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DEVELOPMENT STATUS AND ENVIRONMENTAL HAZARDS OF SEVERAL CANDIDATE ADVANCED ENERGY SYSTEMS

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by
Morris M. Penny
Sidney V. Bourgeois

Lockheed Missiles & Space Company, Inc.
Huntsville Research & Engineering Center
Huntsville, Alabama 35807

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EPA Project Officer

William Cain
Power Technology and Conservation Branch
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

When energy and material resources are extracted, processed and used, changes are produced in the existing environment that in many instances are undesirable. These undesirable changes resulting from both substances and effects comprise what we define as pollution. Pollution of air, land and water may adversely affect our aesthetic and physical well being. Protection of our environment requires that we recognize and understand the complex interaction between our industrial society and our environment.

The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies aimed at minimizing, abating and preventing pollution from industrial and energy-related activities.

Several advanced energy concepts are currently being considered as future sources of energy. Concurrent development of environmental protection measures and energy conversion technology will avoid possible delay of commercialization. This document presents a review of the development status and anticipated environmental hazards of several of these advanced energy concepts.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

The report gives a review of the development status of several advanced energy concepts and discusses the primary environmental hazards of each system.

Systems reviewed include potential new sources of energy and improved energy conversion. Each system is evaluated with respect to its development status, and estimates made as to when each will begin to contribute significantly to U.S. energy needs. Appraisals were made of the environmental impact of each system including assessment of the adequacy of pollution control technology and potential gross ecological impact. The overall conclusion is that each energy system has a negligible or mild direct environmental impact when compared with conventional fossil fuel and nuclear systems, but that indirect impacts for some of the energy systems could be severe and need further study to quantify their impact. Considering both the expected environmental impact and period of technology break through/commercialization, the following order of R&D priorities on the candidate energy systems has been developed: high temperature turbines, ocean thermal gradients, windmills, magnetohydrodynamics, metal vapor (potassium) Rankine topping cycles, hydrogen fuel cells, thermionics, electrogasdynamics, and thermoelectric conversion.

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Section 1
INTRODUCTION

The objective of this study is to review the development status and anticipated primary environmental hazards of candidate advanced energy systems. Systems evaluated included potential new sources of energy, improved energy conversion devices, and direct energy conversion systems. Potential new sources of energy considered were ocean thermal energy conversion (OTEC) and wind power. Improved energy conversion devices considered were magnetohydrodynamics (MHD), hydrogen fuel cells, potassium topping cycles and high temperature turbines. The direct energy conversion devices considered were thermionic, thermoelectric and electrogasdynamic systems. Advanced energy systems undergoing similar evaluations in other studies, but not considered here, include coal conversion, oil shale, geothermal, breeder and fusion nuclear power, energy from wastes, solar, biomass, and tidal energy.

This type of study is required to ensure that environmentally acceptable systems will result from the search for viable alternate energy sources to our nation's dwindling domestic fossil fuels. Integrating environmental control into the design of a developing technology should prove to be cheaper and more effective than retrofitting pollution control devices to existing utility or industrial facilities. Concurrent development of environmental protection measures and energy conversion technology will also avoid possible delay of commercialization which would occur if existing and probable pollution regulations are ignored until the completion of development.

For the candidate energy systems considered in this study, the environmental research and development priorities and timing will be presented from a compilation of the following information:

- An evaluation of the current development status of the technology
- An estimate of when the subject technology may begin to contribute significantly to U.S. energy needs
- An appraisal of the environmental impact of the technology of each system when applied as operating systems including assessment of adequacy of control technology, potential gross ecological impacts, etc.
- A summary of ongoing federally funded research.

This information was obtained from the existing technical literature and/or by interviewing knowledgable personnel from government, industry and educational institutions. The major published source relied upon for general information was Ref. 1, whereas the principal interviews were with personnel from the Energy Research and Development Administration (ERDA), Electric Power Research Institute (EPRI) and principal investigators in the various technology development efforts. Descriptions of on-going federally funded research were obtained primarily from ERDA and the Smithsonian Science Information Exchange (SSIE).

The overall conclusions of this investigation are that each of the energy systems considered has a negligible or mild direct environmental impact when compared with conventional fossil fuel and nuclear systems, but that indirect impacts could be severe and need further study to quantify their impact.

The sections that follow are: a summary of technology development status, environmental impact and research and development needs; detailed discussions of each advanced energy system; and finally, a concluding section which presents the conclusions and recommendations of this study.

Section 2
OVERVIEW

The development status and anticipated primary environmental hazards of the following advanced energy systems has been reviewed:

- MHD (Open and Closed Cycle)
- Hydrogen Fuel Cells
- Potassium Topping Cycles
- High Temperature Turbines (Open and Closed Cycle)
- Ocean Thermal Gradient
- Wind
- Thermionic
- Thermoelectric
- Electrogasdynamic

A summary of ongoing federally funded research of these systems has also been compiled. Based on the preceding information, recommended environmental R&D priorities for these candidate energy systems have been identified.

2.1 DEVELOPMENT STATUS AND PROJECTED ENVIRONMENTAL HAZARDS

A concise overview of the development status and an environmental appraisal of each energy system is given in Table 1. Although each energy system under consideration usually possesses several distinct variations and alternatives, the particular system chosen in Table 1 was considered the most likely to provide the earliest, significant contribution to U. S. energy needs (i.e., open cycle MHD in Table 1, rather than closed cycle MHD). The particular systems chosen for inclusion in Table 1 are described in the following sections.

Table 1

OVERVIEW OF THE DEVELOPMENT STATUS AND ENVIRONMENTAL IMPACT OF THE CANDIDATE ADVANCED ENERGY SYSTEMS

Energy System	Development Status/ Power Capacity	Efficiency	Most Probable Method of Utilization	Earliest Widespread Commercial Utilization	Percent of U.S. Energy Needs	Environmental Appraisal — Direct — Emissions	Environmental Appraisal — Direct — NSPS Status*	Environmental Appraisal — Indirect
MHD (Open Cycle)	Experimental/18-32 MW	55-60%	Baseload (Topping Cycle)	2000	Unknown	Moderate	Yes	Moderate
Hydrogen Fuel Cells	Experimental/26 kW	55-70%	Peak Power Demand	1995	Unknown	Negligible to Moderate	Unknown	Moderate
Ocean Thermal Energy Conversion	Conceptual/100 MW	2.5%	Energy Storage Special Purpose	1990-2000	1-5%	Negligible to Moderate		Moderate to Severe
Wind Power	Experimental/100 kW	30-37%	Energy Storage	2000	1-20%	Negligible	Unknown	Moderate
High Temperature Turbines								
Steam	Experimental (GE)/2MW	50% at 2800F	Baseload	Unknown	Unknown	Moderate	Yes	Moderate
	Production	38-40%	Baseload	2000	80%			
Gas	Production	Simple Cycle 30% Combined 46% Regenerative 40%	Peak Power Demand Intermediate	1980	$\sim$25%	Moderate	Yes	Moderate
Thermoelectric Converters	Experimental/Low Power	4-6%	Special Purpose	Unknown	Unknown	Negligible	Yes	Moderate
Thermionic Converters	Experimental/Conceptual (Utility Application 22 MW)	1-15% 20-25%	Special Purpose Topping Cycle	2050	Unknown Unknown	Negligible Moderate	Yes	Negligible
Potassium Vapor Topping Cycle	Experimental/250 kW	50-55%	Topping Cycle	1990	$\sim$15%	Negligible to Moderate	Yes	Negligible
Electrogasdynamic Converters	Experimental/30W	Unknown	Special Purpose	2000	Unknown	Negligible	Yes	Negligible

*Meets present NSPS emission rate limitations for coal fired boilers.

The categories of development status considered in Table 1 ranged from conceptual, experimental, demonstration and production (these are with respect to a utility size power plant). Conceptual stage projects refer to those in which only paper studies, detailed design and/or limited laboratory scale testing of components are underway. Experimental systems consisted of those which had progressed to bench scale or pilot plant testing of the full system or where major subsystems were undergoing large scale demonstration tests. Demonstration status refers to those systems undergoing semi-works or full-scale testing of an integrated plant containing all the subsystems, instrumentation, and process control of a commercial unit. A unit is considered ready for commercial application if all development and demonstration phases have proved its technical and possible economic feasibility, and if several units are in full-time use.

Appraisal of environmental impacts are rated as negligible, moderate or severe. Where possible, these descriptors are in comparison with the impact associated with New Source Performance Standards (NSPS) or other regulations which apply to utilities with conventional (500 to 1000 MW) coal fired steam plants.

Distinction between direct and indirect impacts consists of the following:

- Direct impacts result from activities on the energy production site (e.g., coal storage, crushing, combustion, and ash and flue disposal for MHD).
- Indirect impacts have their environmental effect at the site of other activities required to support the advanced energy development (e.g., emissions from CdS photovoltaics used as collectors of solar energy), or offsite considerations such as weather modification, and more general considerations such as aesthetics and land use.

Predictions of wide scale commercial utilization were primarily based on Refs. 1, 9 and 19 and upon conversations with key ERDA and EPRI personnel. Significant, widespread utilization is defined as 1% of total U. S. consumption.

2.2 FEDERALLY FUNDED RESEARCH

Ongoing, federally sponsored research in the nine candidate energy systems is summarized in Table 2. One-hundred forty-four studies totaling over $26 million were being performed by six federal agencies (ERDA, NSF, DOD, NASA, EPA and FEA). Wind energy was receiving the greatest funding and number of studies in 1975, while thermoelectric conversion was receiving the least funding. Eight percent of the total number of these studies were identified as devoted to environmental considerations.

2.3 ENVIRONMENTAL R&D RECOMMENDATIONS

All of the advanced energy systems considered in this study are summarized in Tables 3 and 4 with respect to their anticipated environmental impact and R&D requirements. Several of the systems were found to have a fairly negligible effect on the environment when a single unit is considered. However, in the case of windmills and ocean thermal conversion systems, a cluster arrangement of many plants will be required to produce a sizable amount of electrical energy. This clustering arrangement could have an adverse impact on the local environment.

Table 3 lists the probable emission source and the environmental impact and R&D requirements, while Table 4 summarizes the time frame for the R&D studies. These projections were obtained by considering the present development status, projected timing of widespread commercialization, adequacy of the environmental data base, expected environmental impact and adequacy of the existing pollution control technology.

As shown in Table 1 most of the systems are either in the experimental or feasibility stages of design at the present time. These efforts should be augmented currently with the suggested R&D efforts if the studies are to significantly impact the preliminary and final design stages. Thermionic and electrogasdynamic direct energy converters operating as a base load unit

Table 2

ONGOING FEDERALLY FUNDED RESEARCH OF CANDIDATE ADVANCED ENERGY SOURCES*

Energy System	Sponsoring Agency	Number of Studies	Environmentally Related Studies	Federal** Funds, $10^3
Wind	ERDA	15	0	6320
	NSF	36	1	2830
	NASA	3	0	430
	FEA	1	0	40
Subtotal		55	1	9620
Magnetohydrodynamics	ERDA	11	1	5110
	DOD	12	0	1050
	NSF	6	0	500
	NASA	1	0	?
Subtotal		30	1	6660
High Temperature Turbines	DOD	1	0	3910
	NSF	1	0	120
	EPA	2	2	50
	NASA	3	0	40
Subtotal		7	2	4120
Ocean Thermal Gradient	NSF	13	2	1440
	NASA	1	0	?
	ERDA	13	1	1360
Subtotal		27	3	2800

Continued

*The primary source of this information is the Smithsonian Science Information Exchange (SSIE). Not all federal agencies supply notice of research projects to SSIE, therefore the above information is probably incomplete. Other sources of information include contacts with agency or contractor personnel.

**1975 grant and contract funds.

Table 2 (Continued)

Energy System	Sponsoring Agency	Number of Studies	Environmentally Related Studies	Federal Funds, $\$10^3$
General or Multi-System Studies	NSF	2	1	1120
	ERDA	3	2	925
	EPA	1	1	25
Subtotal		6	4	2070
Thermionic	ERDA	1	0	450
	NASA	4	0	30
Subtotal		5	0	480
Potassium Topping Cycles	ERDA	1	0	300
Electrogasdynamics	DOD	5	0	220
	NSF	1	0	40
Subtotal		6	0	260
H_2 Fuel Cells	NASA	1	0	140
	NSF	1	0	30
	EPA	2	1	20
Subtotal		4	1	190
Thermoelectric	DOD	1	0	90
	NASA	2	0	?
	ERDA	1	0	40
Subtotal		4	0	130
Total		144	12	26,630

Table 3

RECOMMENDED ENVIRONMENTAL R&D PRIORITIES FOR CANDIDATE ADVANCED ENERGY SYSTEMS

Energy System	Type of Emission	Control Technology Needs	Indirect Effects
MHD	Alkali Salt Seed NO_x	Seed Collection Combustion Mods.	Effect on Animal and Plant Life
Hydrogen Fuel Cell	Leachate Sludge	Define Control Technology Needs	To be Determined
Windmills	—	—	Weather Modification Land Use Aesthetic
Ocean Thermal Energy Conversion	Undersea Plumes, Spills, Leaching	To be Determined	Addition of Nutrients to the Surface Waters Effect of Cold Water on Surface Marine Life and Weather Shipping Lane Interference
Potassium Topping Cycles	Potassium	Define Control Technology Required	Effect on Animal and Plant Life
Gas Turbines	NO_x	Combustion Modification, etc.	Smog Acid Rain
Thermionic Electrogasdynamics	SO_x, NO_x, Fly Ash	High Temperature Control Technology	Similar to Conventional Coal Fired Steam Plants

Table 4

RECOMMENDED TIME PHASE FOR ENVIRONMENTAL R&D OF CANDIDATE ADVANCED ENERGY SYSTEMS

Energy System	R&D Task	Technology Breakthrough**	Earliest Expected Widespread Commerical Use	R&D Task*	Current Development Status for Utility Power Generation
MHD	Seed Collection Device Efficiency, NO_x Control	1985	2000	1976	Experimental Units Have Been Demonstrated
Hydrogen Fuel Cells	Control Technology Definition	Existing	1995	1976	Demonstration Unit in Operation
Windmills	Environmental Assessment of Weather Modification	Existing	2000	1976	Demonstration Unit in Operation
Ocean Thermal Energy Conversion (OTEC)	Environmental Assessment of Undersea Plumes and Upwelling	1990	1990	1976-1977	Conceptual and Feasibility Studies
Potassium Topping Cycles	Environmental Assessment to Identify Emission Sources, Rates and Control Technology	1980	1990	1976	Experimental Unit Under Construction
High Temperature Gas Turbines	Design Most Effective Control Technology for Low Grade Petroleum Fuel	Existing	1980	1976	Production
Thermionic Electrogasdynamic	Define High Temperature Control Technology Requirements	1976 1976	2050 2000	1976 1976	Experimental Conceptual
Thermoelectric	Unknown	Unknown	Unknown	Unknown	Current Efforts Limited to Space Applications Due to Extremely Low Efficiency

*Order of R&D Priorities

- High Temperature Gas Turbines, OTEC, Windmills
- MHD, Potassium Topping Cycles, Hydrogen Fuel Cells,
- Thermoionic, Eletrogasdynamics, Thermoelectric.

**Not necessarily for utility or electrical power applications.

are considered to be impractical. However; operating as a topping cycle, these systems can quite possibly be utilized to increase the thermal efficiency of the power plant. As noted in Table 4, thermoelectric conversion, as a result of very low efficiencies, is considered impractical for utilization in any manner in the production of electrical power on a commercial basis.

Section 3
MAGNETOHYDRODYNAMICS

3.1 DESCRIPTION OF THE SYSTEM

The magnetohydrodynamic (MHD) generator produces electrical energy directly from thermal energy. It is a heat engine that combines the features of the turbine and generator of the conventional steam plant by replacing the rotating wire conductor with an electrically conductive fluid. Three variations of the MHD concept have received consideration for power generation:

Open Cycle System: The working fluid is generated by combusting a fossil fuel. The combustion products are made conducting by seeding with an easily ionizable element, such as an alkali metal, and by elevating the combustion gas temperature by feeding the combustor with preheated air. The gases are accelerated to high velocities by converting their thermal energy to kinetic energy through the use of a subsonic to supersonic expansion nozzle. The magnetic field is positioned in the supersonic portion of the nozzle. The gases are then cleaned and allowed to exhaust from a stack.

Closed Cycle System: The closed cycle system is conceptually the same as the above open cycle system. The primary difference between the systems are: (1) the conduction gas is circulated in a closed loop. Since the working fluid is never lost there is more latitude available in choosing the working fluid and in obtaining electron densities that give sufficient conductivity, and (2) the thermal energy is provided by a nuclear reactor or by an externally fired source.

Liquid Metal System: In this system a liquid metal is mechanically pumped through the magnetic field.

The present state of MHD technology indicates the open cycle system is the most promising "near term" candidate energy system. Both the open and closed cycles are considered to offer sufficient energy generation potential to warrant further development. The open cycle system is closer to development than the closed cycle system (Ref. 1). The closed cycle system has basic problems of enthalpy extraction, generator and diffuser efficiency which must be solved. The liquid metal system has primarily been oriented toward space power systems where the elimination of rotating machinery is the objective.

The abundance of domestic coal makes it the most attractive candidate fuel for MHD power plants. Cesium is technically attractive for seeding the gases in the MHD generators. However, economics indicate that potassium is the material that will most probably be used. The MHD energy system that will be considered in the following discussion is the open cycle (Fig. 1, Table 5) which is coal fired and potassium seeded.

3.2 EFFICIENCY

MHD power systems have potentially higher efficiencies than conventional steam and other turbogenerator type energy conversion systems. First generation plants are envisioned to operate in the binary cycle mode. The MHD system would serve as a topping cycle to a conventional steam plant where the predicted overall plant efficiency is in the range of 46 to 50%. The ultimate efficiency is projected to be in the range of 55 to 60% (Ref. 2). The closed cycle MHD system appears to be capable of efficiencies of 50% when operating at temperatures on the order of 2900F. The liquid metal MHD power system is predicted to have overall efficiencies competitive with those of modern steam systems when operating at the same maximum cycle temperature and should have efficiencies approaching 50% at an operating temperature of 1600F (Ref. 1).

3.3 SIZE LIMITATION

Magnetohydrodynamic generators become more efficient with increase in size. This is because friction effects and heat losses become less significant as the MHD ducts become larger (i.e., surface-to-volume ratio decreases). The size limitations for the MHD central station power plants will be dependent on limitations of supporting equipment such as pumps, heat exchangers, etc.

