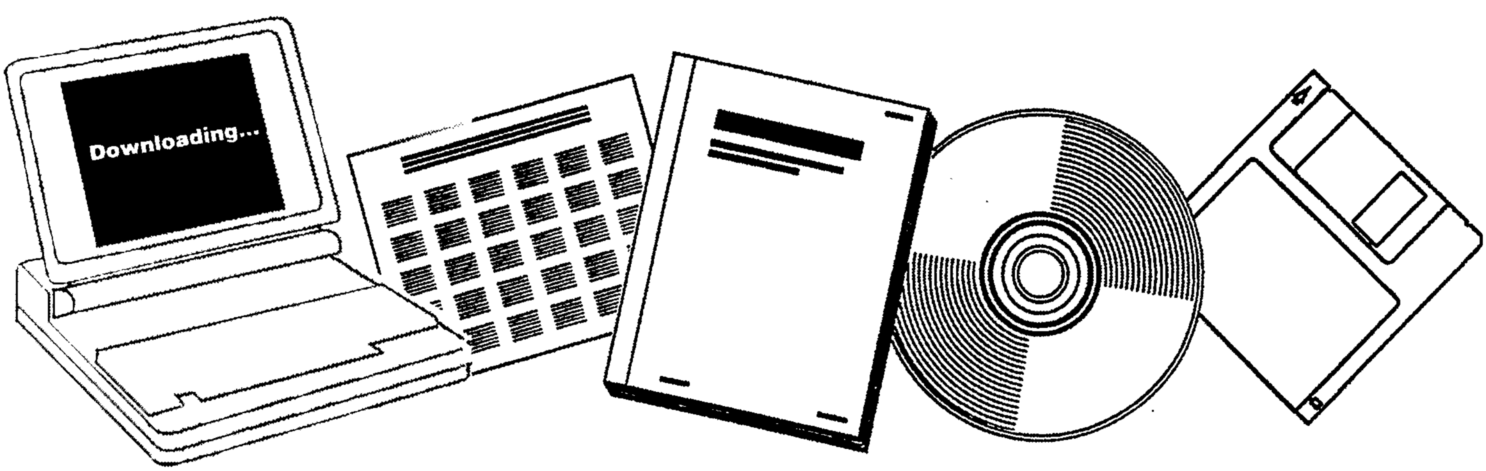
ADVANCED CONVERSION: C-1-B ADVANCED CONVERSION

USAEC, WASHINGTON, D.C

11 NOV 1974



ERDA CONTINGENCY PLANNING DOCUMENT

RESEARCH AND DEVELOPMENT
ASSIGNED TO ASSISTANT ADMINISTRATOR FOR
CONSERVATION

ADVANCED CONVERSION

C-1-B ADVANCED CONVERSION

NOVEMBER 11, 1974

PREPARED BY ATOMIC ENERGY COMMISSION

ADVANCED POWER CYCLES

Responsible Cadre Member: David S. Gabriel

Report Prepared By: G. Newby, I. Helms, M. Farfel, P. O'Riordan, D. Gabriel

Scope: The attached report (a) briefly considers the importance of advanced power cycles in economics and conservation, (b) reviews and summarizes Ray report recommendations, (c) reviews status of technologies, (d) reviews FY 74 and 75 budgets to extent possible, and (e) presents preliminary program issues, options and conclusions.

Budget Analysis: Significant budgetary problems are summarized as follows:

	$ Millions
Total U.S. Government FY 74	28.0 (Includes DOD, NASA)
Total U.S. Government FY 75	29.8 (Excludes DOD)
Our estimates for Ray Report Program - FY 75	57.0
Funds Recommended in Ray Report - FY 75 to 79	495.0
Funds Required to Accomplish Ray Report - FY 75 to 79	650 to 1200

<u>Tentative Conclusions</u>: In relation to the program content on conversion in the Ray Report, program planning and budgeting is a major problem. The future significance of the work has not been properly recognized and a practical plan consistent with budgetary constraints has not been developed.

I. BUDGET ANALYSIS

A. PROPOSALS - PRESIDENT'S BUDGET

A review of the funding chain of events from the receipt of energy proposals by the Panel on Conversion Techniques to the amount included in the President's FY 75 budget, indicates that the program proposed in the Ray report cannot be accomplished within the dollar limits recommended. Table 1 compares the various budget amounts (including our estimate of amounts for FY 75) required to accomplish the Ray report. Table 2 shows similar data for the five-year period FY 75 - FY 79.

In conducting this review, including looking at the basis included in proposals, drafts of panel reports, etc., it is our view that a realistic estimate of funding directly related to the Ray report program content and schedule was not done. Our guess is that to accomplish the objectives stated could require a factor of two over the dollars shown in the Ray report.

To perform the program requires funding around $50 to $60 million in FY 75 and would cost in the range of $650 to $1200 million over the 75- 79 period. Our estimate of the program recommended by Dr. Ray assumes that a "single source of supply" would be utilized for the different technology areas, i.e., no parallel efforts on the same technologies. It should also be made clear

Table 1. FY 1975 Funding - Advanced Power Cycles (In Millions)

	A Proposals Submitted	B Panel Spread	C English Report[1]	D Ray Report Cadre Assn.[1]	E President's Report	F Req'd To Accomplish Ray Report
High Temperature Gas Gas Turbines (Includes HTGR Helium Turbine)	78.5	34-83	15.0	18.3		28
MHD	43.7	20-35	10.0	7.0		12[2]
Potassium Topping Cycle	15.7	4-7	3.0			5
Fuel Cells	33.5	13-31	5.5	5.5		10
Advanced Concepts	8.3	5-10	2.0	2.0	—	2
Total	179.7	76-166	35.5	32.8	29.8	57

[1] Coal gasification, waste fuel and enabling technology deleted to be consistent with cadre assignment.

[2] To meet USSR commitment on MHD would require an additional $6.5 million.

Table 2. FY 75-79 Funding - Advanced Power Cycles (In Millions)

	A Proposals Submitted	B Panel Spread	C English Report	D Ray Report	E Req'd To Accomplish Ray Report
High Temperature Gas Turbines	1300	375-1200	225	315	315 to 600
MHD	600	143-349	95	90	80 to 200
Potassium Topping Cycle	420[1]	60-102[2]	65[2]		90 to 200[2]
Fuel Cells	440	116-205	80	80	130 to 150
Advanced Concepts	40	25-50	10	10	25 to 50
Total	2800	719-1906	475	495	640 to 1200

[1] Included demonstration plant after pilot plant.

