is successful. Federal funding of up to two thirds of the demonstration plant costs depending on the risk involved, should be provided. These demonstration projects could cost from $100 million to $250 million depending on the unit size and the degree to which they are integrated into exsiting plants as opposed to the construction of a complete plant.

The Federally funded portion of the above program will require $100 million for the four pilot projects and other smaller scale efforts through 1976. Demonstration plant funding in the 1970-1980 period for two approaches will probably require a Federal contribution of $400 million dollars. Such a program provides a way of using abundant U.S. coal resources to produce a clean burning natural gas substitute in the event future discoveries fail to meet U.S. needs in the future. It should be recognized, however, that even the most optimistic estimates of natural gas reserves are substantially less than our coal reserves and that eventually we must utilize coal to meet a portion of our gas demands.

This schedule represents a prudent development program which provides for first generation gasification plants this decade and advanced gasifiers early in the eighties. A so-called crash effort to introduce advanced gasifiers appreciably sooner does not seem justified in terms of the relatively small reduction in gas cost relative to the risk. Inasmuch as the gasifier technology for both High and Low Btu gas processes has many similarities, the pilot scale program should be advanced as rapidly as possible in the next two to four years to permit an improved technological base for taking both programs to the demonstration level as quickly as possible. It may be advisable to fund additional pilot projects if sufficiently promising new options are identified.

Coal Liquefaction

Coal represents the nation's most abundant fossil fuel resource and the one which must ultimately be looked to for the full range of hydrocarbons that are currently derived from oil and gas. Thus the development of technology to produce hydrocarbons from coal can have an important role in supplementing our domestic oil and gas resources and in improving our bargaining position with the oil exporting countries. Coal derived liquids with a minimum of hydrogenation could offer an attractive method for producing an environmentally acceptable fuel for use under boilers. Such a fuel could be used to fire boilers burning oil and those designed for coal. Increased hydrogenation further reduces the sulfur level of the liquid product and can produce a broad range of hydrocarbons for use as home heating oil, gasoline, jet fuel or petrochemical feed stocks.

The recommended program has the following objectives: 1) expansion of the fundamental knowledge in coal chemistry and catalysis to assure more attractive long range options when the needs are expected to be even more acute than at present; 2) evaluation at the pilot plant level of the various approaches to liquefaction; 3) development of an adequate source of hydrogen to supply a liquefaction industry; 4) development of commercially practicable means of reducing the solids content of product streams to acceptable levels; 5) development and demonstration of environmentally acceptable means for sulfur disposal and finally, 6) demonstration as soon as possible of commercially scaled facilities to produce a broad product range at minimum cost.

As discussed earlier there is a substantial research and development base from which to launch such a program. Its pace will be in large part determined by the funding made available and the willingness to assume risk. It seems reasonably certain that the program proposed will succeed in producing clean liquids from coal within the eight year period, but the cost of these products cannot be accurately predicted at the present time. It is certainly above present petroleum derived fuel prices, but not above the prices forecasted by some for later this decade. With these factors in mind the program recommendations are intentially "aggressive", but not so costly as to be out of line with potential benefits.

The program includes major efforts in the areas of solvent refining and catalytic hydrogenation. There are several competing approaches in each category, and at least one from each should be advanced to the demonstration scale as rapidly as pilot plant results justify. One other demonstration project from either of these two areas or from among other approaches should be initiated within the 8 year program period if pilot plant performance is satisfactory. Several of the prime candidates have already been operated at a small pilot plant scale. The confidence in going from these plants to a demonstration plant varies from process to process and needs to be evaluated on an individual basis.

The two solvent refined coal pilot plant projects should provide much of design information needed to launch a demonstration scale project. Such an effort could begin within the next year and be on line by 1977 or 1978, depending on the time required to supply essential information from the pilot plants.

The H-Coal process is similar in certain respects to the H-Oil process which is available on a commercial basis. The process is also based on a sustained research and development effort supported over many years by a number of oil companies. Exxon, which has participated in the H-Coal program, and Gulf are known to have candidate processes, although the latter is likely to require a pilot scale effort initially. Other possibilities exist and should be given consideration for support at an appropriate level.

The funding level recommended provides 250 million dollars for four pilot plant studies and related developmental efforts over the next five years. At least two thirds of these costs should be provided by government if necessary. Completion of the present pilot plant efforts (all at a small scale are included) and larger pilot programs, where necessary, are included as is hydrogen production.

Three demonstration projects over the next eight years are projected to cost 900 million dollars, a substantial fraction of which should come from industry and be recoverable in part from the sale of product.

Supporting Research

The emphasis in the discussion above has been on process development and demonstration. Additional research should also be directed at more basic supporting areas, particularly fundamental physical-chemical processes and pre-development process element research. Such research is inexpensive compared to the potential benefits in improving existing processes and developing new ones.

In the area of fundamental processes, increased understanding is required of coal reaction mechanisms both in terms of solid-gas contacting processes, catalysis, dissolution, pyrolysis, hydrogenation, etc.

In the area of pre-development process element research, work is required on the problem of feeding and removing solids, both coal and ash, with high pressure process. Another important problem is the separation of undesirable components from product streams. This would include methods for hot gas clean-up and the removal of solids from liquid streams.

Although much of this supporting research is appropriate for universities, it should not be totally disconnected from the more advanced industrial process development.

A 250 million dollar effort over the next 10 years is recommended. In addition to research and development results, it should help insure the availability of trained manpower needed to develop this industry. A first year funding of 20 million dollars is recommended. This would include Bureau of Mines (fundamental and applied) coal research, the reactivation of CRESAP for component development and testing, and support of university and other research activities. This funding should come primarily from government and serve to augment industry's efforts.

Program Summary

Table III-10 presents a summary of the program elements and estimated funding levels discussed above.

IMPACT OF IMPLEMENTATION

Successful development of fluidized bed combustion techniques would provide an alternate approach to meeting NO_x and SO_2 emission standards. The Reference Energy System postulates the satisfaction of those standards via the route of stack gas scrubbing, so the impact on the Reference System would be primarily economic. It is not possible at this time, however, to estimate the potential economic advantage of fluidized bed combustion over stack gas scrubbing as on a SO_2 control technique.

The implementation plan for the low Btu combined cycle concept assumes that in the year 1985 and 2000, 25% and 50%, respectively, of coal-fired central station electricity is produced by this concept operating at 50% overall thermal efficiency. The changes in resource consumption and environmental effects are tabulated in Table III-10. As in the previous case, it is assumed that there will be no further reductions of SO_2, NO_x, and particulate emissions below the level of the standards assumed in the Reference Energy System.

A year-2000 Perturbed Energy System was analyzed to evaluate the impact of coal liquefaction. In this case coal is converted to synthetic gasoline at an efficiency of 60% to satisfy 25% of the automotive market, replacing gasoline obtained from crude oil. The resource and environmental impacts are tabulated in Table III-10.