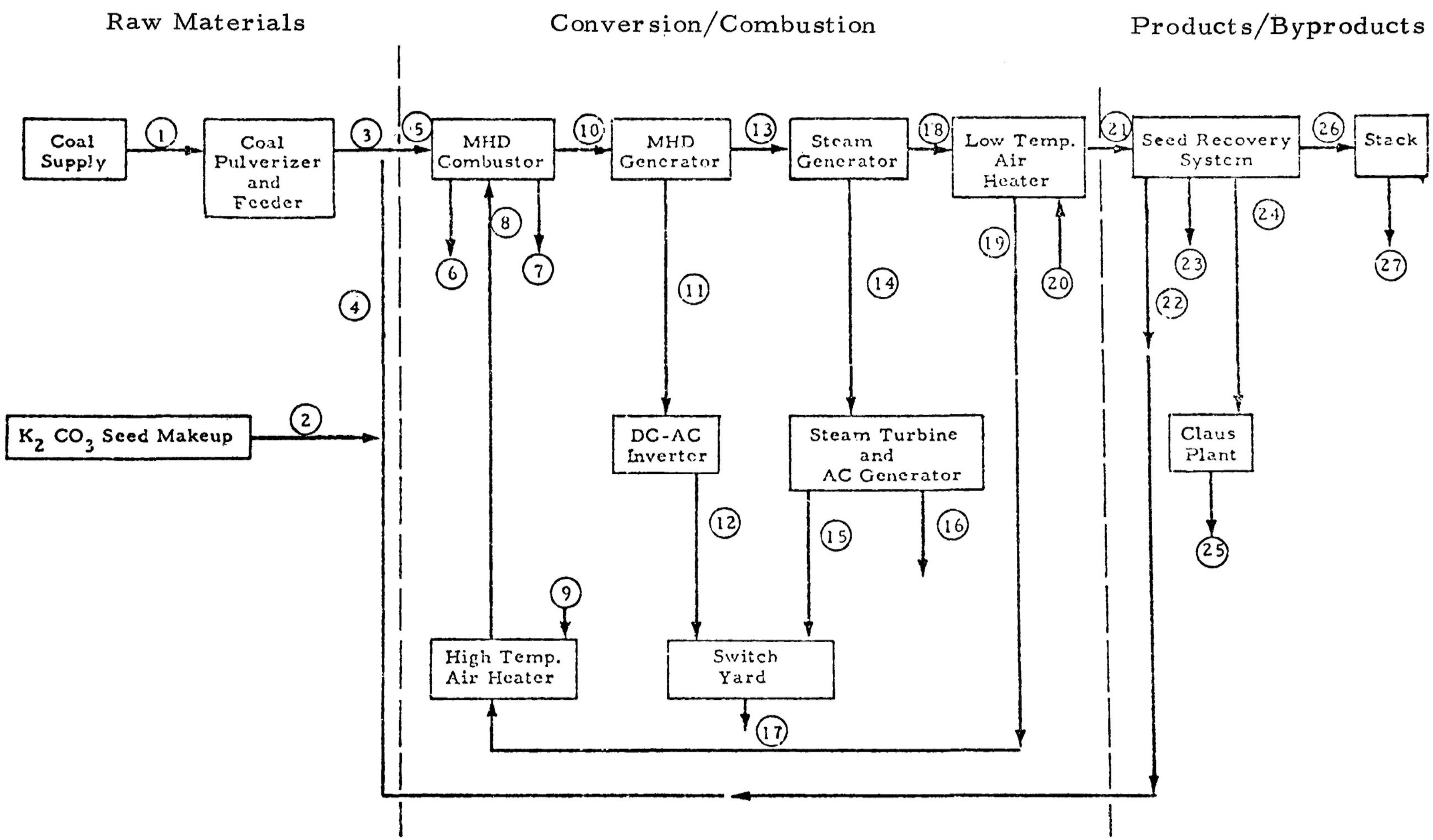

Fig. 1 - Unit Operations for an MDH Power Plant

Table 5

MHD POWER PLANT PROCESS STEPS DESCRIPTIONS

Station	Description
1	5.15×10^5 kg Coal/hr or 3.96×10^9 kcal/hr
	Coal Analysis: 8% Ash
	1.1% Sulfur
	7683 cal/gm
2	1210 kg/hr K_2CO_3 Seed Makeup
3	Pulverized Coal, 70% Through 200 Mesh
4	40,200 kg/hr K_2CO_3, Seeding Material
5	5.55×10^5 kg/hr Seeded Coal
6	Solid Waste: 30,900 kg/hr of Slag Rejected, 807 kg/hr K_2CO_3 Lost
7	Combustor Heat Rejected 5.54×10^8 kcal/hr
8	Combustor Air Feed at $\sim 1370^{\circ}K$
9	Air and Fuel for High Temperature Air Heater
10	Plasma at $2480^{\circ}K$
11	DC Current From MHD Unit
12	AC Current From DC-AC Inverter
13	MHD Exhaust Gases at $\sim 1700^{\circ}K$
14	Steam at $\sim 800^{\circ}K$
15	AC Current
16	Heat Rejected from Steam Turbine
17	2,300 MW Electrical Power Output
18	MHD Exhaust Gases
19	Heated Air (Low Temperature)
20	Air Supply
21	MHD Exhaust Gases
22	Recovered K_2CO_3, 39,000 kg/hr

(Continued)

Table 5 (Concluded)

Station	Description
23	Solid Waste:
	10,000 kg/hr of Fly Ash
	403 kg/hr of K_2CO_3
24	H_2S from Seed Recovery System
25	Usable Sulfur ~5600 kg/hr
26	Exhaust Gases
27	Gaseous and Particulate Waste
	860 kg/hr NO_2
	24 kg/hr SO_2
	515 kg/hr Particulates

3.4 DEVELOPMENT STATUS

MHD technology has developed primarily over the past 17 years. Initial developments were made in the United States, however major efforts are now being conducted in other countries, particularly the U.S.S.R.

The MHD generator will serve as the upper portion of a binary generation cycle. A conventional steam turbine driven generator will serve as the bottoming portion of the cycle. This development of MHD technology has centered not only on MHD generator components such as superconducting magnets, combustors, seeding techniques, etc., but also on components of the overall power generation system.

Two large experimental MHD generators for short duration operation were built in the middle 1960s to provide an understanding of the MHD process and to provide experimental data for prediction of MHD generator performance. Both were built by Avco under Department of Defense funding. The larger one, called the MK-V produced an output of 32 MW. The smaller one, located at Arnold Engineering Center, Tullahoma, Tennessee, had an output of 18 MW (Ref. 3). The smaller unit, called the LORHO, is presently being modified for performance demonstration experiments (Refs. 4 and 5). It is scheduled to be operational by mid-1976.

Several smaller units with power levels of a few kilowatts have provided design data and information regarding long-term operation of MHD generators under conditions simulating those in commercial power generation. These efforts have primarily been carried out by Avco, the University of Tennessee Space Institute and Stanford University (Ref. 3).

Efforts relating to the overall MHD system, seed recovery, and the environmental aspects of the system are being conducted by the ERDA's Pittsburgh Research Center (Refs. 6 and 7).

The U.S.S.R has an extensive MHD development program in progress. Their U-25 plant is a natural gas fired pilot plant with a designed output of

25 MW. It includes a dc to ac inverter and feeds power into the Moscow grid system. In addition to this facility the U.S.S.R. has three smaller facilities for research on specific aspects of the system. The U.S.S.R. is presently designing a 200 to 600 MW commercial demonstration generator (Refs. 3 and 8).

MHD efforts are also underway in Japan. The most significant of these efforts is the development of a small pilot plant. Other countries that have recently started MHD research are Germany and Poland.

3.5 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

MHD is presently at the stage of development that a demonstration plant must be constructed before MHD can progress to the point of making significant contributions to the U.S. energy needs. MHD units for emergency and peaking power may be available as early as the 1980's, however, it is the consensus of experts that it will be around the year 2000 before MHD will make significant contributions to the U.S. energy needs (Ref. 9).

3.6 COSTS AND BENEFITS

Although the technical feasibility of MHD power plants has been demonstrated, the concept is still in the developmental stage, and thus very little information has been developed on the projected economic benefits to accrue from central station MHD power plants. The higher efficiencies projected for the various MHD systems must provide sufficient fuel cost savings to compensate for the capital costs of the MHD systems. Most of the economic studies carried out have been for open-cycle plasma-steam systems. The first generation open-cycle MHD topping systems for electrical generating plants may conceivably compete successfully with conventional steam stations in areas of high fuel costs. Future nuclear power plants would have an economic advantage over open-cycle fossil-fueled MHD power plants only in areas where fossil fuel is relatively expensive.

3.7 APPRAISAL OF ENVIRONMENTAL ASPECTS

The effluent problems associated with MHD power plants are essentially those associated with the energy source (i.e., fossil, or nuclear fuel). For coal fired systems these have been found to be SO_2, NO_x, particulates and thermal. The MHD concept has the potential to reduce thermal discharge and conserve fuel supplies when compared with conventional power plants because they are predicted to have improved energy conversion efficiency. The total quantity of thermal emissions will be reduced in inverse proportion to the improvement in efficiency.

Seed material must be removed and recovered from the effluent gases for environmental as well as economic reasons. Seed materials being considered are alkali metal salts whose release to the environment as finely divided salts would be undesirable. Furthermore, the cost of these materials dictate that they be recycled for economic operation. The SO_2 emission is expected to be about 5 ppm which is orders of magnitude below the NSPS for fossil fuel fired facilities. Experimental studies have shown that 99.8% of the sulfur in 2.2% sulfur coal can be removed (Ref. 4). The NO_x emission is expected to be about 135 to 300 ppm (Ref. 13) or possibly lower depending on the cool down rate of the gases. In present experimental facilities as much as 95% of the particulates have been removed from the effluent gases (Ref. 13). The open cycle MHD system is estimated to meet or exceed EPA requirements for SO_2 and NO_x at costs that are predicted to be below burning 2% sulfur coal.

The need to reclaim seed material for the MHD system has provided for high efficiency particulate control. Experimental data indicates that particulate emissions will not be a problem. Consequently, it appears that emission control technology for MHD systems is adequate.

3.8 MHD RESEARCH

A substantial number of government and non-government agencies have assumed active roles in the U.S. commercial MHD electric power development effort. The Energy Research and Development Administration, through its MHD Project Office, has been assigned the lead role in the national program, in which capacity it has established a centrally organized national research program on MHD involving a large number of U.S. institutions, e.g., Avco Everett Research Laboratory, University of Tennessee Space Institute, Massachusetts Institute of Technology, Stanford University, General Electric Company, Westinghouse Corporation, MEPPSCO, Inc., Argonne National Laboratory, National Bureau of Standards, STD Corporation, Arnold Engineering Development Center, Fluidyne, Pittsburgh Energy Research Center, and others. Other U.S. Government agencies such as the National Science Foundation, the National Aeronautical and Space Administration, and the Office of Naval Research, are also funding MHD research directly, as is the Electric Power Research Institute (Ref. 13).

In calendar year 1974, the MHD program was significantly expanded through the availability of a total worldwide budget of $7,750,000 in FY 74 and $12,500,000 in FY 75 (Ref. 14). Table 6 gives the funding in MHD research outside the U.S.

Table 6

MHD RESEARCH LEVELS OUTSIDE THE U.S. (REF. 14)

Country	Financing	Institutions	Remarks
Switzerland	1968-1972: FS 2.1 million	Commission federale pour l'encouragement de la recherche scientifique. Government aid temporarily suspended; new possibilities being studied. Research carried out at Institut Battelle, Geneva.	Direct conversion into electricity by closed cycle process.
Japan	Yen 6.4 billion from 1966 to 1975	MITI (Ministry of International Trade and Industry).	Research on long-term operation, heat exchanger, seed recovery, heat-proof materials, superconducting magnets; this work is centered on a 1,000 KW MHD test plan.
Netherlands		Universities	
Sweden	SK 0.4 million p.a.	AB Atomenergi	Exploratory work on open-cycle MHD systems.

Section 4
HYDROGEN FUEL CELLS

4.1 DESCRIPTION OF THE SYSTEM

The fuel cell (Fig. 2) is a device that produces electrical energy from the controlled electrochemical oxidation of fuels. The basic components of a simple hydrogen-oxygen fuel cell are the electrodes (anode and cathode) and the electrolyte, which can be either acidic or basic. The reactants are normally consumed only when the external circuit is completed, allowing electrons to flow and the electrochemical reaction to occur. When the external circuit is completed, an oxidation reaction, yielding electrons, takes place at the anode and a reduction reaction, requiring electrons, occurs at the cathode. The electrodes provide electrochemical-reaction sites and also act as conductors for electron flow to the external circuit.

Continuous operation of the cell necessitates the removal of heat, water and any inert material that enters the cell with the reactants. Reaction kinetics are usually enhanced by the incoroporation of a catalyst, such as platinum, on the high surface area electrode surfaces. Power is produced as long as fuel and oxidant are supplied to the fuel cell and the external circuit is closed, allowing current to flow.

Hydrogen fuel cells are not currently envisioned as primary energy sources (i.e., baseload power generators). Their application appears rather to be in peak load demand application, or for dispersed generation of electrical power in residential or small community sites, or at electrical substations.

Two modes of hydrogen generation are currently under development (Ref. 15) for fuel cell operation: (1) steam reforming of hydrocarbons and coal, and (2) electrolysis of water.

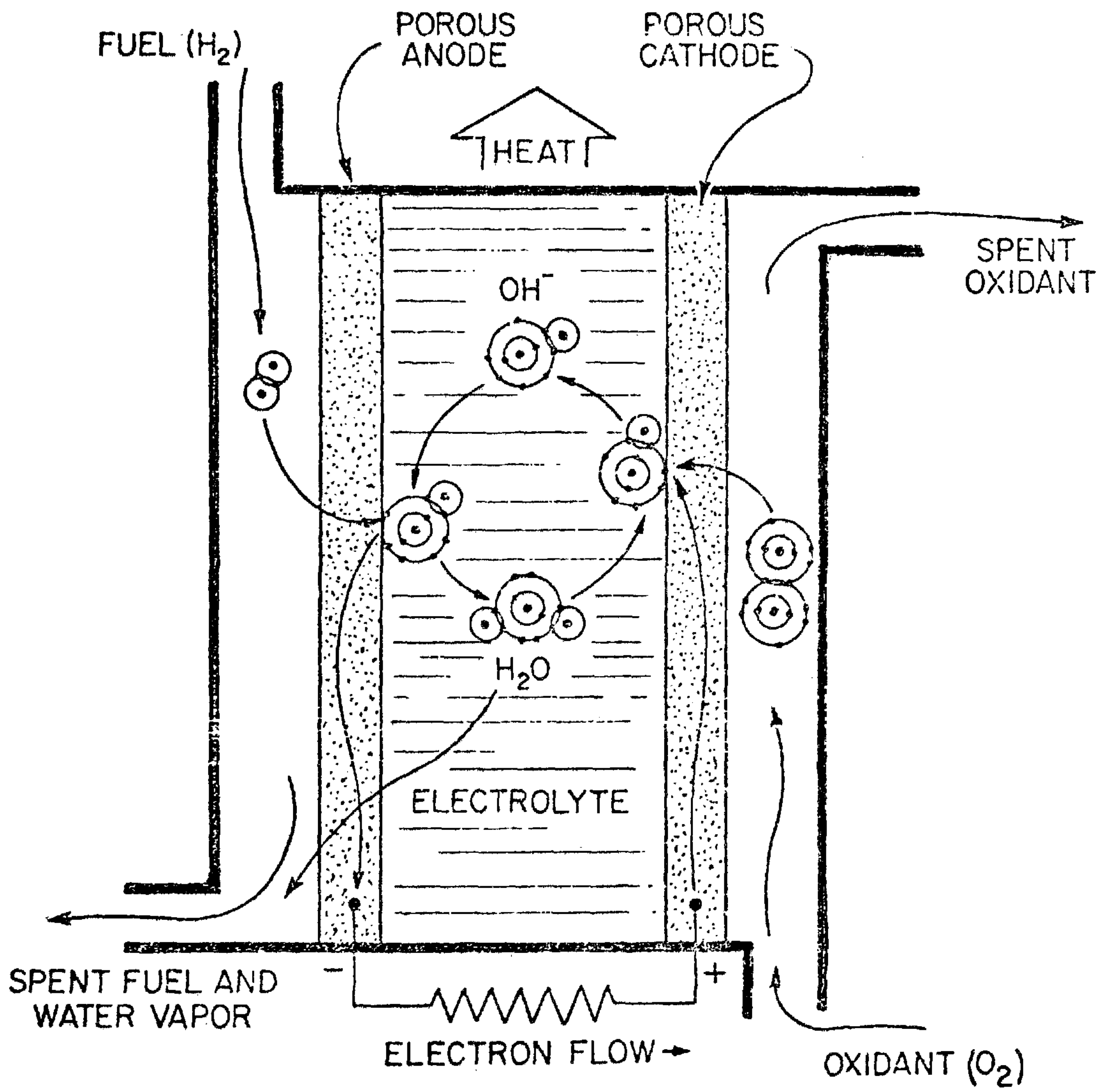

Fig. 2 - Electrochemical Oxidation of Hydrogen in a Fuel Cell

Steam reforming is an alternative mode of fossil fuel combustion. Effluent from the fuel cells provides heat to reform hydrocarbons, such as natural gas, and yields a hydrogen-carbon dioxide mixture. Heat produced in the cells is also used to preheat the water used in the reforming reaction. If given proper treatment, hydrogen can be used directly in the fuel cells as can the fuel gas from coal gasification.

The electrolysis of water to produce hydrogen and oxygen is an energy storage and/or transmission application. This method is quite suitable for utilization in conjunction with nuclear power plants which operate most efficiently when generating in the base load power demand mode. During nonpeak power demand periods, excess power from the nuclear plant is utilized to produce hydrogen and oxygen from the electrolysis of water which could be then used in fuel cells during later peak demand power period to reconvert to electrical energy.

4.2 EFFICIENCY

The theoretical maximum efficiency of a fuel cell is a function of the fuel and oxidant used. Where systems are integrated, as with a reformer, the theoretical efficiency is based on the primary feed material rather than on the fuel that is electrochemically oxidized. Projected reference efficiency limits (Ref. 1) based on laboratory investigations and system studies are given in Table 7.

Table 7
FUEL CELL EFFICIENCIES

Fuel	Cell Voltage	Theoretical Cell Efficiency	Projected System Efficiency, 1980
Hydrogen	1.23	0.83	0.65
Methane	1.06	0.92	0.30 - 0.55
Coal	1.02	1.00	0.70

Gross efficiency is the product of the theoretical maximum efficiency and the ratio of the operating voltage to the theoretical voltage. For hydrogen-fuel cells, this efficiency today is 0.54 to 0.61.

Because of extensive heat transfer and mass transfer interactions, subsystem efficiencies cannot be multiplied to determine the overall efficiency of integrated fuel cell power system. The present published efficiency of conversion of chemical energy from natural gas fuel to ac electrical energy for the 12.5 kW Pratt & Whitney system (Ref. 15) is 40 to 45%. The large central-station version of this system is projected to have an overall efficiency of nearly 55%. The Westinghouse high-temperature system concept was estimated to be able to operate at a projected efficiency of 58% for the 100 kW size and at nearly 70% for 1000 MW based upon dc output.

4.3 SIZE LIMITATIONS

Several fuel cell power generation systems in the 10 to 20 kW range have been constructed and operated. The modular construction of fuel cells and power-conditioning equipment allows a nearly direct proportional scaling into the multi MW range. Plumbing, wiring and fault-isolation equipment requirements are also nearly proportional to the system power capability. Fuel conditioning and control equipment have a scaling factor of 0.9. Systems can be demonstrated in small sizes, and full-scale systems can then be produced by conventional engineering techniques. Systems using fuel reforming or high-temperature cells are significantly more efficient in large sizes (> 100 kW) due to the reduction in external surface area per unit volume.

4.4 DEVELOPMENT STATUS

Several fuel cell power generation systems in the 10 to 20 kW range have been constructed and operated. The modular construction of fuel cells and power conditioning equipment allows a nearly direct proportional scaling into the multi-MW range. No control stability or complexity problems are introduced in paralleling fuel cell banks to construct large systems. In fact, overall system reliability is improved through load sharing in multistack systems and as a result of the capability to replace modular units on a programmed basis.