[2] Demonstration plant estimated at $335 million is not included in 75-79 estimates.

that significant additional funding past FY 79 would be required to achieve the end point objectives leading to commercialization. The increase of approximately $27 million over the President's FY 75 amount could possibly be reapplied from enabling technology efforts and funding and basic research areas discussed later.

B. ALLOCATION OF FUNDS BY AGENCIES

We have attempted to evaluate not only the application of funds by technology to be pursued but also the allocation of funds to effectively utilize existing Federal agency capabilities. Table 3 provides the FY 74 and 75 estimates by agency included in the President's budget. We have also added what we estimate to be other funds being expended in the advanced power cycle area in FY 1974.

It should be noted that increases in FY 75 over FY 74 are insignificant. In addition, it appears that much of the capability that exists in NASA and DOD in the advanced power cycle area has not been incorporated into the agency allocations. Although the DOD and NASA funds might be directed at applications which are not directly transferable to terrestrial civilian applications, the research being conducted is the only research underway in some cases and is very basic to advanced power cycles in the fields of MHD, turbines and fuel cells.

Table 3. Advanced Power Cycles - Funding By Agency (In Millions)

	Cadre Estimate of Government Funding FY 74	President's Budget FY 74	President's Budget FY 75
AEC	1.5	.7	5.8
D.O.I.	11.0	11.0	14.0
NSF	3.2	3.2	10.0
DOD	10.1	-	-
NASA	2.0	-	-
Other	.2	-	-
Total	28.0	14.9	29.8

Table 4 further expands the amounts shown in the President's budget. We have assumed a more detailed break than we actually have data for. We believe that the total amount for gas turbine development is now allocated to the helium turbine for the HTGR. The assumed breakdown is based on the relative emphasis provided OMB by D.O.I. and NSF in their comments on the Ray report and their respective energy supplements. Without detailed data on the NSF budget to confirm it, we believe that the NSF allocation as stated in FY 74 and FY 75 includes other areas than advanced power cycles. We believe that funding shown for NSF was based on the total NSF request for improved efficiencies and included in addition to advanced cycles both automotive power systems and energy transmission and storage systems. Our estimates take this assumption into consideration, as well as our belief that other agencies should be assigned technology areas to assure continuity of programs, take advantage of existing capabilities and facilities and receive most effective output of limited funding.

C. OTHER FUNDING COMPLICATIONS AND POTENTIAL SOURCES ENABLING TECHNOLOGY

Both the English report and the Ray report included in the energy conversion area fund for enabling technology in the amount of $2.0 million in FY 1975 and $2.0 million/year over the period of FY 75-79. This enabling technology was primarily supportive of advanced

Table 4. Advanced Power Cycles - Cadre Estimated Breakdown of Funding

	President's Budget FY 74	President's Budget FY 75
AEC	.7	5.8
Gas Turbines		5.0
MHD		
Potassium Topping Cycle		
Fuel Cells		
Advanced Concepts (Thermionics)	.7	.8
D.O.I. (OCR)	11.0	14.0
Gas Turbines	1.0	1.0
MHD	5.3	9.0
Potassium Topping Cycle	1.0	3.0
Fuel Cells	.5	.5
Advanced Concepts	.5	.5
Other (Eval., Analysis)	2.7	-
NSF	3.2	10.0
Advanced Cycles - Fuel Cells, Potassium Topping, etc.	1.3	2.3
Advanced Auto Propulsion	-	1.2
Energy Fuel Transmission Storage	1.9	6.5

DOT, NASA, DOD-ONR funds potentially related to this category are not included.

power cycles. Effort was to be directed in materials R&D focused on high temperature aspects of material performance in specific applications. This enabling technology is an important link between development applications and multi-directional basic research and is necessary to support the advanced cycles area. It has not been included in the cadre assignment of funds, and it is questionable whether it was included in the President's $29.8 million amount for improved conversion efficiency. We believe the $2.0 million per year has been included in the cadre assigned Fossil Fuel-Advanced Technology. It is important to integrate the enabling technology efforts into the advanced power systems to achieve better utilization for the research and technology areas pursued.

D. SUPPORTING PROGRAMS

The Ray report and the President"s FY 1975 budget identified funding for supporting programs in addition to the energy research and development program. Under these supporting programs, basic research related to energy is included in the President's budget at a level of $175 million in FY 1975. These funds are allocated to AEC - $60 million and NSF - $114 million. It is our guess from reading through the various press releases and budget submissions on energy supplements to OMB that approximately $5-10 million of each agency's research programs is related to basic materials and chemical research associated with MHD, turbines and fuel cells. Because of the research and technology nature of the bulk of the programs included in advanced power systems, it is difficult to distinguish between the basic research included in the supporting area and the fields of effort proposed in this report. Further identification of the support research is necessary and closer interfaces established in the planning and execution phases. It may be advantageous to either transfer or direct this basic research to the development/application area.

E. FUNDING PARTICIPATION BY INDUSTRY

In the Ray report it was estimated that industry participation would approximate three times the Government's investment in the conservation area to meet the short term objectives (to 1985). It was estimated that approximately a one-to-one ratio of participation between industry and Government to meet mid-term objectives (1985-2000) would materialize. As the bulk of the advanced power systems proposed would not achieve commercial operational status until after mid-1985, we believe that industrial participation during the FY 75-79 period will only approximate 30% of the Government's participation. Our estimate of industrial investment over the 75-79 period is shown in Table 5. Our review assumes this participation by industry is necessary to achieve the objectives of the Ray report.