TABLE III-10

Impact of Clean Fuels from Coal Percent Change From Reference Energy System

	Combined cycle Year 1985	Combined cycle Year 2000	Coal liquefaction to produce motor vehicle fuel--Year 2000
Sector replaced	coal-fired electric	coal-fired electric	automotive
% of sector replaced:	25%	50%	25%
Resources			
Nuclear			
Coal	-4	-8	+17
Oil			-6
Natural gas			
Environmental effects			
CO_2	-3	-8	+4
CO			
SO_2			
NO_x			
Particulates			
Hydrocarbons			
Radioactive materials			
Land use			
Other effects			

F. ADVANCED CYCLES FOR POWER GENERATION

INTRODUCTION

As the demand for electricity continues to grow at a more rapid rate than overall energy demands, it becomes increasingly important to develop higher efficiency generating systems. Current power cycles that are employed to convert the thermal energy content of fuels into electricity range between 30 and 40% in conversion efficiency. The inefficiency in the cycle is represented by thermal energy lost in discharge gases and by the thermal energy removed from the working fluid in the condenser.

There are two basic approaches to achieving better utilization of the energy content of the fuels used in power plants. One approach involves utilization of what otherwise would be waste heat for heating and other applications. Such "total energy" systems are discussed in the section on Urban and Residential Energy Utilization. The alternate approach, involving new power cycles and devices that can convert thermal energy to electricity at higher efficiencies, is addressed in this section.

The advanced systems that have been proposed for application to central station electric generation include a variety of topping and bottoming cycles that could be used with conventional steam cycles and alternates to the basic steam Rankine cycle. Implementation of these systems would result in the more efficient utilization of resources and reduced environmental impacts. Some may have an economic advantage over current technology; however, this cannot be determined until the demonstration phase is reached for a given system.

The thermal efficiency of a power cycle is determined by the temperatures at which heat is added to and rejected from the working fluid. The conventional Rankine steam cycle is limited to a top temperature of 1000 to 1100^{o}F for structural and metallurgical reasons, although the combustion temperature of the fuels may be significantly higher. The thermal efficiency of the steam cycle falls in the 35 to 42% range. Topping cycles achieve higher efficiencies by employing a higher temperature working fluid such as air or liquid metal so that thermal energy may be added to the cycle at a higher temperature with the reject heat from the topping cycle supplied to a steam cycle. Gas turbines, liquid metal cycles, and MHD generators may be employed as topping cycles.

Fuel cells may provide still another alternative for high-efficiency electrical production. The primary fuel form in this system must be converted to a mixture of hydrogen and carbon monoxide before it is supplied to the cell.

Bottoming cycles, using such working fluids as ammonia, freon, isobutane, and methyl chloride, have also been proposed for use with the steam cycle. In such a system heat would be rejected from the steam cycle at a temperature well above the ultimate sink temperature and used to heat the working fluid of the bottoming cycle. In this concept, the large lower pressure stages of the steam turbines are replaced with a more compact turbine operating on the bottoming cycle fluid and may result in some cost reduction. The system also avoids freeze-up problems encountered in using dry cooling towers with a steam cycle, since the working fluid in the bottoming cycle will generally have a lower freezing point than water. The technologies proposed for bottoming cycles may also be employed apart from the steam cycle with low temperature heat sources such as geothermal and solar energy.

A Brayton cycle using helium as a working fluid appears to have potential advantages in its ability to operate at higher temperatures and discharge waste heat directly to the atmosphere. Such a system is a natural for use with helium gas cooled reactors. The Feher cycle combines advantages of the Rankine and Brayton cycles by operating in the supercritical region. Carbon dioxide is one working fluid that has been suggested for such a system. The high pressure at which the system operates poses some mechanical problems, but permits the construction of a relatively compact power plant that can be used for central station power plants or for propulsion systems in ships and larger vehicles.

CURRENT STATUS OF ADVANCED CYCLE TECHNOLOGY

The current status of technology for the various advanced cycle concepts is discussed below.

Combined Cycle Systems

Gas turbines for utility use have become quite common in recent years, particularly for peak load applications. More recently gas trubines coupled with conventional steam turbine systems have been marketed as combined cycle power producing packages. Gas turbines operate at high temperatures, but their exhaust gases typically exit at such high temperatures that the thermal conversion efficiencies are low. For peak load purposes the operating flexibility provided by turbines compensates for the poor conversion performance. However, by using the exhaust gases as a heat source for a steam cycle the resulting combined cycle performance is comparable to the best obtainable with conventional systems today. As gas turbine material and design technology improves so that inlet gas temperatures can be increased, the efficiency of these systems will increase significantly.

While combined cycle systems have been closely tied to the development of low Btu gasification, other clean fuels can also be used as long as particulate materials are reduced to a level where blade damage is avoided. The Office of Coal Research low Btu Gasification Program also includes a combined cycle development program as part of its overall objective. In such systems low-Btu gas is burned with excess air in a gas turbine combustor. The resulting combustion gases at 5 to 30 atmospheres and 1800 to 1900°F are expanded in a gas turbine generator and exhausted to the atmosphere through a heat recovery boiler where superheated steam is generated to drive a steam turbine generator. About half of the output power is produced by the gas turbine generator and the other half by the steam turbine generator. This mix varies greatly depending on which of many possible system designs is utilized.

The current status of low-Btu coal gasification is discussed in the section on Clean Fuels from Coal. A 0.3 to 1.2 MW coal gasification plant for power generation has been designed. At the operating temperatures indicated above, the operational efficiency of the combined gas turbine-steam cycle would be equivalent to that of the conventional steam cycle but might be lower in capital cost. As improved gas turbines are developed to permit higher inlet temperatures, higher efficiencies can be achieved. At a 3000°F inlet temperature, a 55% cycle efficiency could be obtained. Much of the development work directed toward high temperature turbine blades has been performed for aircraft applications. These program are continuing with support from the Defense Department.

Alkali Metal Topping Cycles

The Alkali Metal-Steam Binary Rankine Cycle is composed of two interconnected power conversion systems; a high-temperature cycle in which a liquid metal such as potassium is the working fluid; and a lower-temperature steam cycle. Mercury topping cycles have been operated in the past by utilities, but the alkali-metal system is still in the development stage. Materials and component development programs were conducted in conjunction with the space power program, but relatively little has been done to apply this to central station power systems.

In its simplest form, heat from the combustion of coal would be transferred to boiling potassium. The potassium vapor exits the boiler at temperatures of 1400°-1750°F and expands through a turbine. The mechanical energy of the turbine is converted to electrical power by means of a conventional generator attached to the turbine shaft. The vapor discharged from the turbine is condensed and recirculated to the inlet of the boiler by a pump. The waste heat of the potassium cycle, evolved during the condensation process, is transferred to a coolant, in this case, boiling water. The steam generated in cooling the condensing potassium then flows through a conventional steam power plant to produce additional electric energy.

