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UNITED TECHNOLOGIES RESEARCH CENTER

East Hartford, Connecticut 06108

R81-955343-9

Final Study Report of an Applications Study of Advanced Power Generation Systems Utilizing Coal-Derived Fuels

Volume I - Executive Summary

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DR No. 6

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Fred. L. Robson
Chief, Utility Power Systems

Date March 1981

FOREWORD

This application study of advanced power generation systems utilizing coal-derived fuels was performed by United Technologies Research Center with subcontract assistance from Burns and Roe, Inc. The study program has been prepared under Contract NAS8-33996 for Marshall Spare Flight Center of the National Aeronautics and Space Administration. The technical work described herein was initiated in September 1980 and completed in March 1981.

The technical results of this application study are presented in two parts. The first part is an Executive Summary (Volume I) which provides a concise review of all major elements of the study. The second part is a detailed Technical Report (Volume II) describing the technology status of the three advanced power generation systems studied (combined cycle gas turbine, fuel cells, and magnetohydrodynamics) and the performance of these generation systems either utilizing a medium-Btu coal-derived fuel supplied via pipeline from a large central coal gasification facility or integrated with a gasification facility for supplying medium-Btu coal-derived fuel gas.

The United Technologies Research Center provided overall program management and the major contributions to the combined cycle gas turbine and fuel cell power plant evaluation. This effort involved:

Fred L. Robson, Program Manager
Robert D. Lessard, Deputy Program Manager
William A. Blecher
Stewart J. Lehman
W. Richard Davison

Burns and Roe provided the major contributions to the magnetohydrodynamics power plant evaluation. This effort involved:

Albert W. Carlson

The study program was conducted under the general direction of Richard D. Kramer and Robert Giudici of Marshall Space Flight Center.

The support and assistance of all the aforementioned individuals and organizations in contributing to the successful completion of this study program is acknowledged with sincere appreciation.

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Final Study Report of an Applications Study of Advanced Power Generation Systems Utilizing Coal-Derived Fuels

Volume I - Executive Summary

One of the most promising methods for utilizing coal for electric power generation is to gasify it and then combust the fuel gas in an advanced technology power generation system. The analysis of gasification/power generation systems has been the subject of numerous studies in recent years. Despite the proliferation of studies it is often difficult to effectively utilize the data generated because of the differing guidelines which have existed among the studies. Consequently, if data were desired for a specific generation system application, it is often necessary to develop the data unique to that application.

Two applications of interest to Marshall Space Flight Center (MSFC) involve power generation systems that either 1) utilize a medium-Btu coal-derived fuel gas supplied via pipeline from a large central coal gasification facility, or 2) are integrated with a gasification facility for supplying medium-Btu coal-derived fuel gas. Although previous studies have considered these applications, the requirement still exists to evaluate the employment of specific power generation systems in these applications, namely, combined-cycle gas turbines, fuel cells, and magnetohydrodynamics (MHD), on a consistent basis. The objectives of this study are to provide 1) descriptions of the state of the art for these conversion systems and projections of future technological advances; and 2) an assessment of the performance of each of these power conversion systems using medium-Btu fuel gas. This document presents the results of Task 1 (Assessment of Systems Technology Status), Task 2 (Description of Advanced Power Systems), Task 3 (Evaluation of Advanced Power System Utilizing Coal-Derived Medium-Btu Gas), and Task 4 (Evaluation of Advanced Power Generation System Integrated with a Coal Gasifier Producing Medium-Btu Fuel Gas).

The work described in this report has been performed at United Technologies Research Center (UTRC) and Burns and Roe, Inc. (B&R) under Contract No. NAS8-33996 with George C. Marshall Space Flight Center of the National Aeronautics and Space Administration (MSFC).

Final Study Report of an Applications Study of Advanced Power Generation Systems Utilizing Coal-Derived Fuels

VOLUME I - EXECUTIVE SUMMARY

Electric utilities in the U.S. are required by law to meet the requirements of their customers for electricity at the lowest cost while meeting increasingly stringent environmental standards. The problem has been compounded by federal laws that preclude the use of clean petroleum-based fuels in new power stations. In recent years, various studies have been carried out to identify technology which could utilize coal or coal-derived fuels to produce electric power at a low cost and in an environmentally acceptable manner.