Table 5. Advanced Power Cycles - Expected Investment By Industry
FY 75-79

	$ In Millions	% of Total Low Range Government Funding
High Temperature Gas Turbines	35	12
MHD	20	20
Potassium Topping Cycle	10	11
Fuel Cells	100	100
Advanced Concepts	5	10
Total	170	Avg. 26

II. CONSERVATION AND ECONOMICS OF IMPROVED CONVERSION METHODS

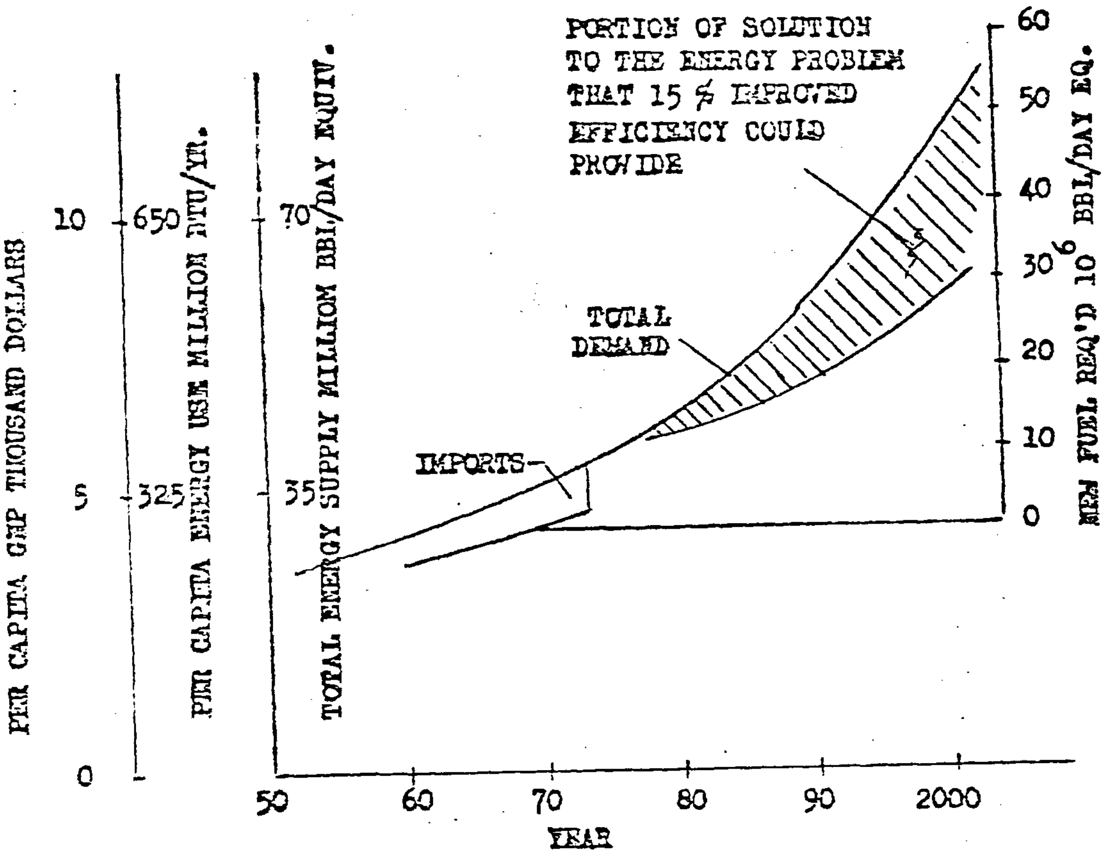
A. DISCUSSION

The conservation and economic benefits of improved energy conversion have been examined on a preliminary basis.

Figure 1 shows the potential contribution which improved efficiency in all consuming sectors could make to future energy requirements.

It is seen that improved efficiency could nearly halve the needed expansion of fuel supply if about 15 percentage points of efficiency increase could be obtained for all energy uses. The electrical utility portion of this in the latter time period will be of increasing importance because this sector will approach 50% of the total energy consumption by 2000 A.D. As a consequence, from about one-third to one-half of the postulated gains from efficiency would come from the electrical conversion sector. Utilization of waste heat could supply a portion of the gain if it comes into widespread practice. However, the principal thrust of this exercise was the investigation of the merits of efficiency improvements in the main conversion methods HTGR, MHD, fuel cells, gas turbines, etc.

POTENTIAL BENEFITS OF IMPROVED EFFICIENCY
IN THE NATIONAL ENERGY PROGRAM



POTENTIAL BENEFITS OF IMPROVED ELECTRICITY
GENERATING EFFICIENCY

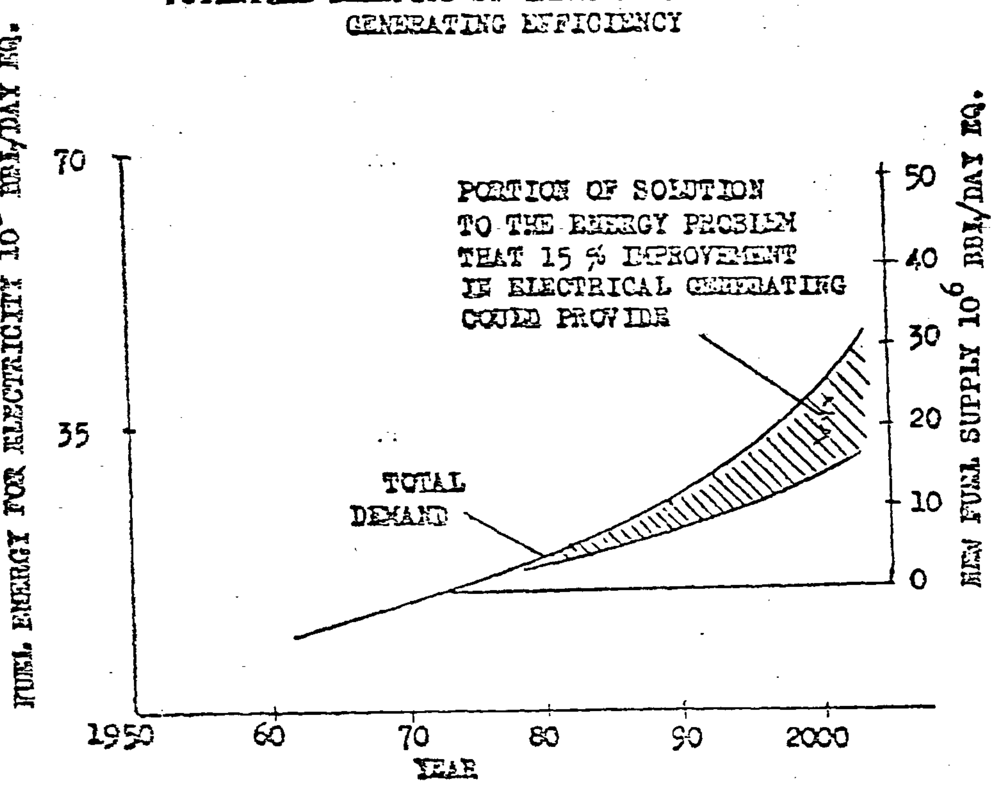


Figure 1

From reference to other studies of the overall energy problem, it appears that electrical sector can respond to the improved efficiency needs as strongly as any other sector.