Several techniques for adding heat to the potassium may be considered. Among these are: conventional coal-firing, submerged combustion, atmospheric pressure fluidized bed combustion, and pressurized fluidized bed combustion. In the case of conventional coal-firing, the spent combustion gases would have to be treated to remove sulfur products before release to the atmosphere. The binary cycle could convert the energy of coal to electricity with an efficiency of about 55%. Furthermore, the costs of the power plant and of the electric power that it produces may be substantially less than that of a conventional steam power plant.

Potassium turbines of about 200 hp capacity have been operated at 1500°F for more than 10,000 hours along with boilers and condensers. The technology for containment of potassium has been established in many thousands of hours of corrosion loop testing.

Closed Brayton Cycle

In the closed Brayton cycle, the gaseous working fluid is compressed, heated, expanded in the turbine and cooled in the waste heat exchanger. In the recuperator the hot gas from the turbine exhaust is used to preheat the compressor discharge gas prior to entering the heat source heat exchanger. Various combustion methods such as conventional coal-fired, submerged combustion, and fluidized-bed combustion can be utilized to supply heat; intercooling or reheat, or combinations of these, can be used to increase the efficiency of the closed Brayton cycle. With a 1600°F turbine inlet temperature, it is estimated that power plant efficiencies as high as 45% can be obtained.

Because the cycle is closed, an inert gas working fluid, such as helium, may be used. An inert gas working fluid is stable at high temperatures and poses no compatibility problems with containment materials. Peak cycle temperatures attainable will be limited only by the strength of the containment and turbine materials at high temperature, and other material properties in the environment of the hot combustion gases. Turbine inlet temperatures in the range of 1200 to 1600°F are presently achievable with the potential of going to higher temperatures likely. The closed cycle, use of an inert gas working fluid, and simplicity of the Brayton cycle offer the potential for an extremely reliable power plant with low capital and maintenance costs.

Additional benefits of the Brayton cycle are its ability to follow a varying demand and its air cooling capability.

Several fossil-fuel burning closed Brayton systems are in operation in sizes up to 17 MWe and a system of 30 MWe capacity is under construction. These units operate at about 1300°F inlet temperature. A 15 kWe test system has operated at 1600°F for more than 10,000 hours.

Feher Supercritical CO_2 Cycle

In principle the Feher cycle is similar to the closed Brayton cycle. A gaseous working fluid would be compressed, heated, expanded in a turbine and cooled in a waste heat exchanger. Heat is transferred from the hot turbine exhaust gas to the compressor discharge gas in the recuperator. More complex cycles employing intercooling and reheat can be postulated to increase plant efficiency. With an approximately 1400°F turbine inlet temperature, power plant efficiencies of 50 percent may be attained.

The Feher cycle and its variations differ from the Brayton cycle in that, although at the high-temperature regions of the cycle the working fluid is well above its critical temperature and pressure, at the low-temperature end of the cycle the fluid is near-critical, or possibly, subcritical. The fluid compressibility under these conditions varies substantially with the compressibility at low temperatures much smaller than at high temperatures. Hence, the energy required to compress and circulate the fluid is much smaller than in a conventional Brayton cycle. Since the fluid must operate near its critical point at the low temperature end of the cycle to take advantage of the low pumping power feature, the pressure levels are set by the characteristics of the working fluid. While many fluids can be considered for use in the Feher cycle, carbon dioxide (CO_2) appears to be the most practical choice at present. This fluid is inexpensive, nontoxic, and relatively stable.

The major advantage of the Feher cycle is its compact turbomachinery. The combination of low pressure ratio, as well as high molecular weight and density, results in much smaller turbomachinery than that of steam-based power plants. This results in additional savings in piping, support structure and building size requirements. Since the cost of the turbomachinery and associated hardware is a significant fraction of the total capital cost of the power plant, the cost savings can be substantial. In addition, the higher average heat rejection temperature compared with steam systems would reduce somewhat the size of dry cooling towers and the cost of these components if they are employed.

Two small supercritical CO_2 test rigs have been operated for brief periods and the thermodynamic and transport properties of supercritical CO_2 have been established. No large or integrated power systems have been operated.

Magnetohydrodynamic Concepts

Open Cycle MHD - The MHD generator operates at high inlet gas temperature and would be employed as a topping device. In this concept a high temperature gas, seeded with an alkali metal to increase its electrical conductivity, is expanded through a channel with a superimposed magnetic field. The induced current is removed by electrodes embedded in the channel wall. Although gas temperatures are several thousand degrees, the metal structural elements of the duct may be held to 500°F or less. The duct coolant would carry off a portion of the total fuel energy which may be recovered in the steam bottoming plant.

The losses in an MHD generator are proportional to duct surface area, whereas the power output is proportional to duct volume, therefore, there appears to be an incentive towards large size for this concept. The absence both of highly stressed moving parts and of requirements for close tolerances are attractive characteristics.

Open cycle MHD plants could theoretically perform at efficiencies in the 50 to 60% range with fast start characteristics. Along with a high single-unit rating, it may be adaptable for use with systems utilizing all primary or coal-derived fuels regardless of ash content.

Approximately $20 million have been expended in the United States since 1960 on MHD generator and plant component development. A 32,000 kW generator was operated for 1 to 2 min duration per run. The long duration generator experience consists of 200 hours for a single test, and approximately 2000 hours cumulative at power levels of 1 to 5 kW.

The air preheater experience consists of 100 hours of operation at 3000°F with seed but no slag and 100 hours at 2000°F with seed and slag. Exhaust treatment resulting in a NO_x concentration reduction to 150 ppm was demonstrated in a two-stage combustion process. A 99+% recovery of the seed has been demonstrated from ash-laden combustion gases.

A one-tenth pilot scale superconducting saddle magnet has been built and tested. Pilot scale and larger solenoids have been built and tested by AEC for use with bubble chambers.

The Soviet Union has built and operated a 25 MW open cycle MHD plant at power levels up to about 5 MW. Current expectations are that a power level of about 12 MW will ultimately be obtainable with the present channel. This unit along with smaller Soviet MHD systems will be utilized for joint testing purposes in the US-USSR MHD exchange program currently underway. The U.S. will be sharing its magnet and channel technology with the Soviets.

Liquid Metal MHD - Liquid metal magnetohydrodynamic (MHD) power conversion devices can be used as a topping cycle for the conventional Rankine steam cycle or as a bottoming cycle with high temperature systems such as open-cycle plasma MHD. The fundamental problem in liquid metal MHD is how to use thermal energy (heat) to accelerate a conductive working fluid (the liquid metal) so that it can pass through the generator duct where it interacts with an electromagnetic field to produce electric energy. Several different approaches for accelerating the liquid metal are being pursued.