Two approaches are currently being followed in the development of the hydrogen fuel cell application to electrical power plants. These are for central station (i.e., base load) application (Ref. 1) and for dispersed generation of electrical power in residential sections, small communities or at electrical substations. Work on the central station application is still in the laboratory and system study phase. Westinghouse, until 1970, was engaged in development work (Ref. 16) for the Office of Coal Research and had developed a preliminary design for a 100 kW system based on gasification of coal and a high-temperature (1870F) zirconia electrolyte fuel cell. The system uses high-temperature materials in the construction of the fuel cell. A porous nickel anode, a stabilized zirconia electrolyte and a porous, tin-doped, indium-oxide cathode are deposited on a 0.5 inch diameter porous, stabilized zirconia tube with appropriate cell interconnections. The total system consists of fuel cell battery tubes assembled into banks, a coal gasifier and ancillary equipment. Cell banks which operate at 1850F are physically located in the fluidized-bed coal gasifier for maximum heat recovery. System development did not proceed beyond the preliminary design stage and is currently suspended.

Pratt & Whitney has a major program for dispersed generation using natural gas reformers and low-temperature (< 250F) fuel cells of the phosphoric acid and potassium hydroxide electrolyte types. The Institute of Gas Technology has been doing complementary work using low-temperature phosphoric acid and higher-temperature (2200F) molten carbonate electrolyte cells. All the above fuel cells will also operate on the fuel formed from coal gasification. This work has been sponsored by segments of the gas industry, American Gas Association, and most recently by the Edison Electric Institute (EEI).

Fuel cells of the type under development by Pratt & Whitney are of the plate and frame type. Simple components produced in high volume are assembled into series stacks and either bolted or bonded together. Flow passages, a porous catalyzed nickel anode, an electrolyte-saturated matrix and a porous catalyzed cathode make up the unit cell. Phosphoric acid is used as the electrolyte by Pratt & Whitney, platinum-rhodium alloy as the anodic catalyst, and platinum as the cathodic catalyst.

In the Pratt & Whitney system, the cells operate at about 230F. This system burns the effluent from the fuel cells to provide heat to reform hydrocarbons, such as natural gas, yielding a hydrogen/carbon-dioxide mixture. (Heat produced in the cells is also used to preheat the water used in the reforming reaction.) Given proper pretreatment, hydrogen can be used directly in the cells as can the fuel gas from coal gasification. Thermal and electrical output from nuclear reactors can be used to produce hydrogen and oxygen via the electrolysis of water. In this manner fuel cells have the potential to become an integral part of electrical systems (Ref. 17) for the dispersion of electrical power. However, it is not known at this time if this approach is being seriously investigated.

Although there have been many successful programs resulting in numerous fuel cell systems for specialized applications, dominant uncertainties remain with respect to commercial power applications because of a lack of:

- Detailed engineering design of low-cost systems
- Detailed design of fuel cells for high-volume production and long life
- Demonstration of the costs, lifetimes, efficiencies, and operational parameters of the projected systems.

Fuel cell systems have been manufactured to date on a limited production basis for space application. Currently five organizations are capable of producing such systems in quantity (Ref. 1): Pratt & Whitney, General

Electric, Westinghouse, Union Carbide Corporation and Alsthom. None is actively marketing commercial systems of significant size. Pratt & Whitney recently conducted extensive field tests of its 12.5 kW natural gas system.

4.5 COSTS AND BENEFITS

Since no large fuel cell power systems have been built, an estimate of the costs is somewhat speculative. Costs, however, have been projected for the coal-fired, high-temperature system by taking into account research and development progress to date and comparing unit costs of various elements with similar items in a coal-fired, steam-turbine power plant. By assuming that the cost of electricity produced by a coal-fueled fuel cell system is equal to that from a steam turbine system, the allowable capital costs for the fuel cell system can be projected. The result of these assumptions and calculations is to suggest that a coal-fueled fuel cell system can produce competitively priced electricity if it can be built for a total capital cost of $294 to $374 per kilowatt electrical. The three critical items are the fuel cell, power inverters and spare parts. Each of these has projected cost ranges that will allow reaching the cost target.

The key item is the cost of the fuel cells. The cost range allocated, $60 to $80 per kilowatt electrical, corresponds to a manufactured cost of $7.00 to $9.30 per pound based on the materials requirements. Total materials costs for these thin-film, solid-electrolyte fuel cell assemblies have been estimated to be about $21 per kilowatt electrical ($2.45 per pound), leaving an allowable margin for manufacturing and assembly of $39 to $59 per kilowatt electrical ($4.55 to $6.85 per pound). These allowable manufacturing costs show reasonably good agreement with independent direct estimates.

The major projected advantage of fossil-fueled, fuel-cell systems for central station power generation is that they operate at a higher conversion efficiency than is possible with any system presently in use. This higher efficiency results in a lower rate of fossil fuel reserve depletion, reduced air pollution and no thermal pollution of natural bodies of water. Projected economics of central station fuel cell power systems show equivalent capital costs and lower operating costs. For dispersed generation of electrical power using fuel cells, the capability for gaseous fuel storage at the point of usage allows a degree of freedom not found in present electrical distribution systems. Coupling a hydrogen fuel cell system to a nuclear powered hydrogen production facility offers several additional potential advantages:

- Improved load factor for the nuclear plant because it is producing a storable fuel
- Enhanced hydrogen supply for use in the chemical and metallurgical process industries as well as for heat in homes and industrial plants, compared with that currently available from hydrocarbon sources
- Pollution free generation of electricity at points of use.

4.6 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

The system being developed by Pratt & Whitney offers the most promise for any near term contribution to U.S. energy needs. The major effort by Pratt & Whitney started in 1967 with the first phase becoming a six year $50 million program. This effort, presently sponsored by 31 gas utilities that make up the Team to Advance Research for Gas Energy Transformation (TARGET) group, has the goal of developing fuel-cell systems using reformed natural gas (methane) as fuel. The developmental work is being done by Pratt & Whitney, who in May 1971 demonstrated a 12.5 kW system supplying all of the electrical energy to a home in Connecticut. This was the first of 60 test installations of various capacities planned, about 50 of which had been installed as of 1 June 1974 (Ref. 1). More than 4000 hours of automatic operation were demonstrated before refurbishing was required.

Pratt & Whitney, in December 1973, announced a $42 million cooperative program with nine electric utilities to develope a 26,000 kW fuel cell. This level of power is sufficient to provide electricity for a community of about 20,000 people, and the manufacturer has estimated that deliveries of these units can begin as early as 1978. The application is dispersed power generation, as with the TARGET program, but in this case the unit of power is larger. The fuel will likely be distillate oils at first, with heavier oils coming later (Ref. 18).

When the constraints of economics and operating lifetime are imposed, the feasibility of wing fuel-cell systems for central station or dispersed power generation is undetermined. The most probable application of hydrogen powered fuel cells will be in peak power demand applications. However, fuel-cell technology is no longer receiving significant funds (Ref. 1). The result is that this energy source is unlikely to contribute significantly to alleviating the U.S. energy needs until 2000 (Ref. 9).

4.7 ENVIRONMENTAL CONSIDERATIONS

Central station systems using fuel cells will produce chemical pollutants similar to those obtained by conventional combustion of the same fuels. The fuel cell, however, is particularly sensitive to the same pollutants, primarily sulfur, now causing concern in conventional steam turbine generator plants. This sensitivity will require extensive fuel pretreatment to eliminate contaminants prior to electro-chemical oxidation. For an equivalent electrical power output, the higher operating efficiency of fuel cell systems will result in a reduction of the total quantity of fuel required and a reduction in the quantity of material discharged in the emission of nitrogen oxides because of the reduced temperatures to which the air streams are exposed. Waste heat rejection is not a significant problem with fuel cell power systems since most of the waste heat is used in the fuel gasification or reforming process. Excess heat is rejected to the atmosphere, and cooling water is not required.

Large numbers of low-temperature fuel cells could have some impact on the catalyst material market and on the natural reserves. However, the catalyst is not consumed except for processing losses, and the total quantity available will be relatively unchanged. The total effect of this utilization of catalyst materials is unknown. (This is a problem common with certain pollution-control equipment being considered for internal combustion engine powered automobiles.)

Increased utilization of dispersed generation of electrical power, made possible by the high efficiency of relatively small fuel cell systems, should have a positive effect on the environment, particularly in urban areas. Gas transmission by buried pipeline requires less land for an equivalent amount of energy transmitted, but the total environmental impact of buried pipelines has not been thoroughly evaluated. The remote locations envisaged for fuel processing plants and the chemical removal of sulfur at these plants should result in a positive environmental effect.

Potential water pollution effects will be limited principally to production of leachate from the fuel cells and sludge disposal from the electrolysis process. However, these waste streams are amenable to treatment using established technology.

Indirect effects relate principally to land use and facility construction on remote sites. These will have to be examined on a per case basis.

4.8 RESEARCH AND DEVELOPMENT CONSIDERATIONS

Before the use of hydrogen as a fuel increases substantially significant changes in production and consumption technologies are likely (Ref. 19). Control requirements should include:

- Establishment of emissions and effluent standards covering the materials suggested for use in high efficiency electrolyzers, high temperature thermal decomposition of water and fuel cells

- Establishment of design guidelines to steer development away from selection of materials that require large amounts of energy or that have large known detrimental environmental impact during their production process.

To ensure that adequate environmental protection measures are incorporated in the development of hydrogen for energy storage and transportation, a periodic review of this development should be carried out. Should environmental or economic attractiveness imply a more rapid move toward deployment of hydrogen technology, a continuing review would be desirable.

Section 5
OCEAN THERMAL ENERGY CONVERSION

5.1 DESCRIPTION OF THE SYSTEM

At many places in the tropical and subtropical regions of the world, ocean surface temperatures are in the 75 to 85F temperature range. The warm surface layer circulates toward the poles where it cools. It then flows back along the deep ocean trenches. In these lower ocean layers (approximately 2000 feet below the surface) the water temperatures are 35 to 45F. This temperature difference between the surface and lower depths has been shown (Refs. 20 and 21) to be adequate to drive a Rankine cycle heat engine.

Both open and closed cycles have been considered. The first plant designed and operated off the coast of Cuba was a French-built open Rankine cycle. It's operation depended upon evacuating a chamber to 0.03 atmospheres at which the warm sea water would flash vaporize. The resulting low density steam drove a turbine and then condensed in a second evacuated chamber by direct contact with cold sea water falling like rain. A plant constructed in this manner designed to develop significant (100 MW) power would require turbines with very large rotors and matching ducts (Ref. 22). A recent study (Ref. 23) indicates that the forces on the turbine blades could be met by low mass structures similar to sailplane wings, which need not be expensive.

To most investigators use of the closed Rankine cycle appears to be the more favorable approach. Instead of evaporating the sea water to drive a turbine, a working fluid operating in a closed loop (Fig. 3) is used to drive the turbine. This is accomplished by evaporating the working fluid at 70F via a heat exchanger with the warm sea water. Candidate working fluids are water vapor, ammonia, propane and Freon (Ref. 1). Ammonia or propane are currently receiving the most attention. For example, ammonia has a vapor

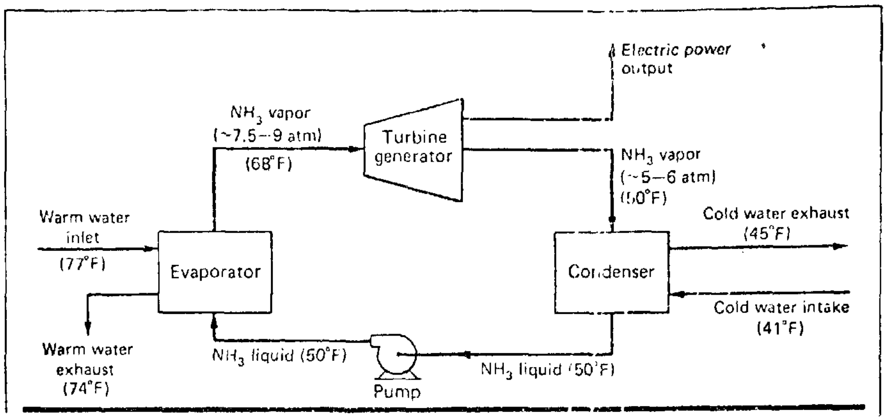

Fig. 3 - Schematic of Closed Cycle Rankine Engine Showing Typical OTEC Parameters

pressure of 8.7 atmospheres at a temperature of 70F so that the turbine can be two orders of magnitude smaller than in the open cycle (Ref. 22). After driving the turbine the ammonia is recondensed at 51.2F by heat exchange with 40F water drawn from the lower ocean depths.

5.2 EFFICIENCY

The closed cycle systems operate on an overall ocean temperature difference of only 68F ($\pm$7F depending on plant location, pipe depth and perhaps the season). Temperature differences in the evaporator and condenser (from sea water to working fluid) are 9F each. Thus only 18F is left for driving the turbine. This yields a theoretical Rankine cycle efficiency (defined as the working fluid's enthalpy change through the turbine divided by its enthalpy change through the evaporator) of only 3.3% (Ref. 22). However, when the pumping power required for the warm sea water, the cold sea water and the working fluid and the efficiencies of the pumps, turbines, and generators are taken into account, the theoretical 3.3% drops to a real net efficiency of only about 2.5%.

5.3 SIZE LIMITATIONS

Size does not presently appear to be a problem. Because of relatively small temperature differences, the evaporation and condensation steps in the cycle require about 4 to 6 million square feet of heat exchange surface per 100 MW of capacity (Ref. 24). Final assemblies are predicted to be about the size of a modern supertanker tunnel on end, and they would float partially above water or be completely submerged. Existing shipyards have the capabilities to construct the assemblies which could be completely assembled at the shipyard and towed to sea or be assembled at sea.

5.4 DEVELOPMENT STATUS

The use of ocean thermal gradients to produce electrical energy on a commercial basis is still in the conceptual design stage. Conceptual designs for working plants have been drawn up, but some problems need more study before a prototype design can be considered. The biggest problems are centered on the heat exchangers for handling the low-quality thermal energy inherent in the concept. Current studies are focusing on increasing the heat transfer efficiency in order to reduce their size and cost and on forestalling problems of biofouling in the marine environment (Ref. 29).

ERDA currently has 30 contracts with companies, universities and government laboratories. The objective is to yield enough information and advances in design to erect a pilot plant by late in this decade and a 100 MW prototype before the mid-1980s. Two contractors (TRW Systems and Lockheed Missiles & Space Company) are currently performing conceptual preliminary design for Rankine-cycle based units.

5.5 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

The relatively low thermal efficiencies and necessity to transmit power from offshore virtually preclude the use of OTEC facilities for commercial power generation. The most attractive thermal gradients are found along the earth's tropical belt where the existing demand for electric power in general is lowest. However, OTEC plants might find their main function as power sources for chemical process facilities (Ref. 24). As an energy storage device the OTEC power output can be used in the production of hydrogen which can be shipped to shore for later conversion to electrical energy or other uses. Ammonia can also be produced.

Energy produced via OTEC facilities for widespread commercial use is predicted by the year 2000 (Ref. 19).

5.6 COSTS AND BENEFITS

If the costs of heat exchangers can be kept down ERDA feels that the concept is attractive despite its low thermal efficiency. Projections of cost (including transmission to shore) indicate it has the potential to be competitive with other means of electrical power generation. TRW foresees operating costs of 35 mills/kWh for its prototype and 20 mills for production units compared to 28 to 33 mills for conventional electricity generation. Lockheed figures are 36 and 21 mills, respectively, with construction costs about $200 million per platform or $1,250/kW. TRW feels that units from its design would cost about $1,000/kW.

The chief benefit to be derived is that the initial costs are the primary costs since no fuel need be purchased to supply energy to the system. Current projections for ammonia indicate a demand of 10 million tons per year by 1985, but new plants may not be able to get natural gas from domestic sources. Twenty-one OTEC plants of 500 MW size could supply the required energy to manufacture 10 million tons per year of fertilizers and chemicals. Other energy-intensive products that could be made at sea include aluminum (from alunina produced from bauxite on shore), magnesium, methanol, sunthetic and liquid hydrogen (Ref. 22). For the long term, liquid hydrogen might become the largest volume product of tropical OTEC plants.

5.7 APPRAISAL OF ENVIRONMENTAL ASPECTS

The OTEC concept as an energy-producing system has received little attention with respect to its impact on the environment. Preliminary indications are that the major influence on the environment will be from indirect effects, though some direct effects should be investigated, including leaching of materials, spills of working fluid, upwelling and undersea plumes from evaporators and condensers.

No appreciable environmental impacts from effluents are foreseen for OTEC plants supplying electric power to shore or making liquid ammonia or liquid hydrogen at sea. For production of other products, the question of effluent wastes will have to be addressed. The effect of the undersea plumes from evaporators and condensers is not known, nor is the potential value of upwelling as a source of nutrients for mariculture. Leaching of materials or spills of the working fluid can occur from an OTEC plant, but the effect is not currently known.

Indirect effects from the OTEC plant include interference with shipping lanes and ecological conditions. Interference with shipping lanes may occur as a result of the number of units and the shear size of each unit required to produce a desired amount of energy. Ecological aspects which must be considered are the effects on warming of surface films and plant breakwater marine life in the area along with littoral drift.

5.8 EVALUATION OF RESEARCH AND DEVELOPMENT REQUIREMENTS

Efforts in research and development should be directed as follows:

- Establish siting limitations for clustered plants
- Assess value of upwelling as a source of nutrients for mariculture
- Assess effect of leaching of materials and spills of the working fluid
- Assess effects of discharged undersea plumes from the evaporators and condensors.

The operation of an ocean thermal conversion plant will alter the local surface temperature, the temperature gradient to depth, and possibly increase local turbulence and currents. These effects, plus the possible biological "pasture" or the artificial surface film (if used to increase surface temperature) will affect the local albedo and the overall energy balance in the vicinity of the plant. The net effect is currently unknown.

ERDA's present plans call for a 100 MW_e sized prototype hull with a 25 MW_e power module to be completed by 1983. A demonstration plant consisting of the same hull but refitted with four advanced power modules is scheduled for completion in 1985.

Section 6

WIND POWER

6.1 DESCRIPTION OF THE SYSTEM

Man's use of the wind dates back many centuries (Ref. 26). The ancient Chinese and other eastern peoples used windmills to pump water and employed sails to drive ships. The Crusaders carried the windmill concept from the Middle East to Europe. Later, the windmill became an important part of rural America, especially in the Midwest. Water pumping was the primary application, but many windmills were employed to generate electricity for farm lighting. Lead-acid storage batteries were used to store energy for use during calm periods. Electrification of rural areas along with the availability of low cost, internal combustion engine powered pumps led to the decline of the windmill; however, some are still in use in remote areas.

The kinetic energy of the winds can be used to produce mechanical energy or electric power. The potential amount of wind energy available is very large. For example, the estimate (Ref. 27) has been made that the energy potential of the winds over the continential United States, the Aleutian arc, and the eastern seaboard is equivalent to 10^8 MW. The most promising regions for wind power applications (Ref. 28) are the New England and Middle Atlantic coasts, along the Great Lakes, Gulf Coast and Aleutian Islands and through the Great Plains, Rocky Mountains and Cascade Mountains.

The capability of a wind machine to exchange momentum is a function of its aerodynamic shape and size; its location in the wind stream, whether its blades are fixed in pitch, controlled in pitch to maintain a synchronous shaft speed, or controlled in pitch to maximize momentum exchange; and whether there is any interference with optimum wake expansion. The best machines are the so-called modern high-speed propeller machines with three or two very-high-aspect-ratio, thin, carefully twisted blades. The less efficient the machine however, the easier it is to start at a low cut-in speed, and the smaller the machine, the lower the cut-in-speed. One can immediately see where cost becomes related to very high efficiency, but machines of very good efficiency can be simple and thus relatively inexpensive and reliable.