This is not to say that efficiency should be thought of in lieu of an expanded fuel supply base, but rather as an augmentation which would help achieve our goals of self-sufficiency sooner and on a more defensible basis with regards conservation and other related issues. A major aspect of this is that a short fall in any of the planned fuel supply sectors could be made up for by improved use of the fuel that is or will become available.

A scoping economic analysis has been made of the fuel conserved and the discounted economic benefits of the fuel saving that might be obtained by implementing more efficient energy conversion methods.

The summary results of this study are shown and indicate that the implementation of improved methods would allow the nation to <u>resume</u> a 50-year trend in electrical conversion efficiency improvement which has apparently just now about peaked-out as indicated in Figure 2. The economic benefits of doing something about this have been investigated. It has been found that the implementation of advanced conversion along the general lines that have been considered in

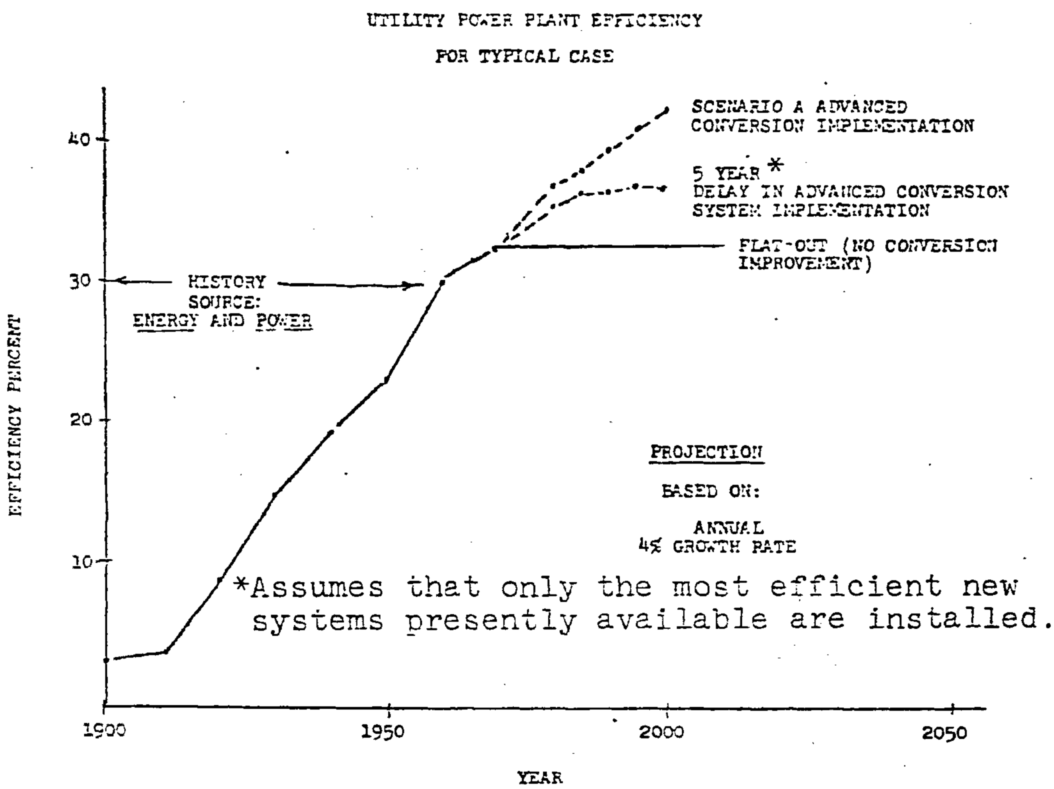


FIGURE 2

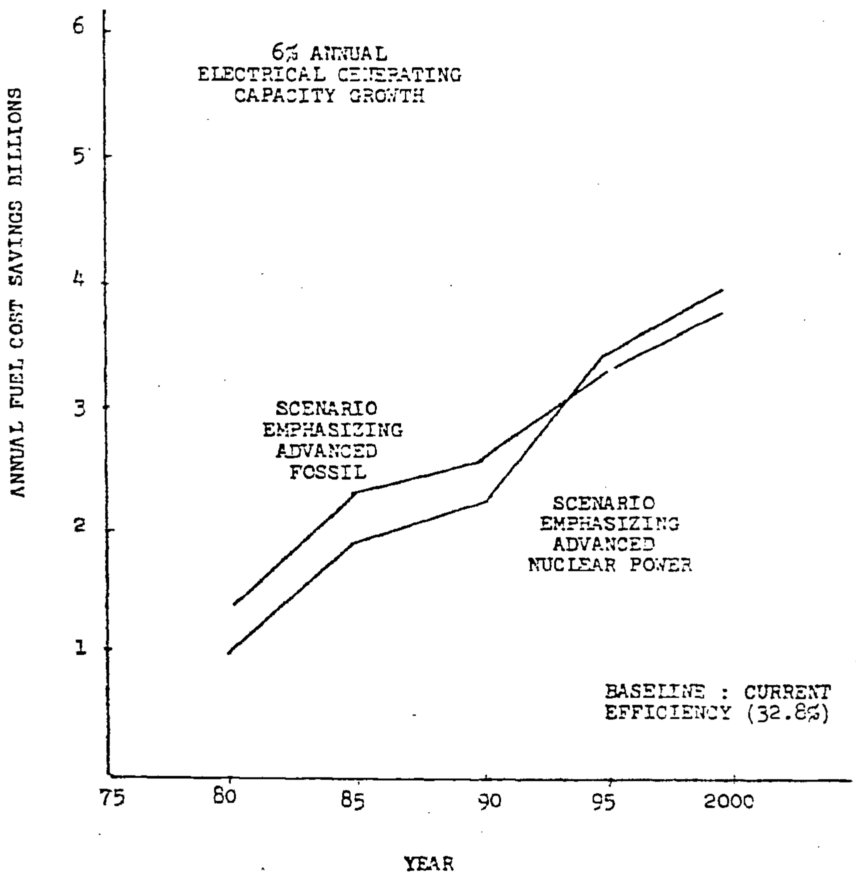


FIGURE 3

the Ray report for the electrical utility industry has a potential between now and the year 2000, conservatively estimated, for saving an amount of fuel equal to five years supply of utility fuel at present use rates. The value of this fuel at 1973 prices is about 50 billion dollars.