One approach involves a two-component system where the heated liquid metal is mixed with an inert gas to form a homogeneous two-phase mixture which is expanded through the MHD generator. The phases are then separated and the liquid pumped back to the heat source. The gas is passed through a regenerator, to conserve the internal energy of the gas, and through a heat exchanger which allows the waste heat to be rejected at any arbitrary temperature above the ambient surroundings. The cooled gas is compressed and passed back to the mixer via the regenerator. This concept is called a two-phase liquid metal MHD generator cycle and has shown considerable promise. The inclusion of a gas turbine in the gas loop may produce a cycle efficiency of about 50% for a maximum cycle temperature of 1600^{o}F.

Another acceleration method being investigated is based on condensing liquid metal vapor from the heat source by injection of a low temperature side stream of liquid metal into the vapor-liquid mixture as it leaves a nozzle. The injection of the side stream is an entropy increasing process which reduces the thermodynamic efficiency. These losses can be minimized to some extent by refinements in the cycle such as multiple expansion of the vapor-liquid mixture or multiple staging with power generation at each stage of the expansion-separation process. Because of the lower thermodynamic efficiency for this approach, projected to be between 7 to 12%, it appears to be most suitable as a topping cycle for a conventional steam plant.

A limited number of cycle analyses have been made and a large amount of effort has been expended in developing alkali metal compatible components for the space program. Liquid metal systems operate at substantially lower temperatures than open cycle gas systems and thus are more easily coupled with conventional heat sources.

Closed Cycle MHD - Closed cycle MHD has been proposed for use as a high temperature topping cycle. The working fluid is an inert noble gas such as helium or argon seeded with a low ionization potential material such as cesium. The bottoming cycle may be a steam Rankine cycle; however, other cycles may be used. A potential advantage of closed cycle MHD over open cycle MHD is that the required electrical conductivity may be attained by means of non-equilibirum ionization at much lower gas temperatures than are required in the open cycle case.

In the closed cycle MHD plant, the pressurized helium would be heated by combustion products in a heat exchanger. To avoid metal corrosion problems at the required high temperatures, it would be necessary to use a "clean gas" fuel derived from a coal gasification process. Because of the superior heat transfer properties of helium, the heat exchanger may not be much larger than the corresponding steam generator. After leaving the gas heater, the helium-cesium mixture passes through a nozzle where it is accelerated to supersonic velocities and passes into the generator which has a transverse magnetic field. Electrical fields, both applied and self-induced in the generator, cause the more mobile electrons to heat up and produce a non-equilibrium plasma through ionization of the cesium. Motion of the plasma through the generator produces electrical fields which drive currents through electrodes, which are in contact with the plasma, to the external load. The output of all MHD devices is a low-voltage, direct current which may be either consumed as direct current or converted to alternating current in an inverter.

After leaving the MHD generator, the helium gas goes to a regenerator, which serves to improve cycle efficiency, to a compact steam generator, and then to the compressor. In the cycle, the low temperature heat is converted to steam which may power a conventional turbine. The shaft output drives both the compressor and an alternator which provides part of the electrical output.

The principal advantage of the closed-cycle MHD plant is that it may accept heat at much higher temperatures than a gas turbine, there being no high temperature moving parts or high temperature seals. Therefore, with higher inlet temperatures, the MHD cycle can be more efficient. Cycle analyses predict that the combined closed-cycle MHD-steam bottoming cycle plants can have an efficiency of 52 to 54%, depending upon the regenerator investment. Most of the interest in closed-cycle MHD has been for its use with high temperature nuclear reactor heat sources. However, developments in the high temperature gas reactor area have had relatively low priority.

Non-equilibrium ionization MHD power generation at levels of several hundred kilowatts for short times has been demonstrated in linear generators driven by shock tubes. Larger shock tube driven experiments with radial generators are presently under construction.

Closed loop experiments with an electrical heater have demonstrated continuous operation for hundreds of hours at temperatures up to 2000°K. Combustion product-inert gas heat exchangers have been operated in the temperature range of interest for closed-cycle MHD.

Low Temperature Cycles

One of the basic limitations in the output of a steam turbine used to turn a generator is the physical size of the low pressure rotating components in the lower stages. At the lower pressures and temperatures existing near the exit from the turbine, steam has a very high specific volume when compared at the same temperature to various other vapors such as ammonia, methyl chloride, isobutane and the freons. Various theoretical proposals have been made to use a variety of these refrigerants as working fluids in binary low temperature bottoming cycles with steam. While improvements in cycle efficiency are relatively limited, the order of 1 or 2%, these developments may make possible substantial savings in capital costs per unit of capacity and permit the installed capacity per single unit to increase above the 2000 MW level. Both of these advances would lower the cost per kilowatt hour.

Most of the fluids proposed for the bottoming cycles freeze at very low temperatures. The potential freezing of water inside the tubes has been one of the major technical problems holding back the wider scale acceptance of the dry cooling tower which rejects heat directly to the atmosphere. Therefore, these refrigerants are also suitable for use in dry cooling towers. These features can greatly simplify the problem of siting in future plant expansion, particularly in arid areas where large coal deposits are known to exist.

It should be noted that even with improved efficiency cycles such as plasma MHD the need still exists for an efficient, low-cost binary bottoming cycle. Some analyses indicate that the highest overall plant efficiencies may be obtained with a plasma MHD top cycle and a liquid metal-steam-refrigerant tertiary bottoming cycle. While such cycles appear complicated, they do match the fluid to the temperature range being covered.

Bottoming cycles have also been studies for application to low temperature heat sources such as geothermal and solar energy. Heat source temperatures from geothermal brines are typically 100°-$300^{\circ}C$, much too low for coupling to a conventional steam cycle. Some success has been realized in the U.S. in developing a cycle for operation around $200^{\circ}C$ and in the USSR at even lower temperatures in connection with geothermal programs. The US-USSR Geothermal Exchange program should prove beneficial to both countries in their efforts to develop conversion systems.

Fuel Cells

The considerable R&D expended on fuel cell technology during the 1960's was primarily aimed at military and space applications. Later, commercial applications became the main focus of activity, with work concentrated on fuel cell systems that would use readily available fossil fuels, particularly natural gas.

Both the Gemini and Apollo space programs were dependent upon hydrogen-oxygen fuel cells for the electrical supply on the spacecraft. A number of practical demonstrations of small-scale fuel cells have been made in such applications as in remote communications relay stations, navigation aids, and electric vehicles.

A number (40+) of natural gas fueled units of 12½ Kw size have been installed experimentally to provide an electric supply for domestic and commercial applications. This development was sponsored by the gas industry under a program known as TARGET. An outgrowth of this program has been a system using distilled type liquid fuels and units of the 10-12½ Kw size are in laboratory operation. The electric industry is now engaged in mounting a program with one manufacturer which if successful will result in producing 60 units of 26,000 Kw size for delivery in the 1977-80 time period.