As part of an overall NASA Energy Systems Division program, the Marshall Space Flight Center (MSFC) contracted with the team of United Technologies Research Center and Burns and Roe, Inc. to carry out a study of advanced power generation systems utilizing coal-derived fuels. The objective of this study was to provide MSFC with the technical knowledge and developmental status in advanced energy conversion systems. To do this, the study compiled the technological status of phosphoric acid and molten carbonate fuel cells, combined gas and steam turbine cycles, and magnetohydrodynamic (MHD) energy conversion systems. In addition, this study provided analyses of the performance of these systems when operating with medium-Btu fuel gas either delivered via pipeline to the power plant site or in an integrated mode in which the coal gasification process and the power system are closely coupled as an overall power plant.

TECHNOLOGICAL STATUS

The three power conversion systems considered are at different stages of technological evolution. A very brief review of the status of each is given in the following paragraphs. In addition, the technology level utilized in the performance analyses is also given. The technology level assumed for each of the power generation systems was that which, in the judgment of the Contractor and NASA personnel, represented: a) the first level of advancement over currently commercially available equipment; or b) the initial level of technology projected to be available for commercial application for systems not currently in commercial operation. Thus, the baseline technologies are those which could be available in the late-1980 decade or 1990 decade for commercial orders.

Fuel Cells

The fuel cell and the flashlite battery operate in a similar manner except that the fuel cell electrode materials are not consumed. In the fuel cell, the electrode material and the electrolyte contain the chemical components which produce the electrochemical reaction. Fuel cell electrodes are generally thin, porous and electrically conducting. Catalysts are used to decrease reaction time. The electrolyte may be acidic or basic; a molten salt or even a solid.

Phosphoric Acid Fuel Cells

The fuel cell type nearest to commercial feasibility is the phosphoric acid cell. In this cell, phosphoric acid is the electrolyte and hydrogen and oxygen are the reactant gases. In this cell, shown schematically in Fig. 1, hydrogen reacts at the anode forming electrons, which pass through the external circuit to the cathode, and positive ions which pass through the electrolyte to complete the circuit. Direct current is produced by the fuel cell so that an inverter is required to adapt the system to the utility grid.

Since the hydrogen is the fuel, other fuel forms are reformed or shifted to hydrogen and carbon dioxide in some type of fuel processor. Air supplies the required oxygen.

Because the fuel cell consists of a number of stacked assemblies, each assembly having an output of 0.65 to 1.0 volts dc, the output can be varied to any desired level. Currently a 4.8 MW (dc)/4.5 MW (ac) phosphoric acid fuel cell is engaged in a demonstration program designed to indicate operability in utility environment.

The baseline technology for phosphoric acid cells is given in Table 1.