This economic question has been further investigated as to the economic benefits as determined by using the social discounting process which is currently being used to measure whether a proposed development program is worthwhile. Using a high social discount rate of 10%, the analysis has shown that the discounted economic benefit greatly exceeds the development costs even when evaluated using 1973 fuels prices. As an example, the annual fuel saved by the use of improved energy conversion methods in an overall program having a 6% annual growth rate of electrical capacity is shown in Figure 3. Figure 4 shows the discounted present value of such savings for variations in growth rate. Figure 5 shows the benefits in "present values" of speeding up the change to improved efficiency or alternatively the loss of "present values" which would be caused by delaying the implementation of more efficient electrical power plants.

Thus, there is considerable urgency involved in this area. Since the development cost of threse advanced conversion methods aggregate about a billion dollars, these economic benefits which have been shown are unusually high for this type of economic

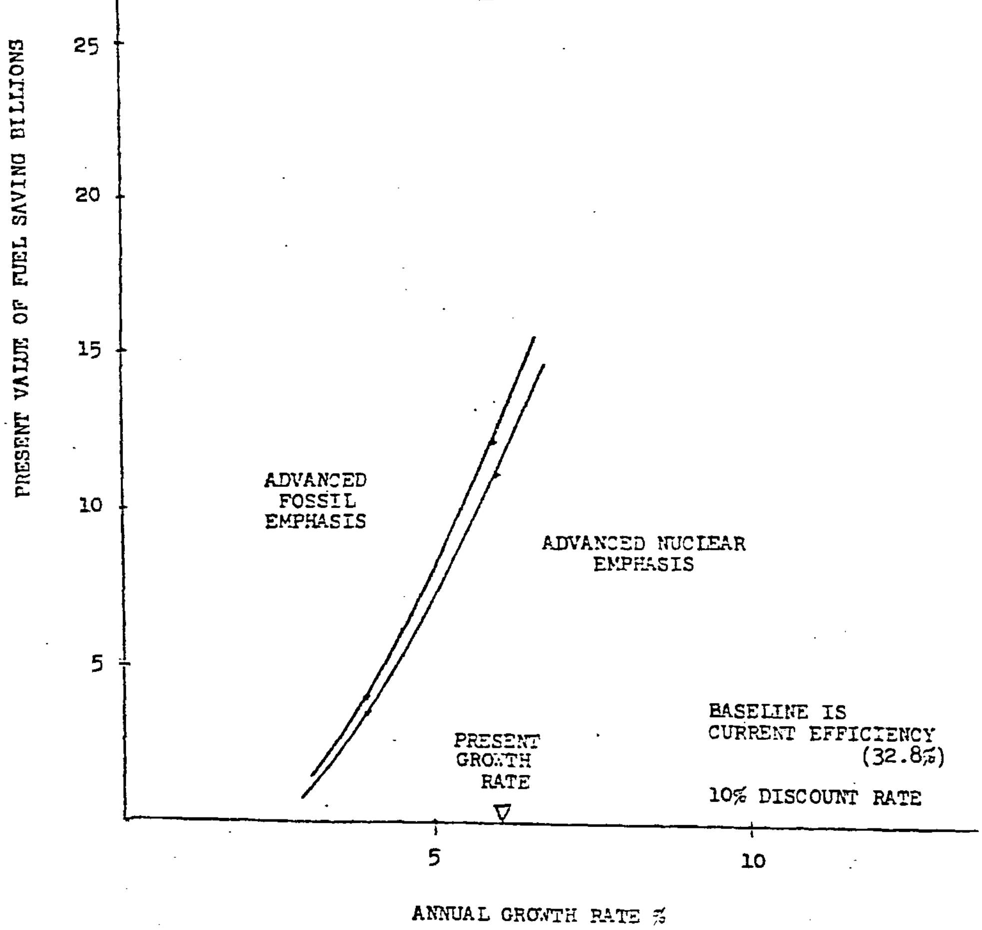


FIGURE 4

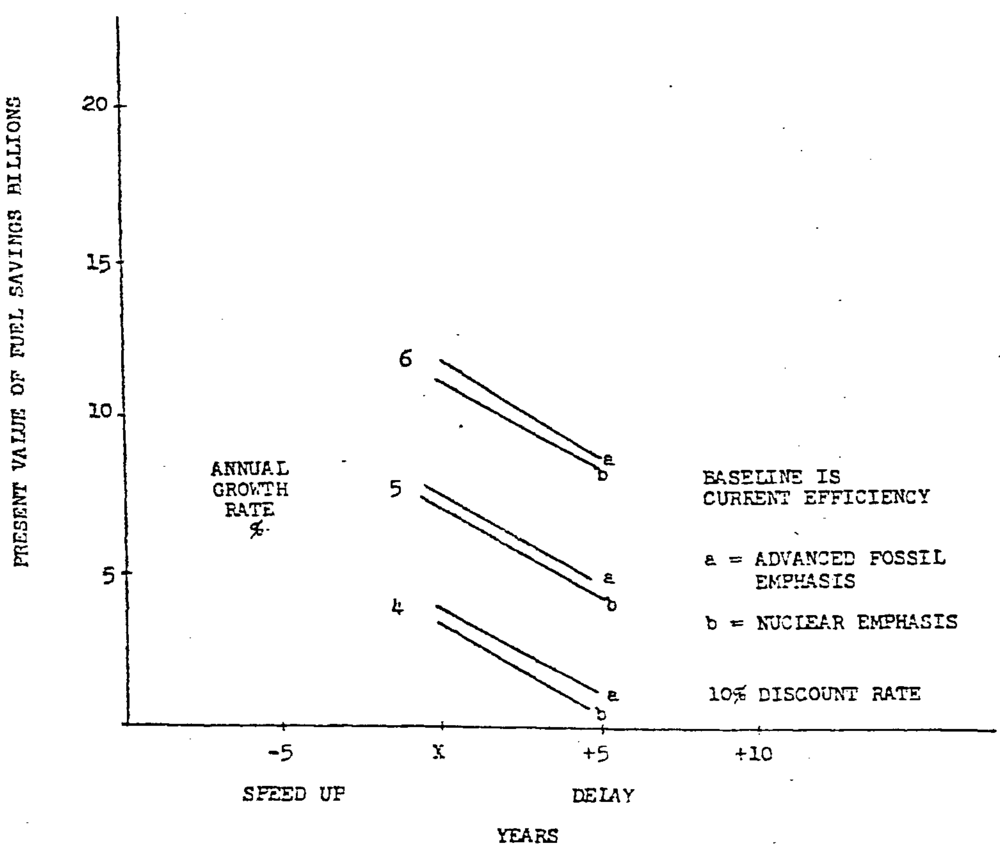


FIGURE 5

investigation since the discounted benefits far exceed the discounted development costs. From this it is concluded that the economic climate for these developments will be exceedingly good in general. Specific proposed programs will require detailed analysis of this type, and it is likely that the benefits of doing the various sub-programs will vary considerably in this regard.