A design study has been performed for a coal-fired central station fuel cell system. In this concept, coal is fed to a fluidized bed of char and limestone where it reacts at 1700° to $1800^{\circ}F$ and 1 atm with

H_2O and CO_2. Fuel gases, H_2 and CO, are formed. The heat required to carry out these gasification reactions is generated in the operation of the fuel cells by fuel oxidation and electrical losses. This heat must be transferred from the cells to the gasifier bed.

Sulfur in the coal released as H_2S is absorbed by lime in the bed, forming CaS. A regeneration and sulfur recovery process is utilized to regenerate CaO for recirculation to the bed and to produce elemental sulfur for disposal. In the fuel cell bank, oxygen from air circulating to the fuel cell banks passes through the solid electrolyte and combines with the H_2 and CO fuel gases produced in the gasifier to form H_2O and CO_2 (mixed with unoxidized H_2 and CO). In this process the tubular fuel batteries generate dc power at efficiencies of about 80%. A portion of the gaseous mixture containing H_2O, CO_2, H_2, and CO leaving the cell bank is returned to the fluidized bed coal gasifier to produce additional fuel gases. A second portion of this mixture flows to an alternate bank of cells where oxidation of the CO and H_2 is completed. Combustion products containing minimal concentrations of SO_2 and NO_x emerge from this bank.

Other types of fuel cells--carbonate cells operating at 1000-1400°F or aqueous electrolyte cells operating at 200-400°F--can be substituted for the high temperature solid electrolyte cells. If these alternate cells are utilized, however, all the heat generated in cell operation cannot be utilized and the overall efficiency of the power generation is reduced.

Fuel cells can theoretically operate at efficiencies of 80% or higher. Overall efficiencies of 60-70% are projected for solid electrolyte fuel cell systems. At the same time, the concentrations of SO_2 emitted from coal-burning fuel cell plants will be well below proposed standards for stationary sources. In addition, no waste heat will be discharged to the cooling water.

PROGRAM RECOMMENDATIONS

Power cycle development has been carried out primarily by equipment suppliers to the electric utility industry to date. Government contributions have been related to space or military programs in general. Although industry is still actively developing advanced options, the increasing importance of improving performance and the numerous options to be researched justifies increased government participation in funding these developments. The Electric Power Research Institute will enable the utility industry to collectively accelerate promising options through the demonstration stage. Joint projects involving all three entities should be pursued in the future. It is imperative that these development efforts be planned, coordinated, and managed to minimize expending funds on options which do not progress as well as others. Program plans for all development activities undertaken is the number one need.

Combined Cycle Systems

The principal research objective of this program should be the development of high temperature gas turbines for utility use. Research on improved materials is essential if inlet gas temperatures are to be raised to the 3000°F level. The Advanced Research Projects Agency of DOD has supported research in this area. These efforts should continue, perhaps on an enlarged scale, and should be accompanied by industry efforts to improve turbine design so that maintenance costs are reduced and performance improved in the larger units needed for power generation. A $100 million over 8 years is recommended for high temperature gas turbine development. Government should provide approximately half of this amount, most of it for materials development and testing.

Alkali Metal Topping Cycles

While these systems look attractive thermodynamically, they could pose equipment, operating and safety problems, which would complicate their acceptance by industry. The results of space program R&D on liquid metal Rankine cycle development should be reviewed along with more recent work by industry and evaluated along with other topping cycle options before progressing to large scale development projects.

Closed Brayton Cycles

High Temperature Gas Cooled Reactors (HTGR) and the Gas Cooled Fast Reactor (if developed) would both utilize a closed cycle helium power system. It now appears that HTGR's are likely to become an important source of nuclear generated electricity during the last two decades of this century. An effort to improve energy conversion with these systems is thus justified and should begin immediately. Turbine design and testing are principal needs. Tests must be conducted on full scale units before inserting them in nuclear plants. This testing will be costly and time consuming. Estimated program costs are $100 million over a ten year period.

Feher Cycle

McDonald-Douglas has carried out development of the supercritical CO_2 Feher cycle with support from DOD for propulsion systems. They have proposed a two-phase program to develop larger units for utility use where it appears to have many of the attractive features of the Brayton Cycle in addition to compactness that might permit the shipment of complete units with a minimum of field construction work required. The operating conditions of the cycle pose some material and seal problems, but they do not seem beyond resolution. As with the alkali metal topping cycles, this system should be carefully analyzed both from its possible use in central station power plants and as a compact propulsion system for ships and large vehicles. The McDonald-Douglas proposal includes a well defined development program which should assist in both evaluating the merits of the program and in managing it.

Magnetohydrodynamics (MHD)

The research and development effort required for open-cycle MHD involves the acquisition of long duration operating and engineering experience in several component areas. The components requiring specific emphasis are MHD channels, air preheater, chemical regeneration systems, and seed recovery systems. Continuation of the current program at the component development and technology levels would require about $5 million per year for several years. Pilot plant construction could be undertaken at a later time pending evaluation of the results of the more basic work. Experience gained through the US-USSR MHD exchange program which incorporates work on the U-25 MHD plant will be helpful in planning US pilot facilities. An additional $5 million/yr over the next 4 years will be required to support US commitments in the exchange program.

Support for liquid metal MHD hot flow tests should continue at the 2-3 million dollar per year level. This program would include US testing in the 1 MW German pilot facility. The lower operating temperatures of these generators provide increased applications in energy systems, both fossil fuel and nuclear. A better understanding of two phase flow phenomena under operating conditions is required to predict ultimate conversion efficiencies. Closed cycle plasma systems are being studied by industry and show promising results. This approach should be reviewed along with the other two before commitments are made to demonstration facilities.

Fuel Cells

A centralized and coordinated program on fuel cell systems for a wide range of applications would provide for the balanced development of this device. Federally supported programs have related primarily to space applications, but these efforts have had important fallout effects on the civilian fuel cell program, supported primarily by industry. The AGA's TARGET program includes field testing of residential and commercial fuel cells utilizing natural gas. Pratt and Whitney is working with the electric utility industry to produce a commercial unit for central station use. This effort is directed at producing 26 MW units for central station power generation. They would feed a distillate fuel to a reformer which would produce a gaseous feed for the fuel cell.

The Federal program should complement these efforts by supporting basic electrochemical research. Systems which appear to offer superior performance to that obtainable from present cells should be considered for larger scale support. The effort should include some development work in addition to the management and coordination of other programs. An annual funding level of about $2 million would be required for such a program.

Low Temperature Cycles

Increased fuel costs and concern for thermal discharges make the use of bottoming cycles more attractive economically than in the past. These cycles could also operate on relatively low temperature energy sources, such as solar or geothermal. The geothermal exchange program with the USSR includes cycle development as an important element.