The most simple configuration is probably that of a single modern high speed wind generator atop the tallest western cedar pole that can carry it in the expected wind regime, with account taken of storm and ice loadings. The best location for the most simple configuration is in a clear area. If the terrain is wooded, the machine will produce well, depending upon how much clearance is provided between tree tops and the swept diameter. From the most simple configuration one can progress down the path of added complexity and cost and added productivity of grouping machines. Where the winds are light to moderate, arrays of large numbers of small machines can produce a significant annual yield, whereas larger machines might not. Larger machines are more economical when the winds are moderate to strong. Concepts for the placement of large numbers of small-to-medium-size wind generators, which share support cost, lead to: (1) structural space array on top of towers, and (2) cable-suspended arrays that would be analogous to hydroelectric dams. Step-by-step transition from a single machine atop a pole to a large number of machines in cable suspension systems can be seen in Figs. 4, 5 and 6.

Traditionally, a wind conversion system comprises a support tower, a rotor, a step-up transmission, and an energy converter, such as an electrical generator or a water pump. A control system can adjust rotor blade pitch and rotate a platform at the top of the tower to keep the rotor facing into the wind. The transmission and energy converter usually surmount the tower; but in some designs the rotor joins a generator or water pump at the base of the tower through a set of bevel gears and a long vertical shaft.

Horizontal axis rotors are the best developed and understood and aerodynamically the most efficient (Ref. 28). However it appears that, for the near

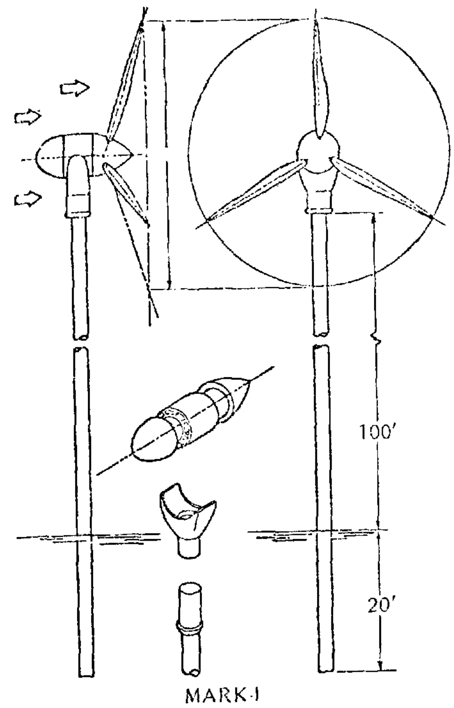

Fig. 4 - MARK-I 20 kW Wind Generator on Single Pole Support

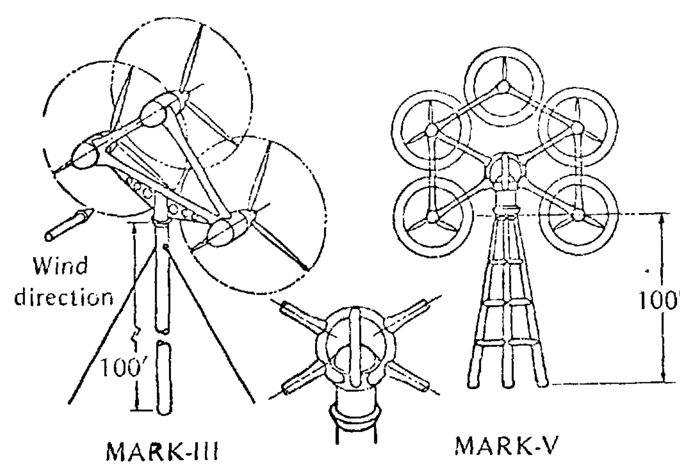

Fig. 5 - MARK-III 60 kW Wind Generator on Stayed 100 ft Pole and MARK-V 100 kW Wind Generator (520 kW Machine) on 100 ft Tower

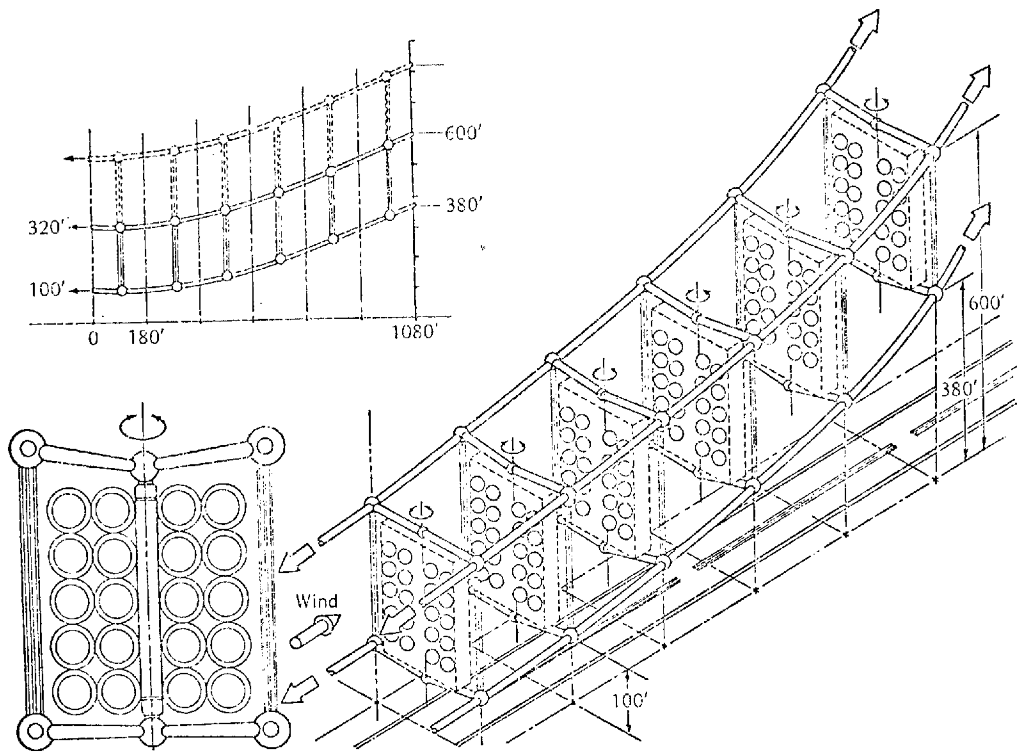

Fig. 6 - Proposed Wire Rope and Kingpost Wind Generator System
Single Bank: 9.6 MW/mile, Double Bank: 19.2 MW/mile

future at least, such rotors will not exceed about 150 feet in diameter and generate no more than a fewmegawatts of power in typical sites with favorable winds.

6.2 EFFICIENCY

No machine can extract all the power in a wind stream. The theoretical limit for rotor is 59.3% of the power in the wind stream passing through the area swept out by the rotor blades. A well designed rotor actually extracts only up to 40 to 45% of the power of the wind (Ref. 28). When the rotor drives an electrical generator through a gear-type transmission, the maximum power output runs between 30 and 35% of the wind power.

The vertical axis lift type Darrieus rotor is an old concept which has never been developed extensively; but is now being considered for both small and large systems. As its principal benefit the vertical axis windmill offers a higher efficiency (35 to 37%). Moreover it is omnidirectional and does not have to face into the wind. It can therefore use a more compact and less-expensive tower than a horizontal axis windmill of the same capacity.

6.3 DEVELOPMENT STATUS

In 1890, the Danish government funded a program to improve windmill performance and develop new concepts. From this program came the first windmill-electric generator. Windmills developed during this period supplied an equivalent of 200 MW of power. During the 1930's interest in windmills was high in Russia, Germany, France England and the U.S. In 1931 the Russians built a 100 kW system which fed power into a large network until it was destroyed in World War II.

The largest electrical system ever operated was the Smith-Putman machine built in Vermont during World War II. The plant was designed to feed power into existing networks and was run a total of 1100 hours during four years. In March 1945 one blade broke at a place where a weakness was known to exist but was not corrected due to war-related shortages. Because there was no gurantee that the extra expenditure and experiments would provide a cost effective plant, the program was terminated in November 1945.

The first large-scale wind turbine (Ref. 28) generator built under current Federal funding resides at the NASA-Lewis facility at Plum Brook, Ohio. It has a horizontal axis downwind rotor 125 feet in diameter designed for a rated capacity of 100 kW in 18 mph winds. The rotor operates at a constant speed, in winds over 18 mph, by feathering the blades. The blades are fully feathered in wind speeds greater than 60 mph and the system is designed to withstand 150 mph winds.

This initial 100 kW experimental system will test components and subsystems and will be used to collect performance data to aid in designing other wind generators, of all sizes. Performance data collected will include energy and power output at various wind speeds; loads, stresses and vibrations in components such as blades, hubs and tower; and the stability and effectiveness of the control systems.

6.4 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

Experience has shown that wind energy conversion systems can be built and operated successfully. Accurate projections of potential wind power market penetrations cannot be made until studies have answered the basic questions of costs, service life, maintenance requirements and applications. However, it is possible to make some preliminary estimates. It has been estimated that about 20% of the electrical power demands in the year 2000 could be supplied by wind power systems (Refs. 1 and 28). This is a somewhat optimistic view which corresponds to the maximum available estimated wind energy. The most pessimistic estimate is approximately 1% of the total yearly electrical needs.

It seems plausible that a sizable export market could be developed, since fossil fuel availability and costs are far more severe in other countries (Ref. 28). This would mean a favorable impact on the U.S. balance of trade.

Whether the windmill can provide any significant energy generation in the future depends on the resolution of two problems (Ref. 1); environmental disturbance and economics.

6.5 COST AND BENEFITS

The best cost estimates based on experience show that wind plant capital costs per kilowatt of installed capacity may eventually equal costs for equivalent-capacity fossil fuel plants (Ref. 29).

Current costs of fossil fuel and nuclear power plants range from 400 to $800 per kW (1974 dollars) with the cost of some future nuclear plants projected to reach $1000 per kilowatt. Costs of large wind turbines are expected to vary according to the number produced annually as follows (Ref. 1): 1 to 100 units — $300 per kW; up to 1000 units — $250 per kW, and; up to 20,000 units — $100 per kW. In terms of average capacity at a favorable (30% use factor), the preceding figures correspond to $1167, $833 and $333 per kW, respectively. The result is that the price of power (in mills/kWh) delivered by wind turbine generators, including fixed charges plus operation and maintenance cost will become more competitive with the price of power delivered by conventional fossil and nuclear fueled plants (including costs of fuel, pollution controls and waste disposal).

If wind turbine generators can be reduced in cost to $500 per kW (average), then wind-generated electricity on a cost basis could replace conventional fuels (but not conventional prices) at the following minumum prices for such fuels (Ref. 1):

Coal — $29 per ton
Nuclear — $146 per pound of U_3O_8.

For most large power systems, where the mix of fuel sources is expected to contain more and more nuclear energy, the outlook for wind as a supplemental source of energy is not promising. For smaller systems and isolated communities that depend primarily on oil fired power plants, the prospects for wind energy applications as a supplemental source of electricity are promising (Ref. 1) if low cost turbines can be developed.

6.6 APPRAISAL OF ENVIRONMENTAL ASPECTS

Wind power systems produce no air or water pollution and little noise. Only a quiet swishing sound can be heard when one stands under a 15 meter propeller-type rotor. However, the "visual pollution" imposed by the wind plants and transmission lines to feed into a power network could be a problem if care is not taken to make the plants aesthetically appealing. Potentially, there could be a land use problem also because a tremendous number of wind plants would be needed to make a significant contribution to the country's future energy needs. Each plant would not require much land; but when a large number (with transmission lines) are placed small distances apart to supply most of the power in a region, the land rights, zoning regulations and reactions of the local citizenry could raise substantial problems.

One estimate (Ref. 1) for wind plants indicated that 350,000 square miles of the Great Plains would be suitable for wind turbines. To supply 15% of the total energy supply in the year 2000 will require towers centered on each square mile, each tower being 600 feet high and containing an array of 20 machines with 50 foot diameter blades. The required land area is approximately equivalent to the combined areas of North Dakota, South Dakota, Nebraska, Kansas and Oklahoma. Actually, the machines would occupy only a small portion of the area, but electrical interconnections and access roads would require additional land. This is just an example which indicates the number of wind plants required to contribute a significant portion of energy. More realistically wind mills will contribute energy to smaller communities and more isolated regions as previously discussed.

Large numbers of densely concentrated wind power generators might alter local wind patterns (Ref. 1) and consequently local weather. This potential effect has not been assessed. The obvious environmental disturbance will be that of aesthetics. Structures of the size and numbers required for large scale power generation may not be palatable to many people.

Regarding weather modification, the effect might be analogous to an increase in surface roughness of the terrain. Conditions may exist for which the effects upon temperature, precipitation, or wind patterns would be significant. It has even been speculated that the addition of angular momentum to the atmosphere may have some relationship to tornado frequency.

Also, the rotating blades may adversely affect the bird population, with a corresponding increase in the insect or rodent population. The "scarecrow" effect may deter some types of wildlife from entering the area. The turbine noise, infrasonic pressure waves, and altered wind patterns could impact wildlife and domestic grazing animals.

6.7 EVALUATION OF RESEARCH AND DEVELOPMENT REQUIREMENTS

The effect of a dense concentration of windmills on local weather patterns is not known. Current power output capability of an individual wind plant virtually dictates a concentration of several plants to supply the power for a community of any size. It is not known if the operation of the windmill will alter the local wind pattern (induced local turbulence from the wash off the turbine blades) or not. Consequently the first order of priority is to determine the effect on local wind patterns. This can be accomplished in a large industrial wind tunnel such as the one located at Colorado State University. Environmental chambers such as this have the capability to model the terrain and examine the effect of structures placed within the terrain. Consequently from scale model testing such as this, the effect of such factors as plant height, blade design, plant density, material requirements and their manufacture, etc., can be studied. ERDA's schedule calls for a 10 MW_e facility to come on line in 1981. Large scale production of wind turbines is slated to begin in 1983. Under optimum conditions, a rated wind energy conversion capacity of 15,000 MW_e is predicted for 1985.

Section 7
TURBINES

7.1 GENERAL

Turbines provide a means to convert the energy contained in a gas stream to mechanical energy via expansion of the gas stream through the turbine. Turbines generally operate in conjunction with a compressor located upstream of the turbine, but driven by the turbine. The function of the compressor is to compress the gas stream to a high pressure before heat addition and expansion through the turbine. The excess mechanical energy, above that required to drive the compressor, derived from the turbine is then used to drive a generator to produce the electrical power.

Turbines are used in both open and closed systems. In an open system a high temperature gas stream from a combustion device passes through the nozzle and turbine and is then exhausted external to the system. A closed system differs from the open system in that the working fluid continually circulates through the system and energy is supplied externally through a heat exchanger. In a conventional steam plant a boiler via a heat exchanger provides high pressure, high temperature steam to the turbine which transfers mechanical energy to the generator. A condenser is then used to extract heat from the steam and return low pressure water to the boiler.

A combined cycle is one which employs some combination of an open and closed cycle operating to produce electrical power. A discussion on turbines utilized by power generation plants naturally divides into steam and gas turbine categories. Steam turbines are utilized in closed systems while gas turbines, depending on the application, are utilized in both open and closed systems. Consequently the following discussion addresses steam and gas turbine applications to electrical power generation.

7.2 STEAM TURBINES

7.2.1 Description of the System

The steam turbine is a heat engine that takes heat from a high temperature source, converts it into mechanical energy, and rejects waste heat at a lower temperature. A representation of the operation of a heat engine is shown in Fig. 7. According to the Second Law of Thermodynamics, to convert all of the transferred heat into mechanical energy is impossible; that is, a heat engine cannot be 100% efficient. The most efficient heat engine operating within the constraints of the Second Law is one that follows a theoretical concept known as the Carnot cycle. While the features of this concept are not attainable in an operating heat engine system, the cycle is useful as a standard in evaluating the performance of actual heat engines.

Steam turbine energy systems are based on the Rankine cycle, a practical modification of the Carnot cycle. In the Rankine cycle, heat from the energy source (fossil fuel combustion gases or nuclear fuel) is transferred to water at high pressure in a boiler and produces high pressure, high temperature steam. The steam enters the turbine where it expands to a low-pressure, low-temperature steam and in so doing does work against the turbine blades, causing the turbine shaft to rotate which in turn drives an electrical generator. After the thermal energy in the steam has been converted to mechanical energy in the turbine, the discharged (spent) steam is converted back into water in a condenser. The water is then pumped back into the boiler and starts the cycle over again. The heat removed in the condenser is rejected to the environment through the use of cool bodies of water (i.e., lakes, ponds or rivers) or of cooling towers. This cycle is shown in Fig. 8.

Modifications to the Rankine cycle which improve its thermal efficiency use the concepts of regeneration and reheat. In the reheat process, a portion of the steam that has partially expanded to an intermediate pressure in the

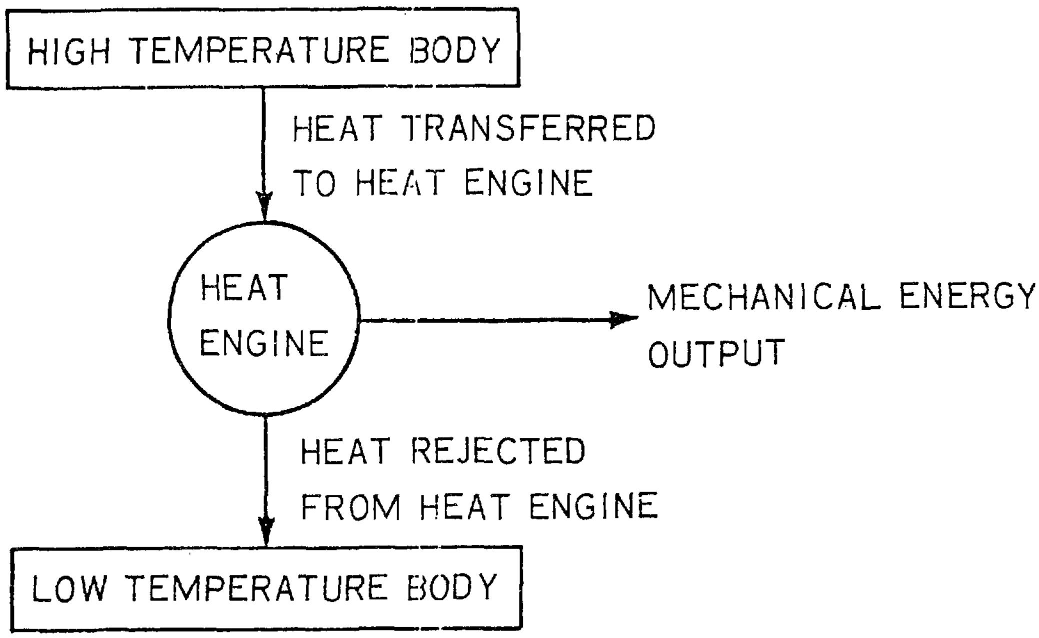

Fig. 7 - Operation of a Heat Engine

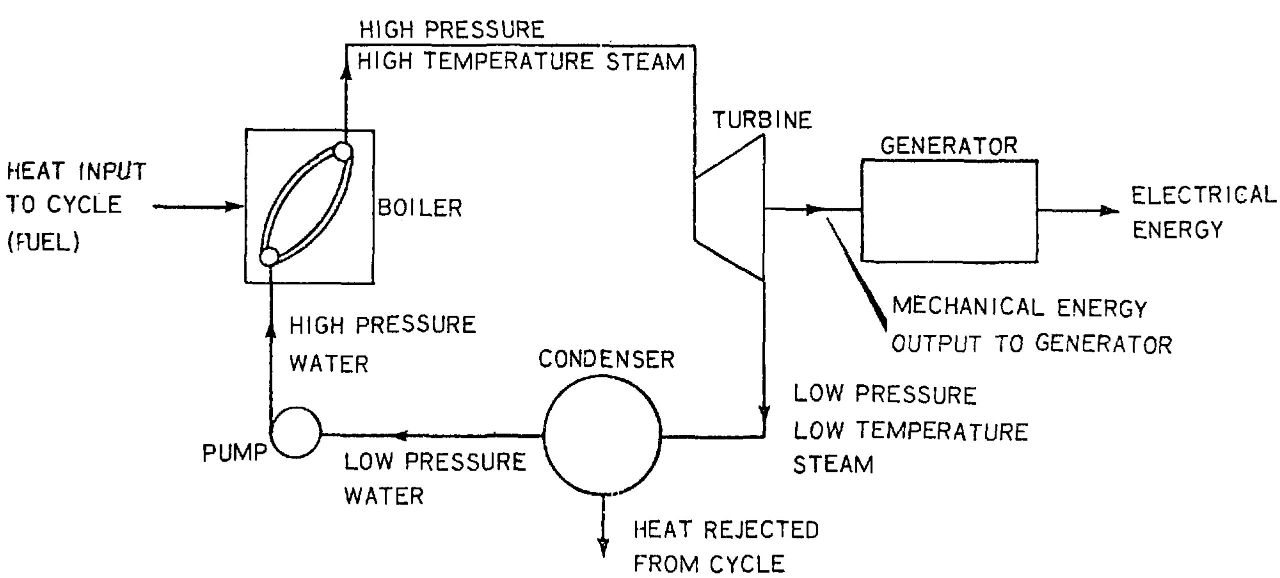

Fig. 8 - Basic Components of a Rankine Cycle Heat Engine
as Used in Steam Turbine Power Plants

turbine is reheated in the boiler and then returned to the turbine to complete the expansion process (Fig. 9). The regenerative process extracts a fraction of the steam from the turbine after partial expansion and uses it to heat the water leaving the condenser before it enters the boiler. The device where this heat exchange occurs is called a feedwater heater. A number of feedwater heaters are generally used in modern systems. This process is shown in Fig. 10.