B. CONCLUSION

It is believed that this area of improved energy conversion is one of the most favorable areas for a conservation and economic payoff. It has not been the intent in this exercise to evaluate the exact ways of doing this nor whether this conversion efficiency area should have more emphasis than other areas such as synthetic fuels, fuels independence, expanded coal use or other conversion measures, etc. This analysis does show, however, that the conversion efficiency area has not had the emphasis that it deserves and which may be essential for achieving our energy goals and of maintaining our energy intensive society.

III. ADVANCED POWER CYCLES - ANALYSIS OF THE RAY AND SUBPANEL VI REPORTS

There are two basic methods for improving the utilization of the fuel used in power plants. One method is to increase the efficiency of electrical energy production plants. Another is to develop techniques for using some of the heat currently rejected as waste for processing or space heating purposes. The Ray and conversion subpanel reports address both of these goals.

The Ray and subpanel VI reports addressed the goal of increasing the conversion efficiency of fuel energy to electricity by selecting those conversion system technologies the subpanel members considered most promising in the foreseeable future and by structuring very general development and demonstration programs for each of them. Emphasis was placed on each selected area in accordance with a general set of priorities assigned to them. The selected technologies and priorities for each are listed on Page 3 of the subpanel report which is included as Appendix 1 to this report for reference purposes.

Of the technology areas listed on Page 3, low BTU gasification of coal, use of solid waste as fuel and enabling technology have been assigned to others for implementation planning purposes and will not be discussed further in this report. While grossly oversimplified, the benefits identified appear somewhat conservative when judged in the light of the analysis discussed earlier in this report. Several of the conversion systems proposed for development conceivably could be used either as primary electrical power generation units or in a topping cycle with other systems such as the conventional steam cycle central station power plant. Gas turbines, MHD generators or thermionic converters could be employed in either of these ways, for example. However, if not used as topping cycles, the conversion system must operate at temperatures hundred of degrees above present day technology in order to achieve reasonable conservation efficiencies. Development and implementation of these very high temperature systems would result in significant improvement over the current utilization of fuels and will greatly reduce environmental heat loads. They may also have economic advantages, but this can be determined only after there are good data on construction operation and maintenance costs for the particular system selected. Topping cycles appear to be most attractive when the thermal energy rejected from the topping cycle can be recovered by a more conventional cycle; the combined efficiency of both cycles is greater than either cycle alone - overall efficiencies of 55 to 60% are possible.

Bottoming cycles are a way of converting low temperature heat to electricity by using fluids which boil at a lower temperature than water. These cycles have significance not only for the bottom end of power plants to recover discharge heat, but also for applications such as geothermal or solar systems at temperatures to 300 or 400°F. Added to conventional steam systems, they permit additional energy recovery of a few percentage points and also avoid freeze-up problems if dry cooling towers are the means of heat rejection, but added to a gas turbine discharge, an additional 10 to 15 points can be recovered.

Fuel utilization can also be improved by recovering and utilizing heat as heat rather than to do work in a conversion cycle. The heat normally rejected from small high temperature gas turbines, modular fuel cells, and other electrical generating systems can be recovered as hot air or steam for space heating or process heat, etc. Such "total energy" systems can result in 70 to 80% utilization of the energy contained in the fuel in those applications where ideal balance between both electrical and thermal energy requirements can be realized. In most applications the utilization will be reduced, depending on the degree of mismatch between supply and load, but the net gain in fuel energy utilization can be enhanced by about 20%

over single purpose uses, making total utilization around 55 to 60%.

A brief description of the basic principles of each of conversion systems identified in the Ray and subpanel VI reports is included in Appendix 2. The following is an analysis of the primary development problems and major tasks needed for program implementation of each of these conversion technology programs.

A. TECHNOLOGY AREAS

1. High Temperature Gas Turbines

The Ray and the conversion subpanel reports identify three gas turbine development programs as follows:

a. A 100 MWe combined-cycle demonstration plant by 1979.

b. A combined electrical (1 to 3 MWe) and space heating system for use in large buildings, housing developments and industry as a "total energy" system.

c. A 250 MWe helium closed-cycle gas turbine and component development and test facility (identified as 750 MWe in the Ray report). This program would be for conversion hardware that would operate in the High Temperature Gas Cooled Reactor (HTGR).

The first of these programs is a low risk development effort but with total costs projected to run to several hundred million dollars. The justification for government support is primarily that it will accelerate the time when the high potential efficiency of such combined gas turbine steam power plants will begin to be utilized in utility systems. Its success depends on much higher than present operating temperatures and on the introduction into commercial use of low BTU gas or an acceptable clean liquid from coal. These fuels are planned to be developed as a separate part of the national energy program. They are included in the review of the direct coal combustion cadre. An alternative approach would be to conduct the needed technologies independently of a demonstration plant program and depend on industry to incorporate the developments into new or upgraded central station plants as they become available. Unfortunately, the efficiency of the coal conversion step is only about 85%. Other than the need for a suitable clean fuel supply system, the principal new technology needed is that required to raise the turbine inlet temperatures and thus the combined cycle efficiency above approximately 40% presently achievable (<u>not counting</u> the loss in the coal conversion step). Higher efficiencies will be possible with either improved blade cooling methods or developing ceramic rotors and blade and nozzle materials capable of operating at approximately 2500°F gas temperatures.