Molten Carbonate

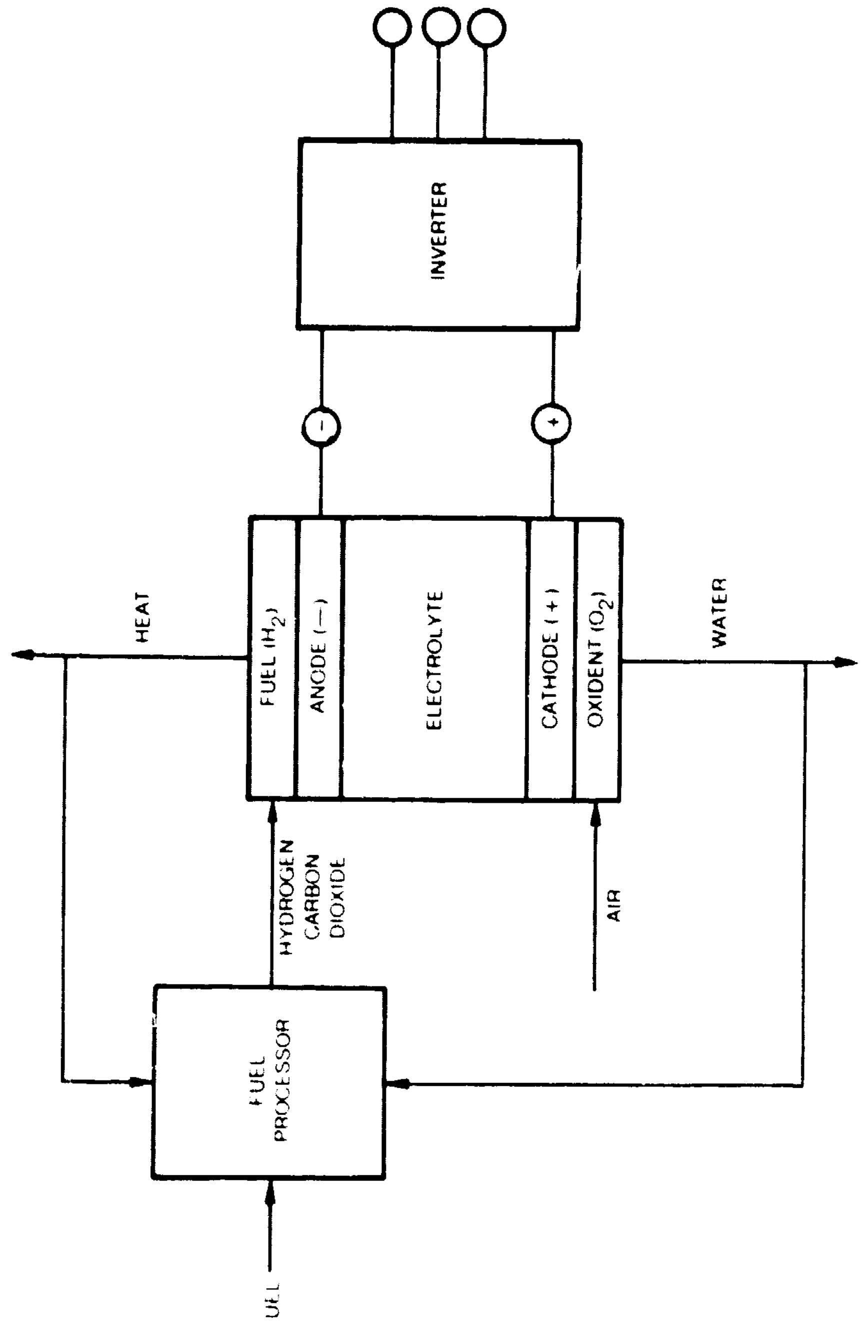
Much of the ongoing development work on advanced fuel cell concepts is being carried out on the molten carbonate cell. In this cell, the electrolyte is a mixture of liquid carbonate salts and small lithium aluminate particles. Electrolyte sheets of about 0.1-inch thickness are made from pressed powder consisting of lithium and potassium carbonate with lithium aluminate. As the cell is heated, the carbonates become liquid but do not flow. The anode is usually constructed of porous nickel and the cathode of nickel oxide, both resistant to hot carbonate attack.

The molten carbonate cell is presently in the laboratory stage of development. Operation of small scale (4 in. x 4 in.) cells is measured in a few thousand of hours. The system, however, offers the potential for highly efficient operation on coal-derived fuels. A typical molten carbonate fuel cell power plant configuration is displayed in Fig. 2 and the baseline technology for this system is given in Table 2.

Combined Gas and Steam Turbine Cycles

The combined gas and steam turbine or, simply, the combined-cycle power system is a joining together of two well-known methods of generating power--the gas turbine and the steam turbine, Fig. 3. Combined cycles using early gas turbine technology have been used for many years in several U.S. utilities. However, to achieve the full advantages of combined-cycle power systems, research and development on advanced gas turbines remains to be done.