Typical steam power plants will use both reheat and regeneration. The extent of reheat and regeneration for a particular plant will be determined by economic considerations, principally the fuel cost. The light water reactor (LWR) nuclear plants in operation today, for the most part, use the regenerative process only because the temperatures available in LWRs are not particularly economical for reheat purposes.

7.2.2 Efficiency

The maximum efficiency for a heat engine is the Carnot cycle efficiency, which is a theoretical efficiency that cannot be achieved in practice but which serves as a measure of performance for actual cycles. The Carnot efficiency is

$$n_c = \frac{T_H - T_L}{T_H}$$

where

n_c = Carnot cycle efficiency
T_L = low temperature of heat rejection, R
T_H = high temperature of heat addition, R

The equation shows that theoretical efficiency is improved by increasing the heat addition temperature, T_H, and decreasing the heat rejection temperature, T_L. Steam turbine systems typically operate between a maximum temperature of 1000F (1460R) and minimum temperature of 70F (530R). A Carnot cycle operating between these temperature limits of heat addition and heat rejection would have an efficiency of 65%.

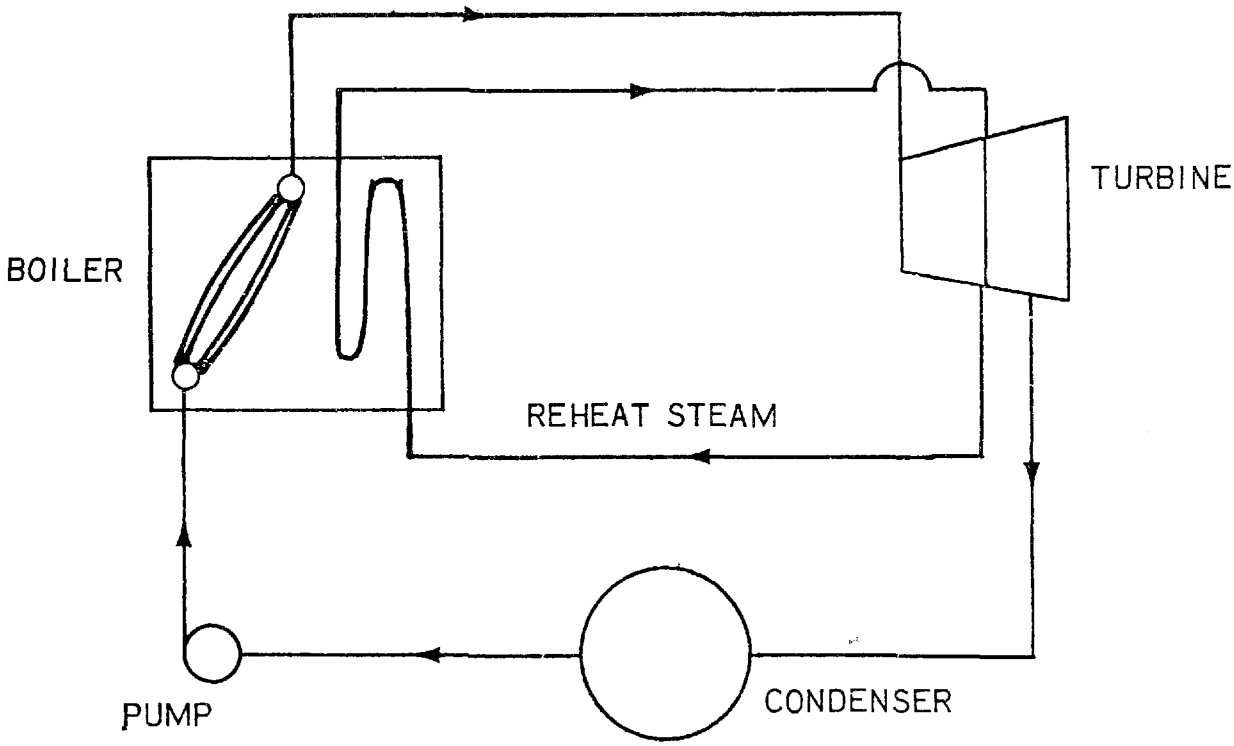

Fig. 9 - Rankine Cycle with Reheat

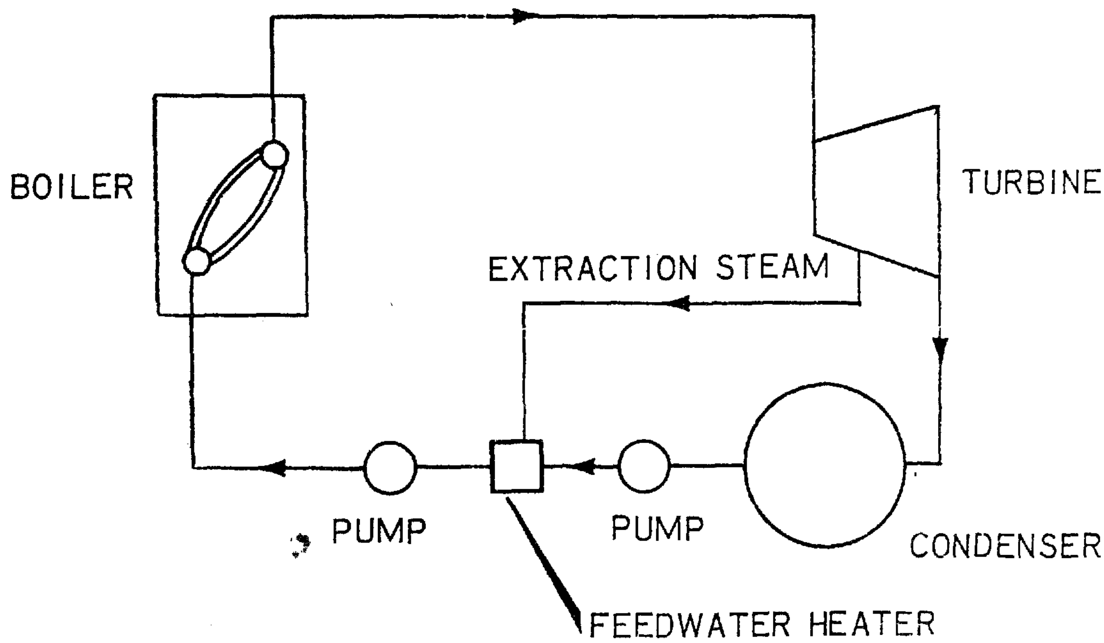

Fig. 10 - Rankine Cycle with Regeneration

Actual steam turbine plant efficiencies for units in the 1000 MW range are on the order of 38 to 40% for fossil-fueled and HTGR units and 31 to 34% for BWR and PWR units. Improvements to these efficiencies through the use of additional stages of reheat and regeneration are not economically practical at the present time, because the increased investment costs offset the operating savings.

Use of higher steam temperatures and pressures to improve efficiency of fossil units is limited because: (1) metals currently used are near their metallurgical limit, and (2) metals that can withstand more extreme steam conditions are too costly to be economical and have a limited lifetime. This is referred to in a new approach by General Electric (Ref. 30) in which the turbine is water cooled, permitting turbine operating temperatures on the order of 2800F. Efficiency is expected to be increased to about 50%.

7.2.3 Size Limitations

The size of steam turbine units is expected to increase above the present maximum of about 1300 MW in order to reduce capital, operating, and maintenance costs on a per kilowatt basis. Although these large units will require some improvements in turbine, generator and boiler design, no major problems are expected.

Factors that may have an effect on plant size are cooling water and land area requirements. Because larger units require greater amounts of cooling water and regulations are being introduced that limit the amount of heat that can be discharged into natural bodies of water, sources of cooling water for large plants have become a problem. Greater land area requirements are a result of larger coal and ash storage areas, flue gas cleaning equipment, and cooling facilities for the condensed cooling water. Dry cooling towers are expected to occupy a position of greater prominence.

7.2.4 Development Status

It is believed that there are not likely to be many major improvements in steam turbine technology. Advanced blade technology, seals, and moisture-removal techniques as well as lower-cost, high-temperature alloys are areas receiving current attention.

A major problem in further development of high temperature turbines is the fact that alloys currently used in turbines are just about at their temperature limits. One line of research is directed toward finding substitute turbine blade material such as ceramics and composites for the alloys.

General Electric is currently developing a new high-temperature turbine (Ref. 30) that should be available to utilities before turbines made from new materials. The GE turbine relies on water instead for cooling vanes and blades. A utility-sized version producing 180 MW is expected to operate at 2800F. Thus far, the experimental device has produced 2 MW at temperatures between 2800 and 3500F and pressures greater than 200 psi.

Water is circulated through the turbine blades through small channels close to the surfaces of the blades thus protecting the metal parts from overheating. Water is ejected from the tips of the spinning blades. The water ends up in a collecting device surrounding the turbine shroud and is returned to a heat exchanger for recycling.

7.2.5 Anticipated Contribution to U.S. Energy Needs

Approximately 78% of the electric generating capacity in the U.S. in 1970 was based on steam turbine energy systems, and this percentage is expected to increase slightly by the year 2000. The remaining 22% of capacity was supplied by hydroelectric (~15%) and gas turbine and diesel electric (~7%) power systems.

The kinds of service provided by the various types of plants can be classified in terms of base, intermediate or peaking load. Base-load units are large, efficient units that operate continuously at or near their full capacity. Typical annual capacity factors (percentage of annual output if operated continuously at maximum capacity) are around 80%. Intermediate load units are smaller, less efficient and typically are required to shut down and start up daily as demand varies. Capacity factors vary from 20 to 60%. Peak load units provide power for short periods of the day, when the demand for electricity is at its maximum, and have capacity factors of 20% and less.

Steam turbine systems are predominantly used for base load and intermediate load service. Base load service is provided by large fossil fueled and nuclear units, whereas intermediate service is provided by either older or small fossil fueled units, originally designed for base load, or newly designed fossil fueled units built specifically for this service.

New peaking service is now generally provided by pumped storage, gas turbine or diesel energy systems, rather than steam turbine systems, because of the quick startup requirements and the economics involved.

7.2.6 Costs and Benefits

The preponderance of the electric generating capacity of the United States today is based on the utilization of the Rankine cycle, which attests to its relative economics. The very wide range of conditions for which an individual unit may be designed (i.e., varying construction conditions, varying labor productivity) leads to significant cost differences of plants installed at different locations within the nation. Environmental control costs will also add substantial amounts to the basic costs of the plant.

Disadvantages exist with the steam turbine energy system that are prompting investigations into alternative electric generation schemes. Principal factors are its associated adverse environmental effects and the desire for higher efficiencies than can practically be obtained from a steam Rankine cycle alone. Low efficiencies result in higher rates of (1) consumption of limited fuel reserves; (2) air pollution; and (3) thermal pollution. The indirect method of electric generation — energy transformations from chemical or nuclear to thermal, from thermal to mechanical, and from mechanical to electrical — along with the large and complex equipment used is also considered a system disadvantage when compared with other generation concepts.

Not withstanding these considerations, the steam turbine system is currently the most economical and technologically developed energy system available to the electric power industry.

7.2.7 Appraisal of Environmental Aspects

The principal means of operating steam turbines in power plants is by coal fired boilers to produce high pressure and high temperature steam. Typical coal fired power plants emit significant quantities of particulates (fly ash) and noxious gases such as sulfur oxides, nitrogen oxides, carbon monoxide and hydrocarbons (Ref. 1). Heat rejected by the condenser cooling water to rivers and lakes is considerable; in 1964, for example, of all industrial cooling water used in the U.S., 81% was used by electric power plants. These aspects have received considerable attention over the past few years. The main consideration is what effects steam power plants currently under development and design have on the environment.

In the foreseeable future, the primary means of steam generation for the steam driven turbine will be a fossil fuel fired boiler with primary emphasis on increasing efficiency of the turbine. An advancement in the thermal efficiency provides the double environmental gain of reducing thermal and other waste emissions to the environment and conserving resources of natural fuel.

7.3 GAS TURBINES

7.3.1 Description of the System

The gas turbine system has the function of converting input chemical energy of fuel into heated, compressed gas that expands while doing work on rotating blades similar to the steam turbine. The mechanical output is coupled to a generator shaft which in turn generates electrical power. Components of this system include a compressor, a combustion chamber, and one or more turbines together with heat exchangers, as called for by cycle design (Fig. 11). In the simplest cycle, no heat exchangers are employed. An important characteristic of the gas turbine is the essential requirement for a clean (no particulates or corrosive components) gas flow through the turbine, forcing the need for a clean burning fuel or a source of high temperature thermal energy, such as a nuclear reactor, where the fuel element coolant is the high pressure heated gas for the turbine expansion.

One of the salient characteristics of a gas turbine is its requirement for a clean fuel so that the gas flow through the turbine is neither erosive (from particulates) nor corrosive (from vanadium, sodium, potassium, lead and sulfur compounds). Calcium is also troublesome because it forms hard deposits. All of these elements are contained in residual fuel oils — the low cost residue of the petroleum refining processes that produce the distillate fuel oils (diesel and kerosene) and gasoline. As a consequence of this, comparatively clean residual and crude fuel oils must be carefully selected, and these must then be treated further before fuel oil products can be used for gas turbine operations. In addition, the growing need for unlimited oil resources for other applications makes this energy source questionable for large scale use in the electric power industry.

Gaseous fuels present no problems of this nature. Natural gas as distributed by utilities is an ideal fuel, but its scarcity also mitigates against use for electric power generation. Considerable attention is being given to the possibility of using high or low Btu gas derived from coal gasification,

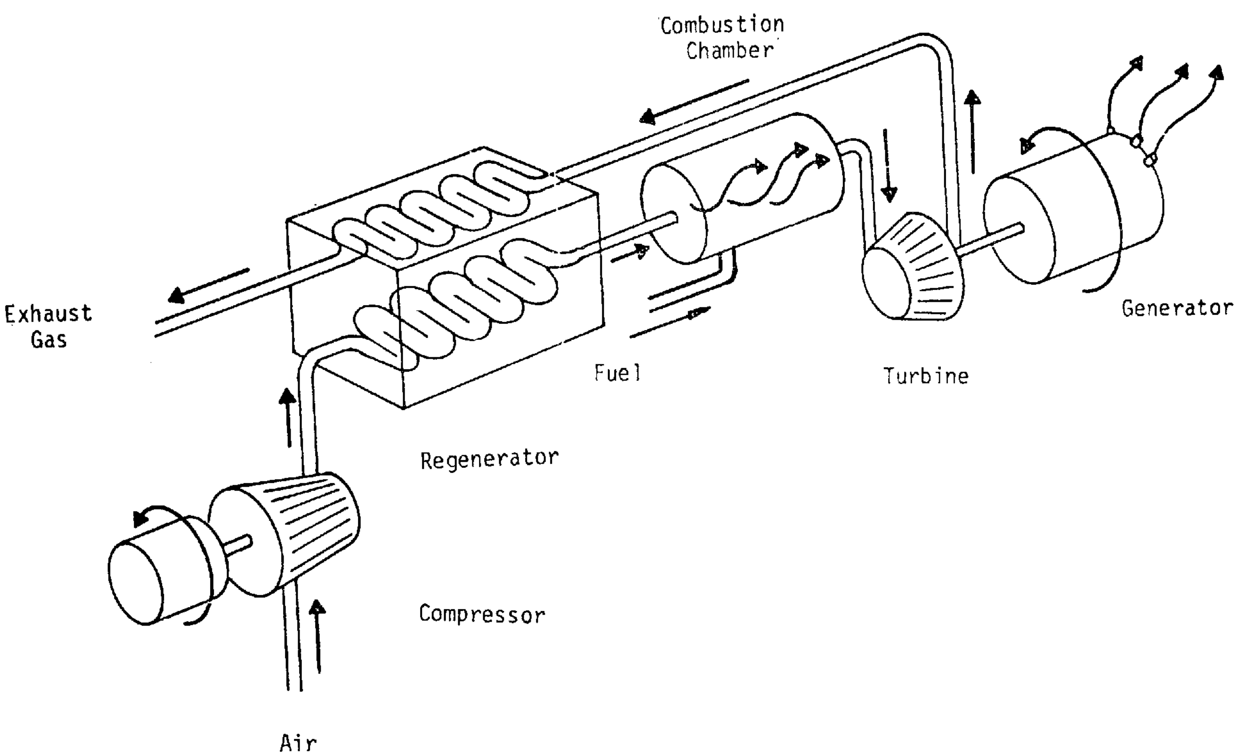

Fig. 11 - Regenerative Cycle Gas Turbine

and there does not seem to be any technical problem in doing so. Coal gasification systems must provide economical techniques for removing sulfur. The gas turbine and the combined cycle plant might adapt very well to this type of fuel.

As discussed previously, high temperature helium gas cooled thermal nuclear reactors coupled to steam turbine converters (Fig. 12) are now being considered by the utilities as a viable alternative to water cooled reactors, and a number of units have been ordered. As a result, increased emphasis may be placed on the closed cycle helium gas turbine rather than the steam turbines as the energy conversion system.

7.3.2 Efficiency

Gas turbine plants now available have the following efficiencies:

- Simple cycle, 27%,
- Combined cycle, 36 to 38%,
- Regenerative cycle, 34%.

With currently available materials and turbine-cooling technology, commercial designs should be available in the 1975-77 period having better thermal efficiencies, by a factor of 1.1 or more, which could make the combined cycle competitive with the best available conventional steam plants. By 1980, further evolutionary progress is expected to yield improvements resulting in a 1.2 miltiplier on present day thermal efficiency performance.