The development plans should also recognize that gas turbine cycle performance and operating reliability are dictated to a high degree by the integral performance and reliability of the high temperature heat exchangers and the control system (including the instrumentation and valves employed). These components, particularly the high temperature elements subjected to cyclic thermal and dynamic loading account for a large part of the system development costs. The plan must include extensive heat exchanger and related ducting brazing, welding and assembly developments supported by associated materials studies and evaluations.

While not a part of the advanced cycles area, the overall energy program should also include development of alternate clean combustion processes for using various types of coal and shale oil "dirty" fuels. From the point of view of advanced cycles, both fluidized limestone bed and pressurized combustion systems should be developed. The latter will facilitate more compact boilers and turbine systems to be developed and utilized in advanced conversion systems. In addition, they would enable reductions in plant and equipment size with associated cost reductions. Developments should also take advantage of the current aircraft turbine engine technologies which are presently capable of operating in military use for short periods at temperatures up to 2500°F under full power conditions and approximately 2200°F under sustained loads. The lifetimes of these units are considerably less than needed for conventional purposes, and these temperatures are, of course, inappropriately high for conventional purposes without considerable development.

For the total energy systems, a technology base already exists for designing the one to three MWe combined electrical and heating units. The subpanel's rationale for this government program was apparently to accelerate the introduction of such plants into the commercial market. The alternative exists here also to wait for the increasing cost of fuel to induce industry to undertake the engineering, manufacturing and marketing of these systems. Such an approach would require that the government structure a program to increase the industrial incentives to undertake the required developments.

The program to develop the 250 MWe helium turbine will be implemented under the ongoing AEC program and, therefore, is not discussed in detail here. Its development will permit the HTGR power plant, operating with a direct cycle turbine conversion system, to be operated with dry cooling towers and thus in locations without need for large cooling water supplies. More important for energy conservation, they can be equipped with efficient bottoming cycles and operated with thermal efficiencies of about 45%.

All of the gas turbine programs would benefit from the supporting research activities that should be conducted simultaneously with their development. The following is a tentative list of these research needs:

- Blade and rotor materials development that will withstand corrosion and erosion environments at temperatures from 2000 to 3000°F. These materials should withstand the pressures and stress conditions for efficient turbine operations over the full range of load conditions. Promising materials being studied and characterized include fiber-reinforced composites of silicon carbide coated boron fiber and carbon fiber reinforced structural ceramics.

- Corrosion and erosion resistant coatings must be systematically developed, studied and characterized.
- Stable fuel combustion nozzles and chambers should be perfected that will handle a wide variety of impure fuels over all operating ranges and conditions.
- Cooling techniques must be perfected for high temperature ducting nozzles, control vanes, blades and rotors. Investigation of transpiration cooling techniques should be continued.
- Improved oxidation resistant and lower cost alloys should be developed and fully characterized.
- New alloy welding and brazing and joining and other fabrication methods will be needed.
- New fuel catalysts are needed to improve combustion efficiencies and assure more uniform chamber temperatures.

The tentative conclusions which are drawn relative to the gas turbine conversion developments are the following.

a. To achieve combined cycle efficiencies approaching 50% requires 2500°F combustion turbine temperatures which are not yet achievable for utility applications. Ceramics for the high temperature components or improved blade cooling techniques are required. Open cycle units must use clean fuels made from coal with a loss of 15% or more in conversion. Therefore, the magnitude of contribution to the national goal of increased conservation of fuel is uncertain and might be too small for the investment required. However, if low BTU gas is available in large quantities at comparative prices, the system will be desirable for peaking and intermediate loads even if the system efficiency including coal gasification is only 40 to 45%.

b. Closed-cycle helium gas turbines for HTGR's will operate at much lower temperatures (because of reactor temperature limitations) than combustion turbines and need neither the high temperature materials development nor the low BTU gas supply. Although high efficiency in the nuclear system is not as important as in a gas or oil-fired turbine, closed-cycle HTGR's will need energy recovery from a bottoming cycle to attain higher efficiency than the steam cycle used on present-day HTGR's.

Bottoming cycle development funds are not now included in the advanced cycle budget.

c. Small "total energy" systems for heat and electrical service make good sense from a conservation standpoint but only if they can be run on coal derived energy. If low BTU gas or fluidized bed combustion can be adapted to these systems, they are capable of about 20% higher overall efficiencies than a single purpose steam plant.

2. <u>Potassium Topping Cycle</u>

The conversion subpanel report proposed a program for the potassium-steam binary cycle which is directed towards a 300 MWe central station demonstration power plant by 1985. The topping cycle in this plant would consist of three potassium-turbine generator system modules, each with 30 MWe capacity. (The steam portion of the plant would generate 210 MWe). The initial effort in the program would be the development of a 30 MWe potassium cycle module, the first of which would be placed on test in 1979.

The technology base upon which this program was based was developed in the space program. Two 300 KW capacity potassium turbines were operated successfully for more than 5000 hours each along with tests on the essential components of the boilers and condensers. In addition, several thousand hours of loop materials testing were completed. As a result, there is high confidence that the predicted thermal performance can be achieved. This program was also supported by approximately 12 million dollars of base technology work conducted at ORNL and NASA during the 1960's.

A significant advantage of this cycle relative to the gas turbine systems is its lower peak operating temperature. A furnace gas temperature less than 2000°F is adequate to generate vapor at 1600°F. At these temperatures, the development of reliable low pollution combustion processes should be greatly simplified. Furthermore, the lifetime of the boiler may be substantially increased with commensurate cost savings.

The primary technical uncertainties are those related to the long-term maintenance and operating costs associated with high temperature potassium systems and the large uncertainty of the initial capital costs for such systems. Additional development work is needed on the potassium boiler, the condenser-steam generator and seals in the potassium turbine. Of particular concern are the combustion gas side corrosion rates associated with the fossil fuels that will be used in the combustion furnace of the potassium boiler.

The program is currently supported by NSF at ORNL at about $500K in FY 1974. This work is for the design, fabrication and testing of a full-scale potassium boiler tube bundle and burner module. OCR is simultaneously sponsoring a $100K central station conceptual design effort at GE with the NASA Lewis Laboratory serving as the Headquarters' contracting and management agency.