The high technology base of the combined cycle is the gas turbine. The gas turbine has been used to generate power for nearly 50 years, but it is best known in its role as the aircraft jet engine. For power generation, the basic components are similar to those used in the jet engine, with additional components used to



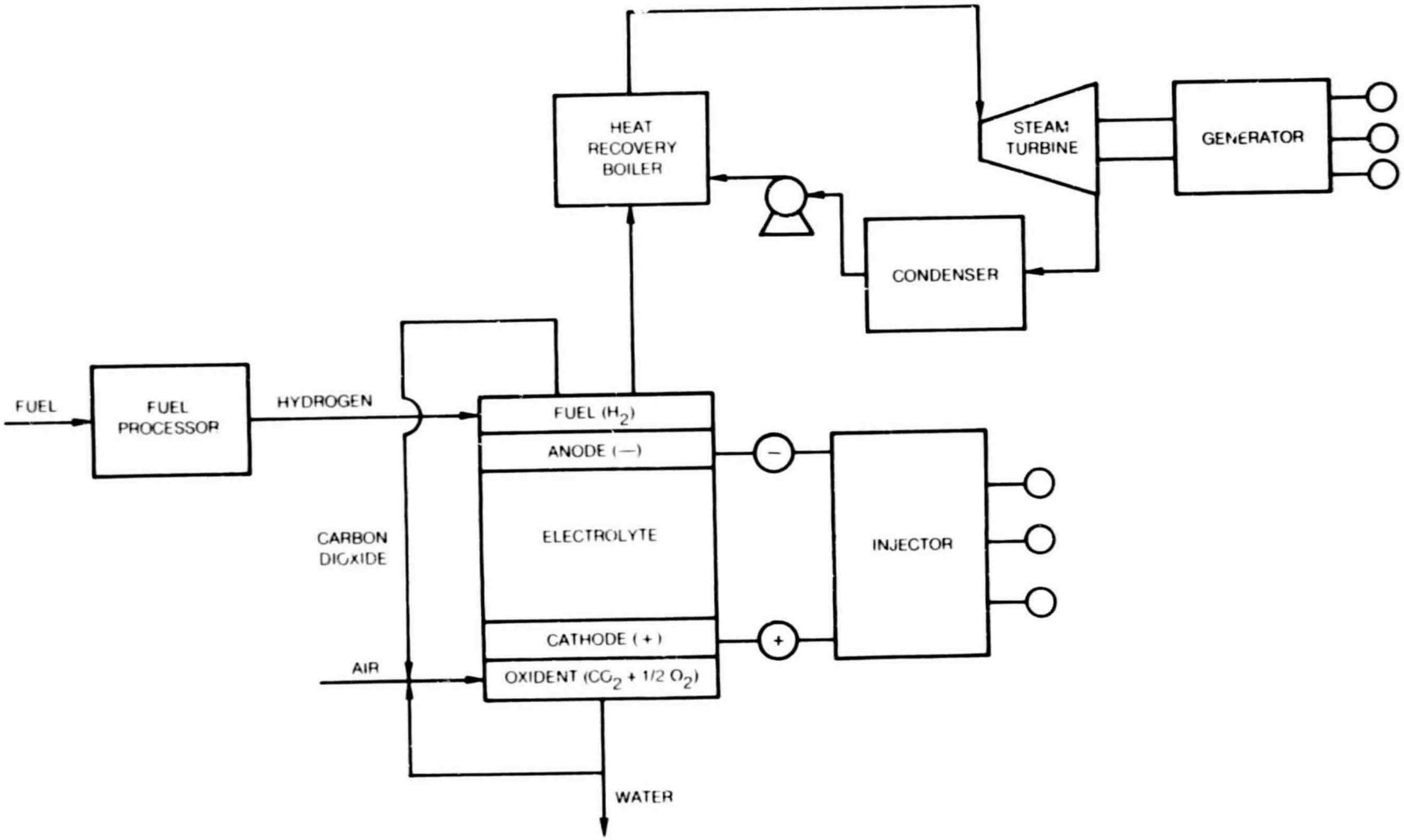
SCHEMATIC OF PHOSPHORIC ACID FUEL CELL POWER SYSTEM

81-3-100-11

TABLE 1

BASELINE TECHNOLOGY FOR PHOSPHORIC ACID FUEL CELL

Cell Voltage, V	0.65
Fuel Utilization, %	90
Oxidant Utilization, %	50-75
Gross DC Power Density, W/ft^2	140-170
Cell Stack Output, MW	.675
Number of Cell Stacks	18
Total DC Module Output to Inverter, MW	12.1
Net Power Plant Output, MW	11.0