This program should identify the most promising fluids for use in the temperature ranges of interest and proceed to develop the necessary components. Expander design to match the fluid characteristics is an important part of the effort. A ten year program requiring an estimated $100 million is recommended.

Program Summary

Table III-9 presents a summary of the program elements discussed above. More details are given on program objectives and cost estimates in the panel report.[14]

IMPACT OF IMPLEMENTATION

The impact on resource consumption of implementing a 50% efficient cycle in the year 2000 to provide 25% of the coal-fired electric capacity was estimated in the section on Clean Fuels from Coal. The cost data and environmental impacts of the various advanced concepts have not been defined in sufficient detail to evaluate their economic and environmental impact.

G. ALTERNATIVE BREEDER REACTORS*

INTRODUCTION AND SUMMARY

With President Nixon's Energy Message of June 4, 1971, a national commitment was made to develop the Liquid Metal Fast Breeder Reactor

* References 15-25 represent a bibliography for this section.

TABLE III-9

SUMMARY OF ADVANCED CYCLES PROGRAM

Program Element	Current R&D Objective	First Year Cost $ Million	Long-term Cost $ Million/yr	Notes
MHD				
Open Cycle	Development of components;	5	32/6	Follow-on to await results of comprehensive cycle analysis
USSR-US Program	Pilot tests on USSR systems	5	20/4	
Liquid-metal	Hot flow tests; 1 MW tests with Germany	3	50/8	
	MHD demonstration (if justified)		100/4	Decision to be based on results of MHD R&D
Fuel Cells	Development of improved system for central station and dispersed use; catalysts; electrochemistry and electrolyte development	2	20/8	This program should provide coordination of current projects; a sizeable industry effort is underway at Pratt & Whitney
Study of alternatives K topping, Feher and others	Design of several power cycles and evaluation of their merits	2	100/8	Most promising cycles will be developed and demonstrated
Closed cycle He system		2	100/10	For use on high temperature gas reactor
High temp. turbine mat'ls; design & testing		10	100/8	Improved gas turbine performance
Low temp. (bottoming) cycles for geothermal & central station use	Fluid property studies; expander design; heat transfer devices; econ. analysis for geothermal & central station use	5	100/10	Geothermal applications, including USSR-US exchange program; central station bottoming cycles
	Total	34	622/10	

(LMFBR) as a major energy source for electric power generation. Because of the commitment already made and the extensive analysis underlying that commitment, the LMFBR program was not directly considered in this assessment. Nevertheless, the successful development of an economical breeder reactor, even though the cost to the government may run to $6 billion, is accepted as a necessary cornerstone of the nation's R&D program. Without such a program our resources of acceptably priced uranium would be rapidly depleted. (See Figure II-13.)

There are two basic types of breeder reactors: 1) those in which the most common uranium isotope, U-238, is converted to fissionable plutonium, Pu-239, and 2) those in which thorium-232 is converted to fissionable uranium-233. Both types extend our effective resources of nuclear fuels. In the U-Pu-239 case, instead of using only 1% of the potential fission energy in uranium (as in a light water reactor), some 70-80% can be used. This is the physical basis for the projected economic advantage of a breeder; the larger capital cost of a breeder reactor (projections range between $25-$65/KWe penalty) are more than compensated for by lower fuel cycle costs. The economic analysis is, of course, strongly dependent on the uranium supply function (amount of resource vs price). As discussed in Chapter II the environmental effects of breeder reactors are expected to be only slightly different from those of current water reactors. Safety problems are somewhat different, however, but it is difficult at this stage in the development of both systems to attribute quantitative differences in this regard.

The importance of the development of a viable fast breeder system dictates that due consideration be given to the finite possibility that the LMFBR will run into difficulties which might prevent or seriously delay its widespread adoption. Thus, this evaluation concentrated its attention on the three most promising alternatives to the LMFBR, the Molten Salt Breeder Reactor (MSBR), the Gas Cooled Fast Reactor (GCFR) and the Light Water Breeder Reactor (LWBR). It addressed the following question: given the state of technological development of the LMFBR, what would be an appropriate distribution of support for the alternative breeders to provide adequate insurance for the overall breeder program.

The general conclusion that resulted from the evaluation was that continued development of the MSBR and the GCFR is advisable. If the realization of these concepts confirms present indications, either one could prove to be a credible alternate to the LMFBR. The development of these two alternatives (whose characteristics and development problems are quite different from those of the LMFBR and from each other's) should continue at least until the success of the LMFBR is even more certain than it is today. By the end of FY 1975 two LMFBR demonstration plants should be in operation abroad. Development of the LMFBR in the United States will be further advanced. Knowledge of the problems, prospects and potential advantages of the GCFR and MSBR will be clearer, if the development programs for these concepts outlined in this report are pursued. At that time the relative prospects for the three concepts should be re-evaluated and a decision made whether to continue or extend government support of development of the MSBR, the GCFR, or both.

The LWBR has a different role to play. It provides means for greatly improving the nuclear fuel utilization of existing light water reactors. It capitalizes on light water technology and does not require development of a wholly new reactor concept. It uses thorium as an alternate nuclear fuel in a breeding cycle. However, its breeding ratio will be much lower than the LMFBR or GCFR, and may not quite reach unity. Consequently, the LWBR will not make as effective an extension of our nuclear fuel resources as these other concepts. Nevertheless, the concept, already under advanced development, merits support as a potential improvement of water cooled reactors.

CURRENT STATUS OF BREEDER TECHNOLOGY

Liquid Metal Fast Breeder Reactor (LMFBR)

As was indicated in Chapter II, the largest item in the Federal energy R&D budget is for development of the LMFBR. The anticipated Federal funding in this program for FY 1973 is approximately $260 million. The program is a highly diverse one including basic materials and reactor physics studies, engineering design, component development and testing, and analysis. A number of liquid metal fast reactors have been built in this country and abroad.

The status of LMFBR technology is indicated by the fact that a large scale (350-400 MWe) demonstration plant is now being designed. This project whose total cost is estimated at $700 million is being supported jointly by the utilities industry and by the government. Construction is scheduled to begin in 1974 with operation possible by 1979.

This plant will not be the first LMFBR demonstration to operate. Table III-12 displays the international competition in this aspect of LMFBR development. The French demonstration reactor has achieved criticality.

Commercial LMFBR plants, postulated in the Reference Energy Systems as being introduced in 1986, would include a number of technical advances over the demonstration plant. The overall plant efficiency, for example, would be on the order of 40-42% rather than 37-38%. These advances, safety studies, long-term materials tests, etc. would continue to require some Federal support although, as commercial viability is attained, the bulk of developmental funds is expected to come from private industry.