7.3.4 Size Limitations

One great advantage of the gas turbine cycle engine is that it lends itself to the concept of modular design and factory fabrication. The result is substantial economies in lead time and in costs for field erection. Another advantage of the modular concept is that good partload fuel economy can be realized by shutting down one or more units when only part of the total capacity

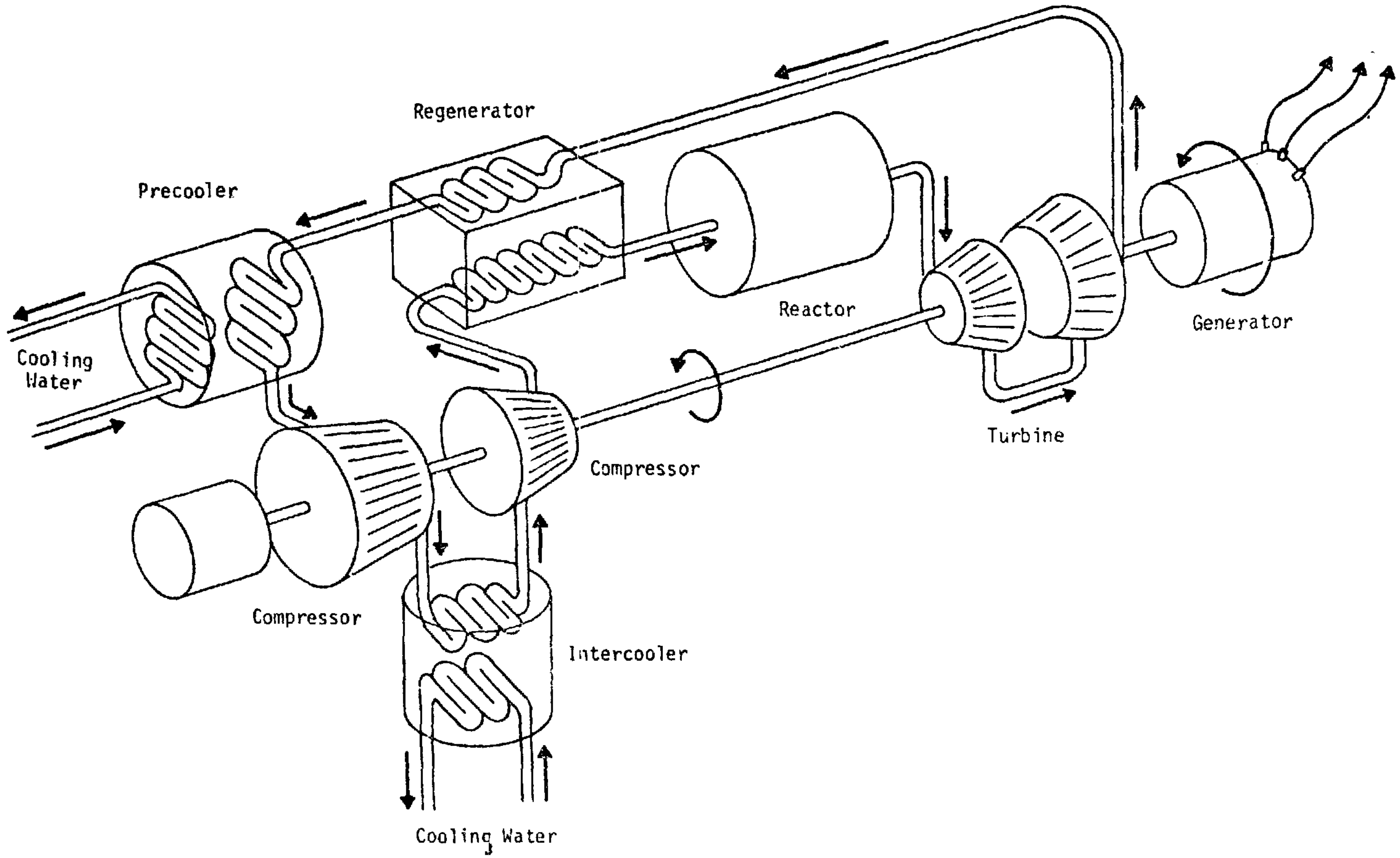

Fig. 12 - Nuclear Cycle Gas Turbine

is needed. Multiplicity of units also affords improved reliability and availability, as maintenance can be done to a single unit with only a partial reduction in capacity. These capabilities are highly desirable for plants used for the midload service range.

7.3.5 Development Status

The outstanding advantages of the gas turbine for aircraft propulsion has produced the research and development effort that led to the improved aerodynamics of flow path design, metal alloys allowing high turbine inlet temperatures, and improved methods of cooling turbine blades and nozzles. The fallout of this technology has greatly improved the position of the gas turbine and has led to its acceptance for peak load central station power service.

7.3.6 Anticipated Contribution to U.S. Energy Needs

Today the simple cycle gas turbine prime mover is favored for new equipment to accommodate the peak portion of the electrical power demand. Fast start, low initial cost, and short delivery time are features desired for peak-load plants and are met by gas turbine units. An important variation of the simple cycle system is the combined gas turbine and steam plant. Here the hot exhaust from the power turbine is used to generate steam in an unfired boiler. The steam is used in a conventional system to generate 50% more power without additional fuel (Fig. 13). The combined cycle thermal efficiency is comparable with that of a modern steam plant and is being used by some utilities for serving intermediate system loads. One forecast is that by 1980 the gas turbine and the combined gas turbine and steam power plant could be providing some 25% of the power requirements of the electric utility industry in meeting peak and intermediate load demands. Gas turbine cycles are expected to be used in high temperature gas cooled reactor (HTGR) and gas-cooled fast reactor (GCFR) systems.

On the basis of present technology, the role of the gas turbine prime mover as an electric power producer through 1990 should be largely in

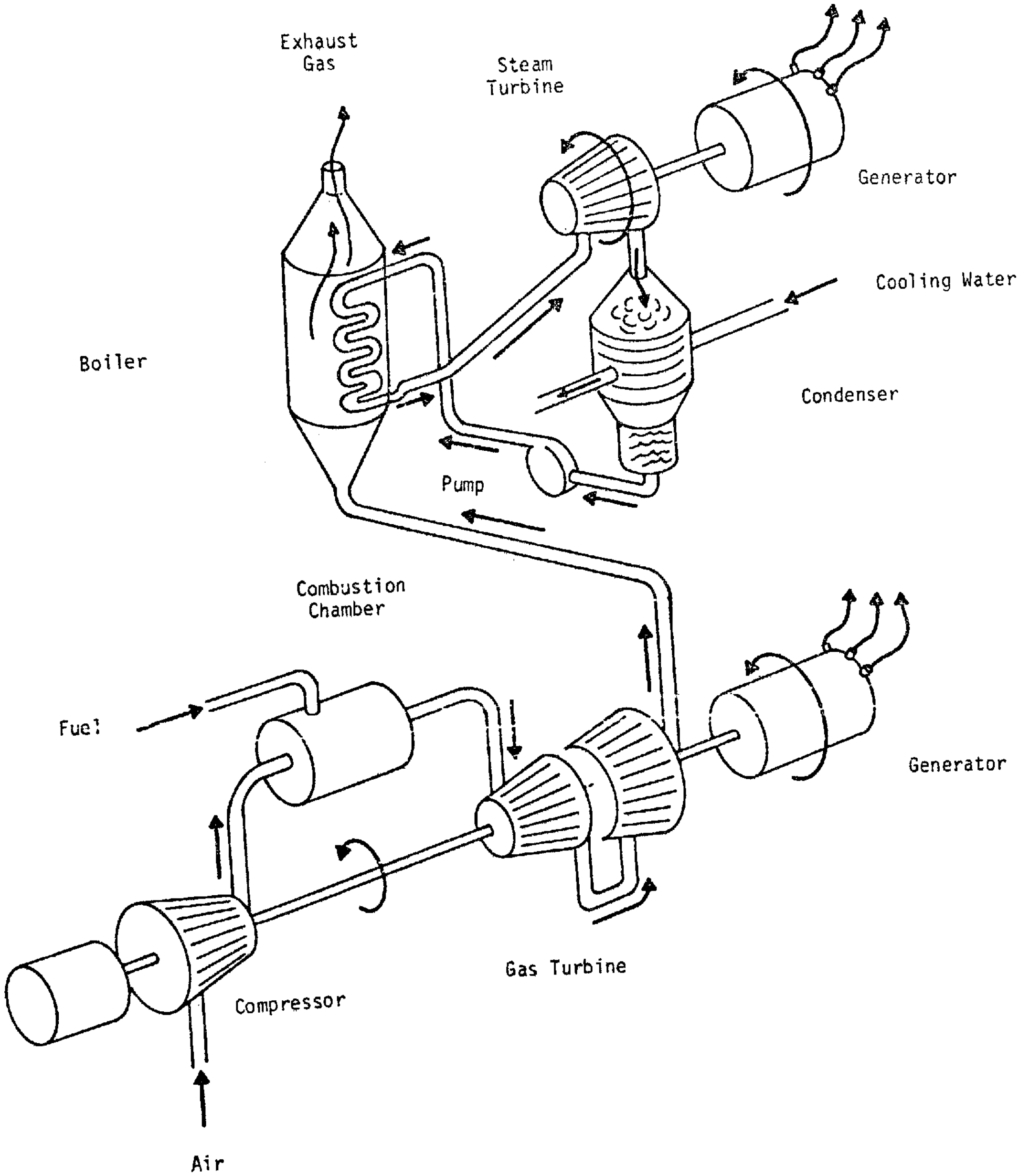

Fig. 13 - Combined Cycle Gas Turbine

peaking and intermediate load operation, where it will contribute possibly as much as 30% of the power capability and about 15% of the total electrical energy production. Developments in gas turbine technology that improve efficiency might make this system more attractive for base load service. Gasification of coal could enhance the gas turbine's position by making it a possible alternative for base load service.

7.3.7 Costs and Benefits

Low initial cost is an area that has made gas turbine energy systems particularly attractive to utilities. The efficiency has been of lesser importance for peaking service, but whether this will hold in the future, because of the dwindling supply of clean fuel, is largely unknown. The relative station costs and performance levels of gas turbine plants are as follows:

Type	$/kW	Thermal Efficiency (%)
Simple Cycle	90	27
Regenerative Cycle	100	34
Combined Gas and Steam Turbine	150	37

The comparable fossil fueled steam turbine plant figure is $180 per kilowatt for a plant without sophisticated environmental controls; this cost could escalate to over $300 per kilowatt when environmental controls are added. The efficiency of modern steam turbine plants is about 39%.

The cost advantages of the gas turbine cycles arise primarily from the elimination of a fired, high pressure boiler with its superheater, reheater and regenerative feedwater heaters. These steam-generating components cost about 40 to $50 per kilowatt. Though a boiler is incorporated in the combined cycle, its cost is only about 15 to $20 per kilowatt, as it is an unfired heat exchanger operating at a low pressure (less than 1000 psi).

Further advantages of the gas turbine are lower construction costs, about $5 less per kilowatt, and lower interest and escalation charges by about $20 less per kilowatt, due in part to much shorter field erection times. Projections for the future indicate that the gas turbine plant advantage in base line cost figures will increase further. This conclusion results from the fact that available technological improvements, which may be incorporated into the 1975-1980 designs, will increase specific power by 40% or more. The result is that a given size (and cost) of turbomachinery has a higher kilowatt rating. Moreover, there will be significant gains in thermal efficiency, although percentagewise not as much as for the rating gain.

7.3.8 Environmental Considerations

The site requirements for gas turbine fossil fuel plants are modest in acreage. The noise levels are low as the high frequency noise typical of turbomachinery may be acoustically treated at low cost.

Stack gas pollutants are virtually nil insofar as carbon monoxide and hydrocarbons are concerned. As a low sulfur, low ash fuel is a requirement for the turbine operation, fly ash and sulfur dioxide emissions are also negligible. However, a present problem area is the stack effluent of oxides of nitrogen (NO and NO_2). The technique now used to treat the problem is to inject demineralized water into the combustion chamber, at a mass flow rate comparable to the fuel rate, for loads above 40% of rating. Most gas turbine manufacturers feel that they will be able to offer combustion chambers that will reduce oxides of nitrogen without the added complexity of water injection.

A set of emission standards is needed (such as the maximum values applying to conventional steam plants) to provide realistic design targets for research to reduce the oxides of nitrogen.

Simple cycle and regenerative cycle plants, relative to the combined gas turbine and steam cycle plants, do not have an extensive requirement for cooling water. The combined gas turbine steam cycle has cooling water requirements about 40% or less than those of a conventional steam plant.

Section 8
THERMOELECTRIC CONVERTERS

8.1 DESCRIPTION OF THE SYSTEM

A thermocouple is a device consisting of two dissimilar conductors joined together to form two junctions and a closed electrical circuit. As long as the temperatures of the two junctions are not equal, a current will flow in the circuit. This effects was discovered in 1822 by T.J. Seebeck (Ref. 31). The Seebeck effect suggests the potential for direct conversion of heat to electricity without the use of moving parts (Fig. 14).

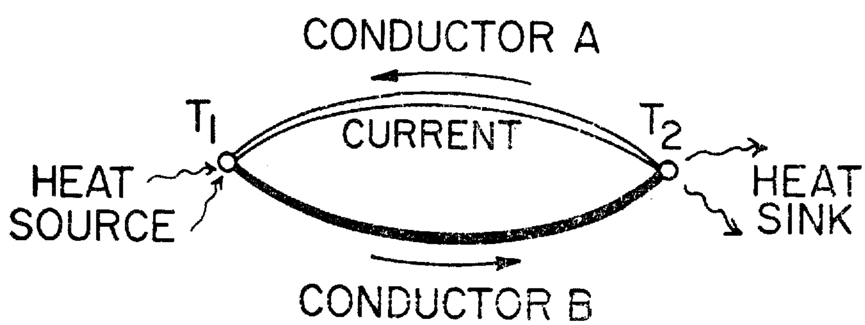

Fig. 14 - Simple Thermocouple

Since a device that utilizes the Seebeck effect is a heat engine, it is subject to the usual laws of thermodynamics and its maximum efficiency is the Carnot efficiency. However, losses always limit a practical device to efficiencies that are some fraction of the Carnot efficiency. For a thermoelectric generator with common metal junctions, and even with a temperature difference of several hundreds of degrees (between hot and cold junctions), this fraction of Carnot efficiency is about 0.1%. For the best metal junction, one formed of antimony and bismuth operating below their melting points, the efficiency is about 1%. To be considered as a replacement for a Rankine cycle (conventional steam cycle) plant, the efficiency must be nearer to 50% of Carnot. It is obvious that materials other than the common metals must be used if thermoelectric power generation is to be economically feasible for large scale applications. A number of materials, elemental and compound, are of interest. In certain cases these materials are semiconductors. Many compounds have been studied but only tellurides of Pb, Bi, Ag, Ge, Sb and Sn [e.g., PbTe, Bi_2Te_3 GeTe•AgSbTe (TAGS), PbSnTe, BiSbTe] and SiGe have been used extensively in practical devices. These materials have potential efficiencies in the range of 11 to 27%. The efficiency of practical devices will be lower.

8.2 EFFICIENCY

Table 8 lists several materials in use in thermoelectric devices as well as some of the parameters pertinent to efficiency calculations. The product ZT_m (T_m is the mean operating temperature and Z is a term called the figure of merit) will determine the percent of Carnot efficiency obtainable. The efficiency obtainable from an operating couple is found using the information in Table 8 and Fig. 15. No material listed, operating with a sink temperature of $27^{o}C$ and a source at the maximum allowable temperature, can approach an efficiency of 20%.

The efficiencies shown in Fig. 15 have been calculated for ideal conditions. Some representative numbers for actual devices as taken from Table 8 show the severity of the materials and engineering limitations for thermoelectric generators (TEGs). A number of TEGs used primarily for space applications (where efficiency is not necessarily the most important consideration) have efficiencies of less than 6% and most are in the 4 to 5% range. TEGs for terrestrial applications have efficiencies generally in the range of 4 to 6%.

Recognizing the reduction in efficiency in a real device, figures of merit above 5×10^{-3} are necessary to attain overall system efficiencies of about 10%. Whether or not this Z is obtainable is open to serious question. A paper published in 1967 by Ure, a well-known worker in the field of thermoelectricity,

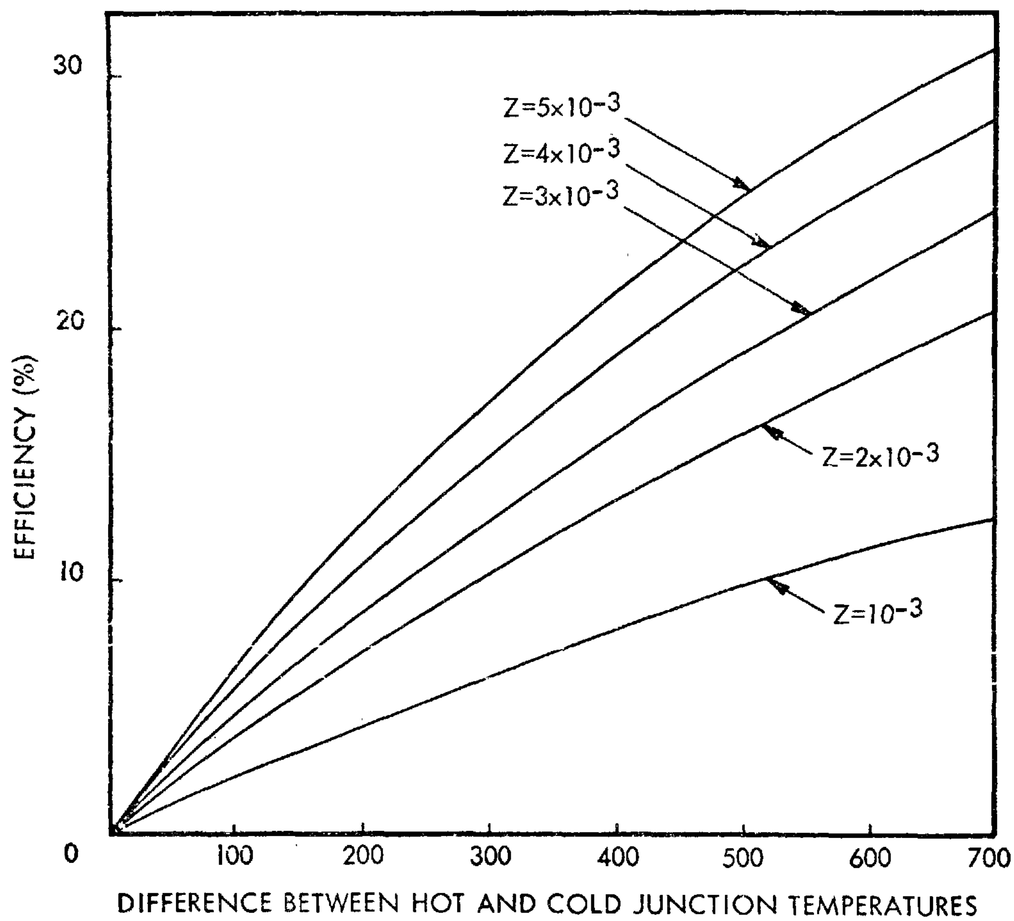

Fig. 15 - Efficiency of a Thermoelectric Generator

Table 8

THERMOELECTRIC MATERIALS*

Materials	Melting Point (C)	Type	Z_{max} (figure of merit)	Temp. for Z_{max} (C)	Max. Operating Temp. (C)
Bi_2Te_3	575	n or p	2.0×10^{-3}	27	177
$BiSb_4Te_{7,5}$	—	p	3.3×10^{-3}	27	177
Bi_2Te_2Se	—	n	2.3×10^{-3}	27	327
PbTe	904	n or p	1.2×10^{-3}	27	627
Ge Te (+Bi)	725	p	1.6×10^{-3}	527	627
ZnSb	546	p	1.2×10^{-3}	227	327
$AgSbTe_2$	576	p	1.8×10^{-3}	427	627
InAs (+P)	940	n	6.0×10^{-4}	627	827
CeS (±Ba)	—	n	8.0×10^{-4}	927	1027
Cu_8Te_3S	930	—	1.5×10^{-3}	827	—
Ge-Si	—	n	9.0×10^{-4}	627	927
Ge-Si	—	p	6.0×10^{-4}	627	927

*D.A. Wright, "Thermoelectric Generation," in Direct Generation of Electricity, K.H. Spring (ed.), Academic Press, New York, 1965.

states that a ZT of about 2 to 2.5 seems to be an upper limit. To obtain a ZT of 2.5, operating between 27C and 727C, a material would need a Z of 3.84 x 10^{-3}. The efficiency would be about 28%. With a Z of 5 x 10^{-3} and operation between the same temperatures, the efficiency would be 32%.