SCHEMATIC OF MOLTEN CARBONATE FUEL CELL POWER SYSTEM

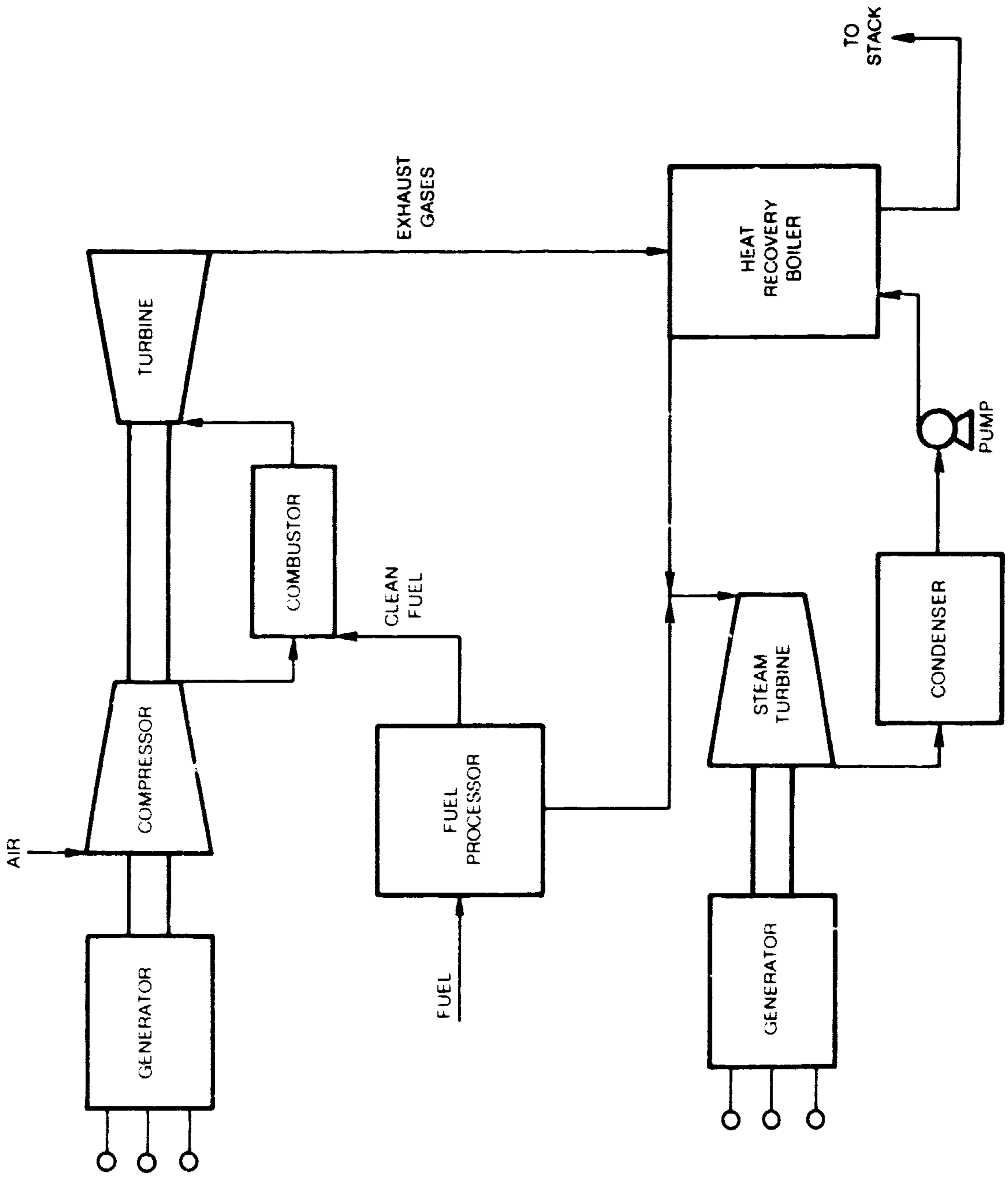
FIG. 2

TABLE 2

BASELINE TECHNOLOGY FOR MOLTEN CARBONATE FUEL CELL

Cell Voltage, V	0.75
Fuel Utilization, %	50
Oxidant Utilization, %	58
Gross DC Power Density, W/ft^2	146
DC Module Output	4.18
Number of DC Modules	250
Total DC Output to Inverter, MW	1044.6