<u>Molten Salt Breeder Reactor (MSBR)</u>

The principal financial support of molten salt reactor development has been provided by the USAEC. A total of around $150 million has already been expended, with a present annual budget of $5 million. The principal developer of molten salt reactor technology has been Oak Ridge National Laboratory (ORNL), which has been conducting work on this concept since the late 1940's. In addition, two industrial groups have engaged in limited technology assessment and conceptual design studies of a MSBR.

Fuel for the MSBR consists of a molten mixture of LiF, BeF_2, ThF_4 and U-233F_4. This fuel flows through the reactor at a rate of 55,000 gpm and acts as the primary heat transfer medium. The core structure is composed of graphite containing passages through which the fuel flows. An intermediate heat transfer fluid, probably another fused salt, is used

Table III-12

SODIUM-COOLED FAST BREEDER REACTORS PLANNED OR UNDER CONSTRUCTION

Under Construction

NAME	COUNTRY	REACTOR PURPOSE	POWER Megawatts (Thermal)	POWER Megawatts (Electrical)	PLANNED INITIAL OPERATION
BN-350	USSR	Demonstration electrical-desalination	1,000	150	1971 (Now Operating)
PFR	U.K.	Demonstration electrical	~600	250	1973
PHENIX	France	Demonstration electrical	600	250	1973
BN-600	USSR	Early evolution electrical	1,500	600	1973
FFTF	USA	Irradiation test facility	400	—	1974
JOYO	Japan	Irradiation test facility	100	—	1973

Planned

NAME	COUNTRY	REACTOR PURPOSE	POWER Megawatts (Thermal)	POWER Megawatts (Electrical)	PLANNED INITIAL OPERATION
PEC	Italy	Irradiation test facility	140	—	1975
SNR	West Germany	Demonstration electrical	750	300	1976
Demo #1	USA	Demonstration electrical	750-1,250	300-500	1979
MONJU	Japan	Demonstration electrical	750	300	1976
CFR	U.K.	Commercial	~3,200	1,300	1980
PHENIX-2	France	Commercial	~3,000	1,200	1980

Source: J. Barnard, et al. "Development of the Commercial Breeders" Nuclear News, December, 1972.

as a buffer between the fuel and the steam generator. To obtain a breeding ratio above unity continuous chemical processing of fuel is required, for three purposes: 1) to strip neutron-absorbing xenon-135, 2) to segregate neutron-absorbing protactinium-233 until it can decay to uranium-233, and 3) to remove neutron-absorbing rare earth fission products.

The major molten salt reactor facility operated thus far is the 7.4 MWt Molten Salt Reactor Experiment (MSRE) conducted at ORNL between 1965 and 1969. A feel for the state of development of the LMFBR is obtained by comparing the properties of that experimental reactor with those of a full scale 1000 MWe MSBR. As shown in Table III-13 the differences are substantial.

Table III-13

SALIENT DIFFERENCES BETWEEN MOLTEN SALT REACTOR EXPERIMENT (MSRE) AND MOLTEN SALT BREEDER REACTOR (MSBR)

Property	MSRE	MSBR
Thermal Power Level	7.4 MW	2240 MW
Fertile Material	(none-mocked up by ZrF_4)	ThF_4
Vessel Diameter	5 ft.	22 ft.
Steam Characteristics	no steam generator	1000^oF supercritical
Capacity of Main Fuel Pump	1200 gpm	16,000 gpm

Nevertheless, the MSRE demonstrated some of the critical features of an MSBR. These properties included the stability of the fused fluorides, the simplicity of reactor control due to the properties of the fluid fuel and the feasibility of operating with a highly radioactive circulating fuel, at least on the scale of this experiment. Development of fuel processing techniques has continued to the point that many of the process steps have been satisfactorily demonstrated.

Operation of the MSRE also disclosed a number of problems. The material used to contain fuel salt in the MSRE, Hastelloy N, developed intergranular cracks when stressed after exposure to salt containing fission products. Fission product tellurium has been found in the cracks and has been shown capable of causing them. Possible solutions include modifying the composition of Hastelloy N, using Inconel-600, which has been shown not to be attacked by tellurium, or using stainless steel. After a presumably satisfactory material has been selected long-term tests to confirm its satisfactory performance when exposed to fluid fuel under reactor conditions will still be required.

Tritium, formed from lithium in the reactor fuel, was found to diffuse through the MSRE reactor vessel and heat exchanger. In a 1000 MWe MSBR, it is predicted that around 1000 curies of tritium per day will end up in the steam. Use of a double-walled steam generator with an He-O_2 atmosphere between the tubes would certainly keep tritium from escaping into the steam but would be costly. Other less costly measures are being considered. Whatever solution is proposed must be demonstrated experimentally.

Fuel reprocessing is a third problem area. It will be necessary to demonstrate satisfactory performance of the processes proposed for uranium removal, protactinium segregation and rare earth removal on a continuous basis. The basic chemistry of the process steps appears to be reasonably well demonstrated, but design of equipment to carry them out and selection of appropriate materials present problems. The frozen wall fluorinator proposed for uranium removal is an untried concept.

Solutions to the three problems just discussed must be found and demonstrated before the MSBR can be considered a practical alternative to the LMFBR or before serious consideration can be given to building a Molten Salt Breeder Reactor Experiment. Many other development projects would have to be undertaken and completed to bring the MSBR to commercial status. Although completion of these other projects will take many years and hundreds of millions of dollars, their success seems reasonably assured.

Gas Cooled Fast Breeder Reactor (GCFR)

Development of the Gas Cooled Fast Reactor is less advanced than that of the Molten Salt Reactor in one respect; no complete GCFR experiment analogous to the MSRE has yet been run. On the other hand, the GCFR uses a fuel element similar in many respects to the LMFBR and employs helium coolant technology and prestressed concrete pressure vessel designs rather similar to the High Temperature Gas Cooled Reactor, so that the GCFR can benefit from the relatively advanced development status of the LMFBR and HTGR.

The principal developer of the GCFR in the United States is Gulf Atomic (GGA). A large number of electric utilities are participating with GGA in engineering studies on the GCFR. These organizations are currently expending $1.4 million annually on GCFR development. The Atomic Energy Commission's FY 1973 budget allocated $2 million to the GCFR. Substantial work on the GCFR is also being conducted in Europe.

To assist in understanding the development status of the GCFR a brief description will be given of the GCFR and its points of similarity to and difference from the HTGR and the LMFBR. Individual fuel rods of this reactor consist of stainless steel tubing filled with pellets of mixed uranium and plutonium dioxides. In this respect they are similar to fuel rods of the LMFBR. They differ from the LMFBR in being roughened on the outside to improve heat transfer and in being vented to the helium coolant by connections at the top leading through charcoal traps to retain fission products.

Helium coolant flows down through the core, with the flow rate to each fuel assembly adjusted by orifices in each assembly to keep the maximum stainless steel temperature below 1292°F, about the maximum proposed for LMFBR's. The mixed helium temperature leaving the reactor is 1010°F. This helium flows through a steam generator which produces superheated steam at 920°F to drive the main helium circulator and, after resuperheating, to generate electricity in a conventional turbo-generator.