8.3 SIZE LIMITATIONS

A thermoelement is inherently a low power device. By appropriate series/parallel electrical arrangements, higher power outputs can be obtained. This modular system lends itself to the construction of high power systems, but still has a very low output for its size and weight.

A 150-W solar powered TEG would use 480 couples, with a weight of 1.62 lb for a power density of 94 W/lb for the elements alone. In the actual generator, this drops to 11.3 W/lb (Ref. 32). A radioisotope thermoelectric generator for use in a Transit navigational spacecraft, TRIAD I, has a power density of 1.2 W/lb for the total assembly. For the thermoelectric panels, the power density is about 6 W/lb (Ref. 33).

8.4 DEVELOPMENT STATUS

Extensive effort has been devoted to the development of thermoelectric materials with a high figure of merit, especially those materials that operate at higher temperatures and efficiency. Silicon-germanium alloys are considered as especially promising for operating temperatures near 1000C, and these materials are under active investigation (Ref. 33).

The techniques of joining the couples to the metal plates to form junctions and terminals are fairly well established, although these joining techniques are more art than science. Each new combination of materials introduces new problems that must be solved before the thermoelectric material can be used in a practical generator. Additional problems are often introduced by the brittle nature of most of the useful materials.

8.5 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

The main benefit of the thermoelectric generator is that it has no moving parts which will tend to increase its reliability and long life. The modular construction of a TEG allows a variety of power levels to be easily obtained for a given basic couple.

The low efficiency and low power output per couple, together with high unit costs, will probably limit the application of TEGs to small special-purpose power sources. The present economics are unacceptable for central-station power application and the low efficiency would create severe drain on our energy resources.

8.6 COSTS AND BENEFITS

Present costs for small fossil fueled TEG systems are about 25,000 to $30,000 per kilowatt electrical. This cost is more than 50 times the cost of a large conventional power plant. There is no large obvious reduction in unit cost that can be projected for increasing plant size since many small elements are required and the high unit cost still prevails. Mass production techniques applied to TEGs would, however, tend to reduce unit costs below what they are today.

An example of the cost of a thermoelectric generator can be found in the catalog of an established supplier of thermoelectric devices (Ref. 34). A 20-W TEG that operates between 125 and 25C requires 26 modules, each containing 31 couples. Since the cost of each module is $60 (1971 catalog price), the cost of the TEG is $78 per watt. More recently, different suppliers offering other types of thermoelectric devices have quoted prices in the range of $40 per watt. There do not appear to be any benefits accruing from TEG for commercial electric power generation.

8.7 APPRAISAL OF ENVIRONMENTAL CONSIDERATIONS

Since a TEG is a thermal conversion device with no moving parts, the only pollution results from the heat source. Naturally, being a thermal engine governed by the laws of the thermodynamics, heat will be rejected to the surroundings.

The low efficiency of the TEG means more thermal energy must be rejected to the environment. Conversely, for the same useful power emitted, more fuel is consumed. With existing low efficiencies, energy sources will be depleted at a faster rate than is now the case. For central station plants this is unacceptable.

Section 9
THERMIONIC CONVERTERS

9.1 DESCRIPTION OF THE SYSTEM

The principle of operation of thermionic devices is based on the emission of electrons from metals at high temperatures. This phenomenon was first investigated by Thomas Edison and was subsequently used as the basis of the conventional vacuum tube.

A thermionic converter is a device that contains an electron emitter and collector in a sealed envelope at reduced pressure. The emitter is heated, increasing the energy of the free electrons in the metal and causing them to travel faster. This increased kinetic energy allows the electrons to escape from the open surface of the hot emitter and to move through an intervening space to the cooler electron collector. With no external circuit connections, a potential difference (voltage) will develop between the collector and emitter. When connected to an external circuit, the potential difference will cause a current to flow (Fig. 16). In a thermionic converter with reasonable spacing between the emitter and collector, some of the emitted electrons do not have enough energy to reach the collector, so they form an "electron cloud" (or space charge) which tends to repel subsequent electrons and hence limit the available current. In order to achieve reasonable power density, a low pressure ionized vapor (usually cesium) is introduced to neutralize the space charge.

9.2 EFFICIENCY

The theoretical efficiency of a thermionic converter is limited by emitter and collector temperatures. As in any heat engine, the theoretical efficiency is seldom attained.

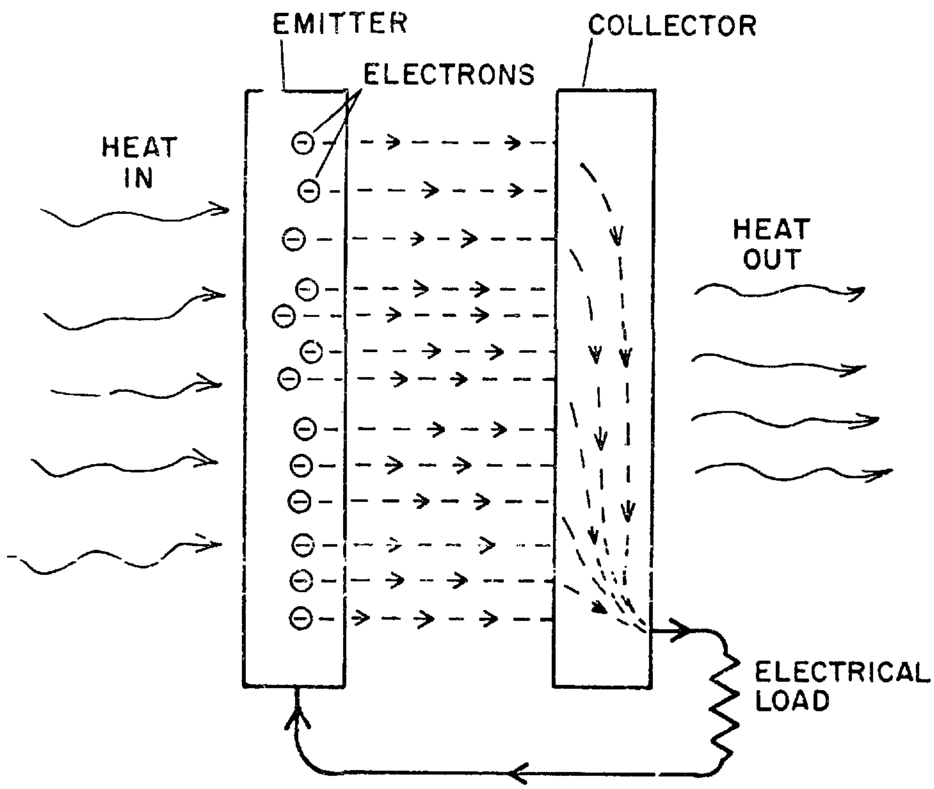

Fig. 16 - Schematic of a Thermionic Energy Converter

The efficiency of the radionuclide powered ISOMITE batteries is less than 1% (Ref. 35). The efficiency of a proposed 5 kW semiportable power supply was estimated to be about 10%. A thermionic power supply utilizing solar energy had achieved 12.5% efficiency by 1964. The TFE* efficiencies (Ref. 36) range from 10 to 16%, and the thermionic converters proposed for use in the fossil-fueled steam plant topping cycle would operate at an efficiency up to perhaps as high as 25 to 35% (Ref. 37).

*Thermoelectric Fuel Element

9.3 SIZE LIMITATIONS

Power systems that utilize thermionic converters will consist of individual units connected in series and parallel combinations to produce the voltage and current requirements for the various applications. Construction will be modular, and the unit size selected will depend on a number of considerations. Thermionic module size in the TVA Bull Run Plant analysis was set at 22 MW. Consideration is currently being given to applications in modified fossil fueled central station boilers with plant electrical capacities in the hundreds-of-MWe range.

9.4 DEVELOPMENT STATUS

Thermionic converter systems can be used with thermal inputs from any source, including solar and nuclear power. However, from the standpoint of central station power application, the major interest in thermonic conversion is as a topping unit for fossil fueled plants. Thermionic converters are most efficient at high temperature, and they match the heat-source properties of a fossil fueled plant well. Central-station nuclear power reactors are not suitable for thermoionic applications since it is not practical to incorporate these conversion systems within the core of the reactor, and neither the water cooled nor the sodium cooled reactors operate at high enough coolant temperature to consider locating the thermionic converter outside the reactor.

Although, in concept, the thermionic converter is a relatively simple device, building long-lived efficient thermionic converters is no easy task. The electrodes must operate close to one another and at high temperature so that the level of power generated is sufficient for practical applications. Also, the high operating temperature leads to high efficiencies. For example, the emitter may operate at 1880F and the collector at 918F. Under these conditions the theoretical efficiency is 41%; however, practical devices will never achieve this ideal efficiency. A high potential efficiency, as well as the feature of having no moving parts, makes thermionic energy conversion worthy of further consideration as a topping system with more conventional power cycles (Ref. 38).

With the exception of the concept developed for application to the TVA Bull Run coal plant, little has been done until recently in evaluating thermionic power systems applied to central station power, particularly not to coal fired plants designed to meet EPA pollution standards. Present program efforts are focusing on these applications again. The state of the art is primarily based on the AEC/NASA program. Based on this work, thermionic devices are technically feasible but need further development to extend their lifetime.

The experimental work of the 1960s identified most of the problem areas in converter design and operation except those of the economics of central station power application. The cesium environment and high operating temperatures can cause emitter vaporization, thermal warping, insulator shorting and seal failures. For space applications, the main problems were concerned with achieving the following:

- Lifetime of at least 5 years
- Reproducible and stable thermionic converter performance
- Demonstration that any electrical arcing that might occur is not destructive to the cell and will not result in excessive power losses
- Qualification to expected shock and vibration environments
- Simplication of fabrication methods and lower costs.

The use of chemical vapor deposition as a technique for cladding converter emitters with tungsten has been successful in establishing stable long term performance. Adoption of fine grained, high density alumina with niobium skirts brazed with a V-60/Nb-40 alloy may eliminate the insulator problems. Finally, the introduction of oxygen into the converter may reduce operating temperatures and improve the overall performance. Both lower cost materials and fabrication methods are required. For topping cycles, research is focused on achieving high efficiency and lower costs at lower and more practical operating temperature ranges.

9.5 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

Thermionic converters have several potential applications ranging from a cardiac pacemaker that operates in the 0.1-mW range to a modified (topping) thermodynamic cycle for a central station power plant that operates at 1000 MW. Thermionic devices, which are coupled with nuclear heat sources, are especially attractive for long range and long duration space applications because of their basic simplicity, the absence of moving parts, and their relatively higher efficiency as compared with other space power generators.

Interest in the thermionic device as a topping unit for conventional central station power plants rests on its potential for increasing overall plant efficiency. Furnace temperatures which are not normally usable in conventional boilers and steam turbines, because of metallurgical limitations, can be effectively used with thermionic converters to increase the overall efficiency of the cycle. An analysis carried out for the Tennessee Valley Authority (TVA) Bull Run coal fired plant shows that thermionic topping might result in an increase of station output from 914 to 1139 MW and a gain in plant efficiency from 41.3 to 50.6%.

A thermionic energy conversion system has the potential to improve fossil fueled plant efficiency from the present 40% to possibly 50%. The system should be particularly adaptable to coal plants in which the combustion chamber temperature is well above the normal working temperature of the steam turbine. Insufficient studies are available to establish requirements of thermionic power systems as applied to new coal plants that will meet EPA standards. At present, low cost, reliable converters have not been developed, and thermionic topping cycles for coal fired steam turbine power plants cannot be justified on an economical basis.

A survey conducted by Chemical Engineering (Ref. 19) indicates the breakthrough in thermionic converters should occur by about 1982. The economic feasibility of the concept and its commercial and widespread use is predicted by about the year 2050.

9.6 COSTS AND BENEFITS

With the exception of certain terrestrial and hydrospace applications, the cost of thermionic converters for producing power has not been assessed. The value of a thermionic converter for a fossil fueled plant can be estimated based on the incremental efficiency produced by a topping cycle operating with no degradation of the steam plant performance. Using a capital cost of $300 per kilowatt-electrical and a fuel cost of 50 cents per million Btu for a coal fired steam plant, the purchase price for each of the thermionic modules could be as high as 15 cents/W and still be economically competitive. Present costs for these devices are considerably higher than this, and current research is directed at achieving significant cost reductions.

The increase in plant efficiency and the apparent ease in incorporating the thermionic modules in the boiler unit of a fossil fueled plant would suggest that this is a fruitful route to follow.

9.7 APPRAISAL OF ENVIRONMENTAL ASPECTS

The operation of a thermionic generator produces no additional pollutants other than those normally present from the particular heat source used. It is important to note, however, that the use of thermionic topping in conventional central station power plants would increase the overall plant efficiency. The topping device, in principle, utilizes all the heat supplied to it with 100% efficiency because its rejected heat is at a temperature above the normal steam cycle operating temperature. Thus, the increase in overall plant efficiency results in less thermal energy rejected to the surroundings for the equivalent electrical power production.

There are no new known environmental effects introduced with a thermionic converter system. With the higher efficiency projected for a thermionic system, the pollutants normally produced by the energy source being used will be diminished for equivalent amounts of electrical energy generated.

Section 10
POTASSIUM VAPOR TOPPING CYCLES

10.1 DESCRIPTION OF THE SYSTEM

Electrical utilities generate most of their electrical energy in fossil fuel fired Rankine cycle steam turbine plants. Some of the low melting point metals, such as potassium (melting point 144F), when vaporized, can be used, like steam, as the working fluid to drive a turbine. The principal advantage of "liquid metals" as the working substance in a power plant is their high boiling or vaporizing temperature at a modest boiler pressure. (For example, potassium boils at 1400F at 1 atmosphere in contrast to water boiling at 662F at 2400 psia.) Mercury, which boils at 907F at 100 psia, can also be considered as a working fluid. The lower boiling pressure allows, in principle, an acceptable boiler cost in spite of the higher boiling temperature. While the liquid metals possess advantages relative to water in the boiler portion of the plant, water has the advantage in the condenser. This difference results from the liquid metal vapor densities being so low which makes the condenser (and low pressure end of the turbine) excessively large and costly. This difference can be resolved by combining a liquid metal Rankine cycle with the water Rankine cycle. In this concept the metal vapor condenser, now operating at acceptable vapor densities, serves as a boiler for the water cycle. Thus, while each individual cycle is not of high thermal efficiency, the binary cycle has a high efficiency because the energy rejection from the high temperature topping cycle is used again in the boiler of the lower temperature water cycle (Ref. 1).

An example of a potassium topping cycle for a conventional steam turbine system is shown in Fig. 17 (Ref. 39). The heat source for this particular binary cycle is a molten salt breeder reactor.

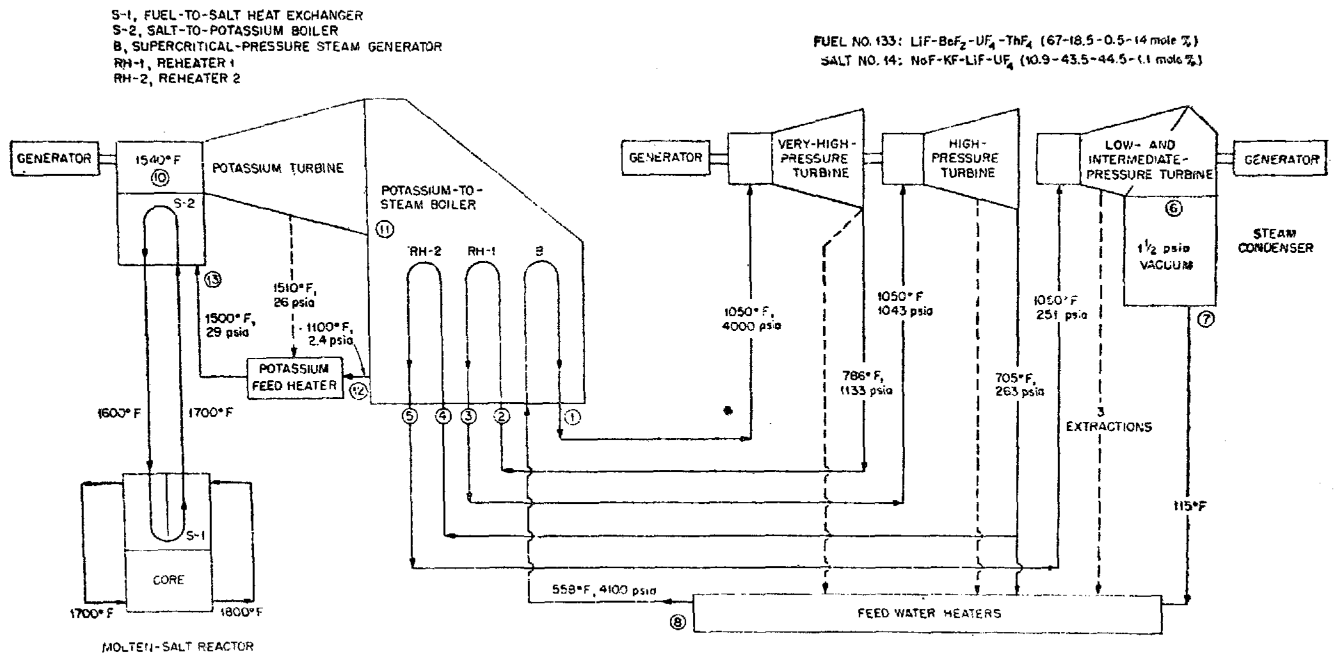

Fig. 17 - Flow Diagram for Potassium Binary Vapor Cycle Power Plant Fueled by a Molten Salt Reactor

10.2 EFFICIENCY

For a coal fueled plant with a boiler efficiency of 90%, the thermal efficiency of a potassium steam binary cycle is estimated to be 50 to 55% or more, over the range of turbine inlet temperatures of 1400 to 1800F. Thus, binary power cycles, with a potassium topping cycle on a steam cycle, possess the potential of a higher energy conversion efficiency than the single fluid steam cycle. Such systems would probably produce lower cost power in plants of large capacity rather than small and would operate more efficiently at design capacity than at part load. Consequently, potassium binary cycle plants should find application primarily as base load plants.

10.3 SIZE LIMITATION

There are no inherent limitations to the size of the mercury or potassium topping cycle plants, because as is currently done in steam plants, capacity can be increased by using multiple units in a parallel flow arrangement (Ref. 1).

10.4 DEVELOPMENT STATUS

The potassium topping cycle has potential for use above about 1400F. There is no previous history of use of potassium topping cycles in utility power plants, but potassium topping cycles for central station power have been studied as far back as the early 1960s. More recently, a potassium topping cycle has been proposed by Oak Ridge National Laboratory for use with the molten salt nuclear reactor (Ref. 39). A three-fluid (i.e., tenary cycle) system involving a gas turbine in addition to the potassium and steam cycles has also been suggested. Alternative fossil fuels considered for this system included coal, oil and gas (Refs. 40 and 41). Others have also studied a potassium-steam binary cycle of more conventional design using coal as a fuel. At present, except for the HTGR, nuclear heat sources for the potassium cycle are nonexistent. Use of the potassium topping cycle with an HTGR has apparently not been investigated. The need to develop high temperature furnaces and boilers as part of a program to bring potassium topping cycles to fruition is recognized.