FIG. 3



SCHEMATIC OF COMBINED CYCLE POWER SYSTEM

81–3–100–13

TABLE 3

BASELINE TECHNOLOGY FOR COMBINED CYCLE SYSTEM

Gas Turbine Flow Rate, lb/sec	860
Combustor Exit Temp., F	2400
Pressure Ratio	12
Power Output, MW	135.7
Steam Turbine Pressure, psia	2400
Steam Turbine Temp., F	1000
Combined Cycle Output,[(1)] MW	402.2

[(1)]Two gas turbines and one steam turbine extract power from the hot exhaust gases. The gas turbine is an internal combustion engine which, in contrast to an automobile engine, is operated in a steady combustion manner. The working fluid--air--is compressed, heated and expanded in independent engine components. Air is first taken into a section of the engine called the compressor where the pressure is increased from atmospheric to 10 or more atmospheres. From the compressor, the high-pressure air goes to the combustor where fuel (either liquid or gaseous) is burned to raise the temperature to about 2000 F or more. This very hot, high-pressure gas is then expanded in the turbine section where it does work by pushing on the turbine blades, thereby turning the shaft on which are attached an electrical generator and the compressor. The gases leaving the turbines are still very hot, perhaps 900 F to 1000 F or more.

The steam portion of the combined cycle closely resembles the conventional steam equipment which generates most of the electricity in this country. However, instead of the conventional boiler which would burn coal, oil, or natural gas, the heat in the gas turbine exhaust is used to raise high-pressure steam. This steam is now the working fluid used in a steam turbine which drives a generator. The combustion gases are cooled to about 300 F before being exhausted from the boiler. Although a typical gas turbine operates between temperature limits of approximately 2000 F and 1000 F at an efficiency of 30 percent, and a steam cycle operates between approximately 1000 F and 100 F at an efficiency of 35 percent, in a combined cycle they operate between approximately 2000 F and 100 F at an efficiency of around 43 percent. If the currently used aircraft gas turbine cooling technology can be used with acceptable life of components for the hot gas path parts of industrial gas turbines, an increase in turbine inlet temperature to 2300 - 2400 F could be expected.