Six separate sets of primary helium circulators plus steam generators are provided. In addition, six separate sets of electric-motor-driven auxiliary helium circulators plus auxiliary heat exchangers are provided to remove fission product decay heat at times when the main helium circulators may be out of service.

The reactor, control rods, steam generators and primary and auxiliary helium circulators, are housed within a steel-lined, prestressed concrete pressure vessel. The pressure vessel is similar in principle to ones that have been built in Europe and to GGA's design for large commercial HTGR's. It differs, however, in being required to hold 85 atmospheres pressure, vs 50 atmospheres in the HTGR. It is contended that the design of the penetrations through the vessel is such as to preclude gross, rapid failure of the pressure vessel.

To limit the consequences of smaller leaks of individual steel penetration closures, a separate secondary containment vessel similar to those proposed for large HTGR's, is provided. In the event of a leak, this secondary vessel would keep the reactor pressure above two atmospheres after pressures in the reactor and containment had equalized, and would prevent further escape of fission products. Maintenance of reactor pressure above two atmospheres and limitation of the rate at which the reactor might depressure are two measures taken to prevent overheating of fuel in the event of a loss of coolant accident. As discussed later, this is one of the most important problems of the GCFR.

Characteristics predicted by GGA for the GCFR are compared in Table III-14 with those for the LMFBR and MSBR.

Table III-14

Comparison between Characteristics of Three Breeder Concepts

	GCFR	LMFBR	MSBR
Maximum Coolant Temperature, °F	1010	1060	1300
Thermal Efficiency, %	38	42	44
Breeding Ratio	1.5	1.28	1.06
Specific Fissile	Core Only		Total
Inventory, kg/MWe	2.44	1.7	1.5

The thermal efficiency of the GCFR is slightly lower than the other concepts because of the greater power needed to circulate helium. The breeding ratio of the GCFR is higher than the LMFBR because of the inertness of helium to neutrons. The specific fissile inventory of the GCFR is uncertain until more tests on GCFR fuel are completed to determine the maximum specific power at which it can be operated. Since the higher breeding ratio of the GCFR offsets its probable higher fissile inventory, it seems likely that there is little to choose between the GCFR and LMFBR in terms of efficiency of uranium utilization.

Because of the similarities in fuel design and the probable similar efficiency of uranium utilization of the GCFR and LMFBR, it seems likely that the fuel cycle costs of the two concepts will be nearly the same. It is difficult to make a valid comparison of capital costs for the two concepts at the present. Nevertheless the possibility exists that the GCFR, if carried to full development, might have a lower capital cost than the LMFBR.

The attainment of a commercial GCFR will require the solution of a number of development problems. Most of these can be solved by straightforward engineering. Three central problems stand out, however, as less amenable to easy solution. These are (1) demonstration of reliable performance of the proposed fuel design, (2) demonstration of the integrity of the PCRV, and (3) proof that cooling of fuel will be effective under all emergency conditions.

Fuel Development - Fuel for the GCFR differs from that for the LMFBR in three principal respects: (1) the outer surface of each fuel rod is roughened to improve heat transfer, (2) each fuel rod is vented through a series of fission product traps to the main helium coolant, to equalize pressure across the fuel cladding, and (3) each hexagonal can, which holds together 271 fuel rods into a fuel assembly, is supported at the top grid plate only. Heat transfer performance of the roughened fuel rods is being checked by experiments in this country and Switzerland, and is expected to be satisfactory.

Venting of the fuel rods to equalize pressure inside and out is called for because of the high and possibly variable external coolant pressure, the internal pressure buildup which would occur as gaseous fission products form, and the difficulty of predicting the mechanical strength of the roughened cladding, especially after high burnup. The fission product venting and pressure equalizing system is complex and much more extensive tests will be required.

The proposed support of hexagonal fuel assemblies only at the top grid plate raises questions about possible flow-induced vibration, distortion under thermal stresses and irradiation, and stability under seismic loads. These questions can be dealt with to some extent by engineering analysis, but complete assurance requires long-term test under realistic reactor conditions.

Finally, there are the same uncertainties about the effect on GCFR fuel of long exposure to fast neutrons and high burnup that make performance of LMFBR fuel uncertain. The fuel test program planned for LMFBR fuel will help to clear up these uncertainties. Because of the novel features of GCFR fuel, however, an extensive test program is needed, first on individual fuel rods, then on complete assemblies, and eventually in either a reactor experiment or demonstration reactor.

Pressure Vessel Integrity - The prestressed concrete pressure vessel (PCRV) of the GCFR is required to hold 85 atmospheres helium pressure reliably for 30 years. This is substantially higher than the 50 atmospheres design pressure of the HTGR, which has been the subject of extensive satisfactory model testing. Model tests of a PCRV designed for 85 atmospheres will be required, with intentionally failed liner or tendons, to ensure that catastrophic PCRV failure will not occur.

Emergency Fuel Cooling - Provision of reliable cooling of GCFR fuel following rapid loss of helium pressure is the most critical development problem of this reactor. GGA has devoted a great deal of attention to this problem and believes that a solution has been obtained by the following measures:

1. Limitation of possible rate of coolant loss through use of the PCRV and provision of flow-restricting orifices to back up seal welds at PCRV penetrations.

2. Prompt insertion of safety rods on reduction in coolant pressure.

3. Provision of multiple primary helium circulators each driven by its own steam turbine and steam generator and speed controlled so as to provide adequate coolant mass flow at all stages of a loss-of-coolant accident.

4. Provision of multiple, electric-motor-driven auxiliary helium circulators which start automatically on a scram and which pick up the cooling service through check valves if the primary circulation rate is too low.

5. Provision of secondary containment to limit the minimum helium pressure in the reactor to around two atmospheres after pressures in the reactor and containment have equalized. GGA has made extensive computer-aided analyses of pressures, flow rates and temperatures as a function of leak rate and location and believes that cladding overheating and melting can be prevented for leaks as large as 100 square inches, four times as large as the largest flow restricting orifice. In addition, extensive tests are planned of the individual components of the emergency cooling systems including performance of the circulators under pressure and flow transients. Before the GCFR can be accepted as a practical alternative to the LMFBR, it is necessary that a realistic demonstration be made of the adequacy of the proposed emergency core cooling provisions in a simulated loss-of-coolant accident. This demonstration could be made either in a special part-scale integral safety experiment like the LOFT experiment planned for light water reactors or in a 300 MWe demonstration GCFR, by deliberately lowering helium pressure at the rate anticipated in the largest anticipated PCRV leak.

Light Water Breeder Reactor (LWBR)

The Light Water Breeder Reactor (LWBR) achieves its performance by improved conservation of neutrons. It does this using three main