During the 1960s, various agencies of the government were engaged in the development of the technology for potassium (and cesium) Rankine space power systems. Several turbines were built and operated on potassium vapor. The largest of these were 250 and 340 hp. The turbine efficiencies were measured and found to be about 75%, confirming design predictions. The blades and disks were, for the most part, fabricated of nickel based alloys. Potassium boilers, condensers and pumps in relatively small sizes have been successfully tested.

The scale-up from current research and development experience for the turbine rating is in the range of 300- to 1000-fold. Thus, turbine blade manufacturing techniques using appropriate alloys must be developed for the very large blade sizes required. Similarly the turbine seal, which must exclude oxygen (air) from the potassium loop, must also be scaled up successfully. Oak Ridge National Laboratory, under a grant from the National Science Foundation, began the construction of a potassium boiler module in 1974. This is a several megawatt capacity unit designed to operate at the 1550F level. The ERDA has recently begun funding of paper studies to utilize fluidized bed coal combustion as the energy source.

In summary, neither mercury nor potassium Rankine topping cycles are now being offered commercially. The mercury system was developed at one time, and the potassium system is under active investigation. Manufacturing facilities and background capability for the equipment in this type of system would be available from a number of well established manufacturers.

10.5 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

Due to the nature of the problems facing the potassium topping cycle energy system, and the relatively small amount of attention the problem appears to have received, it is not possible at this time to accurately estimate when this energy system may begin to contribute significantly to U.S. energy needs. Widespread use could possibly occur by the 1990s if much larger research and development funds are invested.

10.6 COSTS AND BENEFITS

No meaningful information exists on the costs of a potassium topping cycle for fossil fuel plants. Clearly, because of the increased complexity, the plant capital costs will be higher than a conventional steam plant but these could be offset by higher plant efficiency. Detailed plant and equipment design studies are needed to develop more reliable cost data.

The major advantage of the binary cycles using potassium with steam is that of increased conversion efficiency. The benefits that stem from an increase in efficiency (such as reductions in fuel consumption, waste heat release, and production of pollutants) will apply to both fossil fired and nuclear plants. The disadvantages (higher capital and maintenance costs and increased complexity of the plant and its operation) will also be applicable to both. The extent to which the advantages will outweigh the disadvantages is unknown.

10.7 ENVIRONMENTAL APPRAISAL

The reduction of fossil fuel consumption due to higher efficiency automatically reduces the quantity of most of the air pollutants produced per unit of electrical energy generated. Likewise, the waste heat discharged by the plant will be considerably curtailed. Accidental discharge of large quantities of potassium to the environment would be harmful to vegetation and animal life in the immediate area of the plant. Runoff of potassium wastes into groundwater, streams, lakes or oceans could be detrimental. At low concentrations, potassium will not be hazardous since it is a normal constituent of foods. Fail safe, 100% efficient seals or the use of suitable scrubbing equipment would have to be developed to prevent the release of sizable quantities of potassium from a power plant.

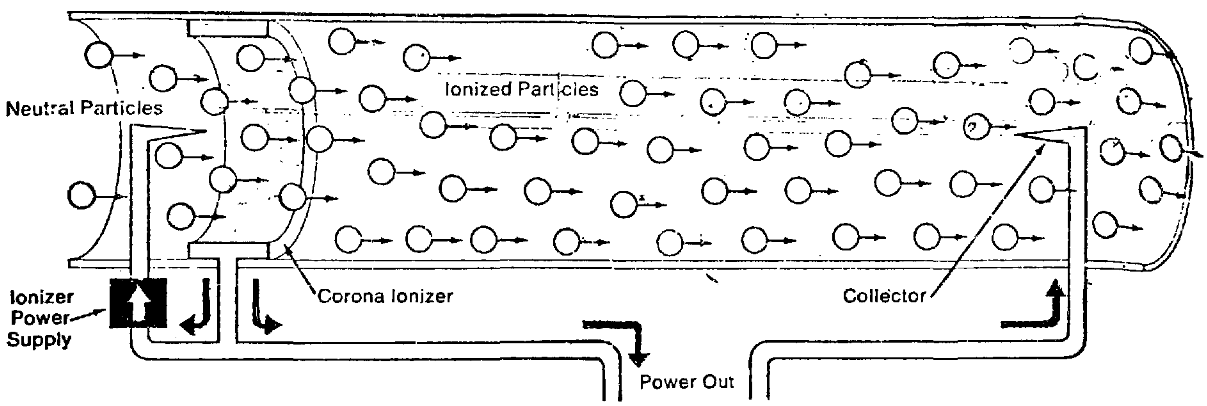

Fig. 18 - Schematic of the EGD Basic Operation

loses kinetic energy which shows up as electricity at the output terminals when the electrons are reunited with the gas at the collector.

The basic difference between the EGD and the magnetohydrodynamic (MHD) generators in that the MHD generator operates by accelerating a highly ionized gas through an electromagnetic field which induces an emf and a current in the gas similar to the armature windings of a conventional generator passing through its magnetic field. The MHD generator produces a low voltage, high current dc power while the EGD generator produces a high voltage, low current dc power (Ref. 43).

Flow velocities in the EGD generator can be supersonic or subsonic. Increasing the flow velocity from subsonic to supersonic speeds permits the tube length-to-diameter ratio to be increased which presumably allows more energy to be extracted from the gas. This increases the output somewhat; however, the relative amount of energy extracted from the gas does not change because more energy is required to accelerate the gas (Ref. 43). That is, the efficiency remains about the same.

The longer length-to-diameter ratio of the tube allows a longer distance between the collector electrode and the corona electrode so that a larger voltage difference can be sustained without exceeding the breakdown voltage of the gas. In this way, the voltage can be increased. Expansion of the gas through a supersonic nozzle can cool the gas to such an extent that vapor droplets are condensed out and these droplets can become the charged particles. However, for large power plants, most experimenters (Ref. 43) feel that the subsonic converter holds more promise. The charged particles in a subsonic EGD generator are typically particles of dust (i.e., fly ash). These particles carry a number of charges on their surface, rather than a single charge captured by the condensing vapor droplet.

The consensus is that the EGD converter must be a slender tube. There must be several stages of the tubes in series to achieve the required efficiency with the gas flow at a subsonic velocity and seeded with small ($\sim 0.2\mu$ diameter) particles (Ref. 43). Gas density must be as high or higher than normal atmospheric density and the temperature must not be so high that charges leak through the insulating walls.

11.1 EFFICIENCY

The overall thermal efficiency of the EGD converter depends strongly on the particle size, the corona charging field and the dust loading. With a dust loading of 0.4 and particles of 2μ diameters, the overall system efficiency has been predicted (Ref. 43) to be 33%. If the same loading is maintained and the particle size decreased to 1μ, the efficiency is expected to increase to 48%. Approximately 10% mass of particulates from conventional pulverized coal combustion are less than 4μ in diameter.

11.2 SIZE LIMITATIONS

Even though the EGD is quite simple in principle there are some fundamental limitations. The first is associated with the required EGD force to oppose the flow of the moving gas. The force is comparable to the force produced by a turbine. That force is given by the product of three factors: (1) the charge on an electron; (2) the longitudinal electric field; and (3) the number of ions per cubic foot of the gas. Now, the maximum longitudinal electrical field is limited by the breakdown strength of the gas so that knowing this number, the minimum number of ions per cubic foot can be calculated and an estimate of the tube length made. However, the ion density has an associated electrostatic field due to the presence of the ions and the balancing charges from which they were separated. If the space in the tube is large; the field produced by the ions themselves can easily exceed the breakdown strength of the gas. This says in essence that for a given chamber size and gas pressure only so many ions can be accommodated. In EGD generators this is referred to as the radial electrostatic field since in the geometry of the EGD channel, the ions are separated from their balancing charges (electrons) in the radial direction only. This radial field is zero at the center of the channel and increases with increasing channel diameter. The induction of radial ion drift imposes a limitation on tube length since the ions cannot be transported many diameters down the tube before they drift into the wall.

11.3 DEVELOPMENT STATUS

The EGD energy converter is still in the experimental development stage. Small scale experiments were conducted in the late 1960s under contract to the Office of Coal Research and in cooperation with the Foster Wheeler Corporation (Ref. 43). A converter was designed as a coal fired EGD test facility with a thermal capacity close to half a megawatt. The configuration contained two channels in series, each 32 mm in diameter and 100 mm long. Each channel produced 30 W at 500,000 V (Ref. 43). Efficiency or power density were not calculated. The final outcome of the program is not presently known.

11.4 ANTICIPATED CONTRIBUTION TO U.S. ENERGY NEEDS

A significant portion of the research and development work on the EGD in the U.S. appears to be directed toward applications other than large commercial power plants, primarily where compactness, mobility and/or non-moving parts are required. Typical applications include power generation for electrostatic spray guns used in paint and coating operations, space vehicle power generation and medical therapy requiring a room to be filled with aerosols.

The future of the EGD as a large scale power generator is unknown at this time. Data published by Chemical Engineering (Ref. 9) indicate that the development of electrogasdynamic generators will show significant progress in the early 1980s with a breakthrough in large scale designs being achieved by 1985 with significant output being delivered by the year 2000.

11.5 COSTS AND BENEFITS

Preliminary cost analysis (Ref. 43) indicates that electrical power via an electrogasdynamic generator can be delivered by high voltage dc transmission at a cost comparable to nuclear power generation. These predictions are based on the assumption of a capital cost saving over conventional coal fired plants of approximately 30% and an overall thermal efficiency in the 40 to 50% range.

A prime advantage of the EGD generator is that it does not require cooling water. Heat rejection is accomplished by exhausting the combustion gases into the atmosphere. This can be important since a principal factor in determining the location of large steam powered plants is the availability of cooling water for condensing the stream. If the power station was a coal fired EGD baseload generator, for example, it could then be located wherever the coal was cheapest regardless of water supply.

11.6 APPRAISAL OF ENVIRONMENTAL ASPECTS

As a large scale power generator, the associated environmental impacts will depend on the method of gas production for the generator. Heat will probably be rejected to the atmosphere, thus eliminating the need for large bodies of cooling water and the accompanying thermal pollution of the water supply.

Exhausting the combustion gases to the atmosphere should not present a problem (Ref. 43). Open cycle systems will have to maintain pollution control of the seeding particles which are expected to be of the order of 4μ or less. Problems (if any) presented by the exhaust gases cannot be assessed at this time since typical operating pressures and temperatures have not been established.

11.7 RESEARCH AND DEVELOPMENT CONSIDERATIONS

Research and development requirements for control technology should be assessed when the preliminary systems studies for large power plants are being conducted.

Section 12

RECOMMENDED ENVIRONMENTAL R&D PRIORITIES FOR CANDIDATE ENERGY SYSTEMS

Most of the advanced energy systems addressed in this report are in the stage of development where the pollution potential has not been seriously considered. This has resulted in part because in many instances only the basic technical feasibility of the system has been studied. One objective of this study has been to identify those areas where the potential for pollution exists in order that pollution control technology (if required) can be developed integrally with the energy conversion technology.

Most of the advanced energy systems examined will use either the conventional coal fired combustion or other low grade fuel to supply thermal energy in the foreseeable future. Each of these systems characteristically has an improved thermal efficiency in comparison to the conventional steam power energy generator. The net result is a reduction in the thermal energy rejected by the system and hence a reduction in thermal pollution. The improved efficiency also has the added advantage of requiring less fuel, and hence less pollution, to produce an equivalent amount of energy by current energy producing plants. However, each system was invariably found to have some unique feature that will require an evaluation of the potential adverse environmental effects.

MHD: The magnetohydrodynamic energy converter is projected to utilize an alkali metal as a seed material for a high energy gas stream with the seed material being collected for reuse. Seed material candidates, such as potassium, can have an adverse effect on the environment when present in large concentrations. Large concentrations can occur from normal operations with inadequate particulate control devices.

An evaluation of the collection efficiency (the size distribution of emissions versus collection device efficiency) should be made and a worst case analysis conducted to determine the expected concentration levels emitted during normal operation. The next step is to determine the need for establishing emission standards and at the same time assess the need for further development of the seed collection technology.

The basic MHD technology has already been developed with construction of a demonstration plant expected in the mid 1980s. To most effectively impact the design of these systems an environmental assessment should be conducted during the 1976-77 time period and an evaluation made of the adequacy of the seed collection technology.

Also, NO_x control technology is required for MHD units because of the emphasis on high temperature combustion. This area of technology is currently receiving attention (Ref. 6), but further research and a continuing assessment of MHD NO_x control technology development is warranted. In particular, EPA should be involved in emission data collection and assessment of ERDA's planned MHD demonstration plants.

An indirect effect which should be investigated is the increase in pollution and energy consumption (if any) associated with the manufacture of large quantities of seed materials. This can be conducted during the same time frame as the environmental assessment of the unit operations.

<u>Hydrogen Fuel Cells</u>: Environmental studies with respect to the utilization of hydrogen fuels in utility size power plants should be directed toward the discharge of waste and wastewater. Most probable discharges will be leachate from the fuel cells and sludge generated by the electrolysis process. A demonstration plant is currently being put into operation. An environmental assessment of the unit operations should be conducted during the 1976-77 time frame to define the emission sources and the expected emission rates. An assessment of the adequacy of existing control technology can then be made.

Ocean Thermal Energy Conversion: OTEC plants will be designed to move large quantities of water through the system and consequently will be rather large structures physically. This, coupled with the requirement for a large number of plants to produce a significant amount of energy, provides some unique environmental situations that are not apparent from a cursory examination. Cold water from the ocean depths used in the condensing phase will be exhausted at a temperature of 45F (a differential with surface water temperature of approximately 30F). The warm water from the exhaust phase will be exhausted at about 74F which is approximately 3F cooler than the inlet surface water. These two streams (undersea plumes) will mix, and coupled with the plumes from adjacent plants, will probably stretch for many miles before equilibrating with the surface water. Two possible consequences of this are modification of the local weather patterns and an adverse effect on the local marine life (i.e., plankton, fish, etc.). Neither of these effects is readily accessible at this time. Recommended research topics include an evaluation of the size of the area affected by the undersea plumes and the associated water temperatures. This can be accomplished with the state of the art of numerical flow analyses. The effect of excess nutrients (probably beneficial) brought to the surface by the cold water upwelling can be studied from samples taken from the ocean depths and the effect correlated with the amount of water expected to be used in the condensing operation. The effect of spills and leaching is not known so that an assessment of control technology needs is required at this time.

The widespread use of the OTEC system is projected by the year 2000. However, rather extensive conceptual and feasibility studies are currently being conducted. Due to the unknown adverse effect of the cold undersea plumes, studies should be initiated as soon as possible to define the interaction of the undersea plumes with warm surface waters.

Windmills: Windmill power plants are also unique in that on an individual basis, each unit probably will have a negligible effect on the environment. However, to produce power for commercial and community use, large numbers of windmills will be clustered. The potential then exists for weather modification and adverse indirect effects (land use and aesthetics). The technology to produce power from windmill plants currently exists. The demonstration unit at NASA's Plumbrook facility has been constructed to provide data for the design of commercial class power generation plants. Consequently, to most effectively contribute to the design of commercial systems, the environmental assessments should be initiated in the current year.

The potential for weather modification can be studied in an environmental chamber. The most profitable approach is to parametrically investigate, windmill size (height, etc.), blade design, clustering and terrain.

Potassium Topping Cycles: The primary environmental consequence of a potassium topping cycle is the accidental discharge of large quantities of potassium wastes into groundwater, streams, lakes or oceans. Fail-safe seals or suitable scrubbing equipment may have to be developed to prevent the release of sizable quantities from a power plant.

The projection of widespread use of the topping cycle is by the year 1990. An appraisal of the effect of the discharge of large quantities of potassium and the state of associated control technology should be initiated during the 1976-77 time period.

Gas Turbines: The basic gas turbine technology is currently well developed and being extended to high temperature operation to increase the thermal efficiency. Gas turbines require a low sulfur, low ash fuel for turbine operation so that fly ash and SO_x emissions are negligible. However, a present stack effluent is oxides of nitrogen (NO and NO_2). The technique now used to treat the problem is to inject demineralized water into the combustion chamber which lowers the flame temperature. For the higher operation temperatures desired new methods of NO_x control will be required; for instance combustion process modification.

A set of emission standards for gas turbines is needed (such as the maximum values applying to conventional steam plants) to provide realistic design targets for research to reduce the oxides of nitrogen.

Research studies on control technology should be initiated during 1976 to define possible candidate schemes which can then be assessed with respect to the most favorable design applications.

Thermionic and Electrogasdynamic Direct Energy Converters: These systems are still in the basic device development stage. Neither converter appears to have much potential as a base load generator. However, utilized as the upper portion of a topping cycle, these systems can increase the thermal efficiency of the power plant. Operating in this manner, the converter would use the flue gas from the coal fired steam plant as the converter working fluid.

The environmental impact of the converter operating in this capacity is not known at the present time. Consequently, an environmental assessment should first be conducted to identify any potential environmental problems. These can then be categorized and recommended control technology studies formulated where necessary to provide adequate pollution control.

Thermoelectric Converter: The extremely low thermal efficiencies of thermoelectrics virtually preclude their being used as power generators in utility size power plants. The required power output means more fuel consumed than competitive systems, with more heat rejected to the environment and consequently energy sources depleted at a faster rate than is now the case. For central power plants this is unacceptable so that no meaningful R&D work is currently envisioned with respect to utility size power generators.

Summary: In conclusion, the advanced energy systems considered in this study are receiving technology development funds at an increasing rate while at the same time are receiving token attention with respect to environmental control. Due to the many benefits of integral development of both energy conversion technology and environmental control technology, it is therefore recommended that substantial pollution control and assessment studies be initiated for these systems within the next two years. Considering both the expected environmental impact and period of technology breakthrough/commercialization, the following order of R&D priorities on the candidate energy systems has been developed: high temperature turbines, ocean thermal gradients, windmills, magnetohydrodynamics, metal vapor (potassium) Rankine topping cycles, hydrogen fuel cells, thermionics, electrogasdynamics, and thermoelectric conversion.

It has also been obvious during the course of this survey that a great deal of emphasis is and will be spent on energy conservation technologies for the industrial and other sectors of the U.S. economy. Very little evidence was found on environmental assessment considerations for these energy conservation technologies. Thus it is recommended that a study, similar to the present analysis, be conducted on energy conservation.

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16. ABSTRACT

The report gives a review of the development status of several advanced energy concepts and discusses the primary environmental hazards of each system. Systems reviewed include potential new sources of energy and improved energy conversion. Each system is evaluated with respect to its development status, and estimates made as to when each will begin to contribute significantly to U.S. energy needs. Appraisals were made of the environmental impact of each system including assessment of the adequacy of pollution control technology and potential gross ecological impact. The overall conclusion is that each energy system has a negligible or mild direct environmental impact when compared with conventional fossil fuel and nuclear systems, but that indirect impacts for some of the energy systems could be severe and need further study to quantify their impact. Considering both the expected environmental impact and period of technology breakthrough/commercialization, the following order of R&D priorities on the candidate energy systems has been developed: high temperature turbines, ocean thermal gradients, windmills, magnetohydrodynamics, metal vapor (potassium) Rankine topping cycles, hydrogen fuel cells, thermionics, electrogasdynamics, and thermoelectric conversion.

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