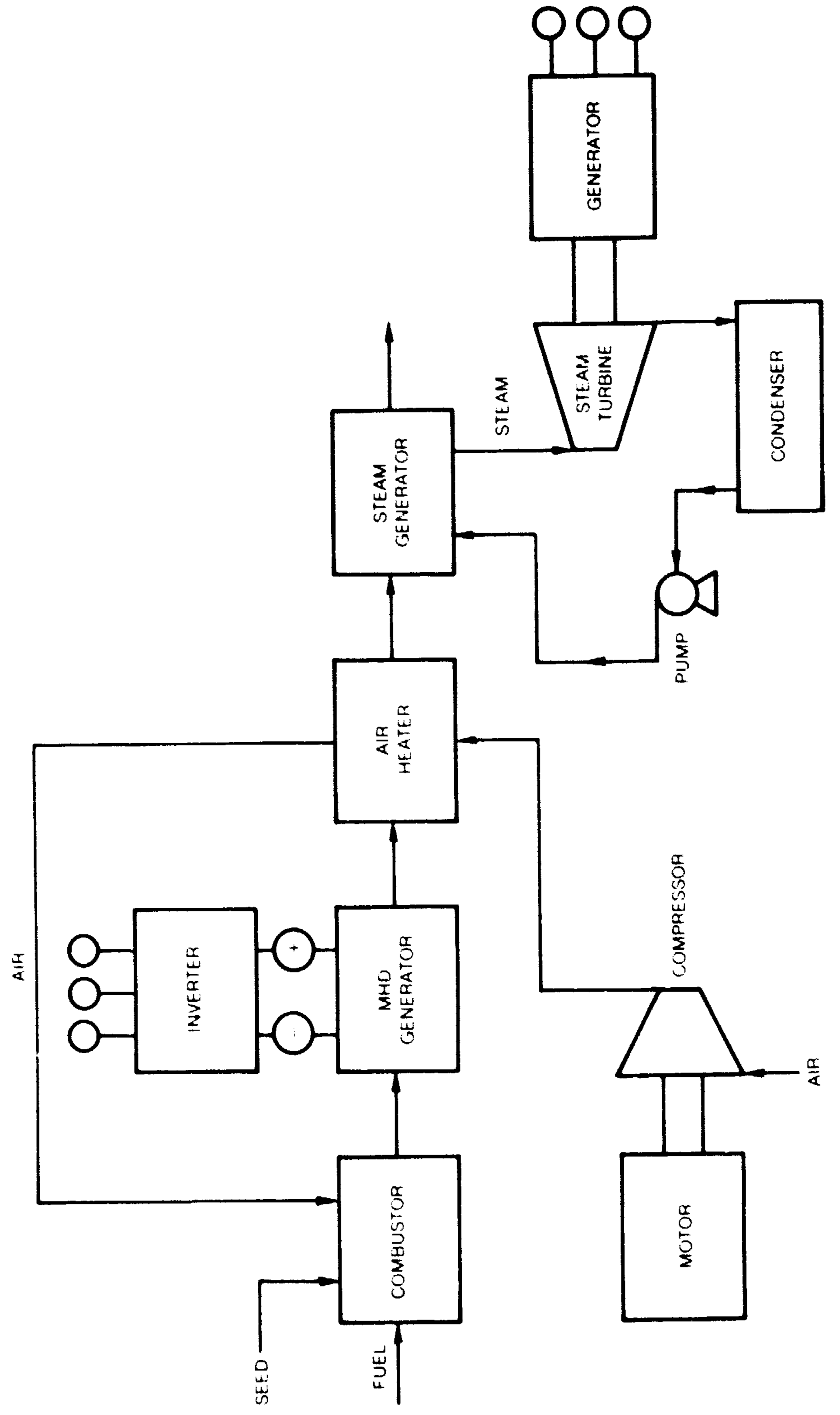
The baseline technology for this system is given in Table 3.

MHD (Magnetohydrodynamics)

In an MHD system, current is generated by the motion of an electrically conducting gas through electric and magnetic fields. The gas is contained in an enclosed duct or generator channel which has two insulating walls and two electrode walls and a magnetic field applied perpendicular to the axis of the duct. As the conducting gas, usually an ionized gas or plasma, flows through the duct, electrical energy is extracted directly from the kinetic and thermal energy due to its interaction with the magnetic field. The MHD generator behaves as an electromagnetic 'turbine,' being thermodynamically equivalent to a gas turbine. (Fig. 4)

The MHD generator operates at a much higher temperature than a gas turbine because in order to ionize gases, temperature of 4000 F or more are required. The ability to contain working fluids at these high temperatures poses one of the major development tasks for the MHD concept.

The MHD system is the furthest from commercialization of the advanced power systems considered. Several small-scale systems have been demonstrated both in the U.S. and abroad. However, a number of basic technological problem areas remain. The performance of the MHD power system, which includes steam heat recovery similar to the combined gas and steam turbine cycle, is very attractive. Table 4 lists the baseline technology selected for this program.



SCHEMATIC OF MHD/STEAM COMBINED-CYCLE POWER SYSTEM

81-3-100-14

TABLE 4

BASELINE TECHNOLOGY FOR MHD SYSTEM

Oxidizer Flow, lb/sec (34% O_2)	1002
Peak Combustion Temp., F	4675
Duct Pressure Ratio, atm	9.1
Magnet Strength, Telsa	6
MHD Power, MW	554
Steam Power, MW	684
Total Power, MW	978.5

PERFORMANCE ANALYSES

One of the more attractive coal-derived fuels is medium-Btu fuel gas. This gas results from the partial combustion of coal with steam and oxygen. The heating value of this mixture of hydrogen, carbon monoxide, carbon dioxide, and water vapor ranges from approximately 250 Btu/ft^3 to 350 Btu/ft^3. (Natural gas, which is nearly all methane, has a heating value of approximately 1000 Btu/ft^3). The medium-Btu fuel gas can be transported economically by pipeline for distances of 100 or more miles for use as an industrial fuel or chemical feed stock. It can also be used for power generation.

Another method of using this fuel gas for power generation would closely integrate the gasification process and the energy conversion system thereby allowing interchange of heat and process streams. This results in an overall power plant which can efficiently convert coal to electricity.

Pipeline Delivery of Medium-Btu Fuel Gas

Medium Btu-fuel gas was assumed delivered by pipeline to the advanced power systems located at some distance from the fuel processing system. Fuel gas from two types of gasifiers, the entrained-flow Texaco and the slagging, moving-bed British Gas Corporation Lurgi-type were delivered to the site. Both gases were cleaned to 100 ppm sulfur and 0.1 percent moisture. There is very little difference between the gases and the performance of the various systems are quite similar with each gas.

Any further conditioning of the fuel gas to meet requirements of a particular power system is done as part of the power plant. For example, carbon monoxide is a poison to the phosphoric acid cell catalysts, therefore, a shift converter to change the carbon monoxide to hydrogen and carbon dioxide is necessary. Similarly, the molten carbonate fuel cell is very sensitive to sulfur, thus, further cleanup to very low levels is necessary. The combined-cycle systems and the MHD systems do not require any gas conditioning.

The performance on the pipeline delivery of fuel gas is given in Table 5 for the phosphoric acid fuel cell, the molten carbonate fuel cell, the combined cycle system and the MHD systems.

Integrated Gasification Advanced Power Systems

With the exemption of the phosphoric acid fuel cell, each of the power systems was integrated with the Texaco- and BGC-type gasifiers. (The phosphoric acid fuel cell does not benefit from integration and therefore was not considered for this application.) Unlike the pipeline delivery systems, there are discernible differences between the two gasifier types. These differences are due to efficiency differences in the gasifiers and also to methods of heat recovery in the integrated plants.

The performance of the integrated power plants are given in Table 6 for the molten carbonate fuel cell, the combined-cycle and the MHD systems.

TABLE 5

PERFORMANCE OF ADVANCED POWER SYSTEMS ON PIPELINE DELIVERY

Power System	Texaco	BGC
Phosphoric Acid Fuel Cell	40.8	40.8
Molten Carbonate Fuel Cell	63.5	58.2
Combined Cycle	51	50.5
MHD	46.3	47.6

TABLE 6

PERFORMANCE OF ADVANCED POWER SYSTEMS INTEGRATED WITH COAL GASIFIERS

Power System	Texaco	BGC
Molten Carbonate Fuel Cell	47.2	46.4
Combined Cycle	39.1	40.6
MHD	35.9	38.9

CONCLUSIONS

The review of the technology status of the advanced systems indicated that the combined-cycle gas turbine systems are commercially available. The advancements in technology required to reach the performance levels projected for the advanced systems are evolutionary in nature and represent logical extensions of technology, available in other areas (aircraft gas turbines).

The phosphoric acid fuel cell appears to be the next most likely candidate for commercialization. The 4.5-MW demonstration plant is of such a scale that extrapolation to larger sizes would involve only replication and would not present any significant technical problems. Because of the nature of the fuel cell, application of the phosphoric acid fuel cell in the nominal 5- to 25-MW size appears most attractive.

It appears that the molten carbonate fuel cell and the MHD systems will have to await the 1990 decade or beyond before commercialization.

A review of the performance of these advanced systems show that their efficiencies are very attractive. On pipeline delivery, they range from 40.9 percent for the phosphoric acid cell to 63 percent for the molten carbonate fuel cell system. A gas-fired conventional steam station efficiency would be in the 37-38 percent range.

The efficiencies of the integrated power plants vary from approximately 39-40 percent for the combined-cycle systems to 46-47 percent for the molten carbonate fuel cell systems. These efficiencies would be compared to that of coal-fired conventional steam stations with flue gas desulfurization to meet the Clean Air Act of 1977 standards, i.e., 33-35 percent. The attractiveness of the advanced systems in terms of performance is certainly apparent.