Tentative conclusions drawn for the potassium rankine combined cycle are the following:

a. The technology base existing for this program is sufficient to assure that the technical goals can be achieved with a reasonable level of confidence.

b. The primary problems that need to be addressed are those to identify the capital and operating costs that will be associated with these systems and the specific data for the design of the long-life, high-temperature potassium boilers, condenser-steam generator and turbine.

c. The low development risks and modest costs, along with the relatave high benefit, result in adequate justification to continue an aggressive development effort.

3. Magnetohydrodynamic Generators

The conversion subpanel report recommends accelerated development of both the open and closed cycle MHD concepts and places emphasis on the former. The proposed program is directed towards construction of a coal-fired open cycle demonstration plant that would begin operation in about 1987. The closed cycle efforts are focused on proof of technical feasibility and the design of prototype systems. The generator and material test facilities will require approximately 60% of what the panel recommended for FY 1975 through 1979 funding. In addition, emphasis is placed on containing the ongoing cooperative program with the USSR. This primarily involves the development, installation and test of generator and magnet components in existing USSR facilities. However, it is not clear that funds for the USSR program were included in the funding proposed.

The conversion subpanel report recommendations were apparently significantly influenced by staff opinions held within the Department of Interior. Evidence for this is the similarity of the program approach outlined in the Advanced Power Conversion Program Report dated December 13, 1973, prepared by the Advanced Conversion Task Force established by Department of the Interior. This report recommends heavy emphasis be placed on MHD development relative to all other conversion technologies combined (i.e., $20 million out of $33.5 million identified for FY 1975 in their report). The MHD section of this report provides in significant detail the elements of the currently planned national MHD program effort and is therefore included in the report as Appendix 3 for reference purposes.

To develop MHD generators, the fundamental physics and chemistry of seed and high temperature plasma impurity attack of the insulators, electrodes and duct materials must be thoroughly investigated. For most of the candidate materials, the required data on the mechanical, electrical, and chemical properties does not exist. It is therefore not possible to make projections with reasonable confidence of the efficiencies, lifetimes or costs that can be achieved. In general, it appears quite apparent that insufficient basic work has been done to justify proceeding into the expensive hardware design construction and test phases of these programs as proposed in the DOI report until the following types of questions can be more adequately answered.

- What is the generator duct life and what requirements need to be met to permit duct design and materials that can eventually result in an economic plant?

- What will be the total cost, both capital and operating, of the resulting MHD plant concepts? This must be answered considering the new innovative materials, superconducting magnets, high power solid-state inverters and high temperature clean-up systems needed.

- What will be the effect on power cost produced as a result of the various subsystems required to assure that successful plant performance is achieved? This must be well enough understood to assure reasonable provisions can be made for both cost and reliability considerations.

It is likely therefore that consideration will be given to restructuring the subpanel program to one where additional research and development be undertaken to greatly strengthen the currently existing data base needed for MHD system design.

The work should be pursued to the point required to permit reasonable MHD system concepts to be defined that have the potential for ultimate economic service after development. This plan would significantly reduce the current high risk of wasting development funds on dead-ended approaches or concepts.

The MHD development program has been evaluated by competent technical people at Westinghouse for over 15 years. They have provided comments on the recommended subpanel MHD development approach. The Westinghouse staff proposed an alternate program plan approach which should be considered in any reassessment of the MHD program. They also favor the open cycle concept in which a high temperature conducting plasma is passed through a suitable generating duct. Since the performance of this duct is probably a limiting feature in evolving a practical MHD system, the initial efforts would be concentrated in this area.

The proposed Westinghouse approach which we believe should be carefully evaluated is the following:

a. Open Cycle Generator Duct R&D -

PHASE I - The design and construction of a small test duct including fuel supply, magnet, air preheater, and scrubber, so that the duct can be tested. Simultaneously, work should be done on promising high temperature side-wall, insulating, and electrode materials. The evaluation of plasma electrical conductivity in separate experiments should be carried out. This work might be completed by the end of 1975.

PHASE II - Based upon the studies completed in Phase I, a larger duct should be constructed in order to evaluate life, cost of construction, and scaling laws. This duct could then be subjected to extensive tests, hopefully in a pre-existing facility, in order to evaluate the performance and compare to predictions made during Phase I. This program could be complete by 1978.

In parallel with the work proceeding on the duct, the following four programs would be implemented:

a. Superconducting Magnet Development

PHASE I - A one-year design and feasibility study would be undertaken to determine the proper superconducting magnet design, insulation system, refrigeration requirements, and performance characteristics that could be used in conjunction with an MHD plant. Phase I could be completed, if initiated early in 1975, by mid-1976.

PHASE II - Construction and prooftesting of the superconducting magnet system. A superconducting magnet suitable for use with an MHD generator would be constructed and tested. The size of the magnet should permit scaling to the larger size required for a demonstration plant.

b. Inverter Development -

PHASE I - During Phase I, which could be initiated as late as 1975, an inverter design would be developed that could be used in conjunction with a moderately-sized demonstration MHD plant.

PHASE II - In 1976-77, an inverter module would be built and tested to determine performance characteristics and projected costs for an MHD plant.

c. High Temperature Gas Clean-up

An engineering study would be initiated to design a high temperature gas clean-up system suitable for use with coal. It is recommended that this study be initiated in 1975. Particulate, SO_2 and NO_x removal will be required, and the system should be developed and tested before 1978.

d. Systems Study

A systems study should be initiated with the ultimate objective of building a 50 to 150 MW electric plant. We would expect the systems study to proceed over the period 1974 through 1977, factoring the input from the various programs described previously.

At the conclusion of the research and development program described, and providing the data obtained indicated that an effective MHD demonstration plant could be built, the demonstration plant could be designed and constructed.

The tentative conclusions which are drawn relative to open cycle MHD development are as follows:

a. MHD gas, open cycle, combined steam plants have the theoretical potential for overall cycle efficiencies up to 60% and, importantly, to handle "dirty" fuel.

b. An established and vigorous ongoing program is already in being both in USA and USSR. Even the most ardent advocates, however, would agree that plant efficiencies of ~ 50% are most likely at first and that 1/2 billion dollars over the period up to 1985-9 will be required to achieve that level in commercial applications. It is not difficult to foresee perhaps a billion dollars. There is controversy about how the program should proceed - some advocate going directly to large (10's of MW) pilot plants - others to conduct component technology prior to pilot plants. Some suggest a national lab, others to do work at existing locations. All advisors take strong stands that work must be augmented.

c. This is a very tough technology comparable with the high temperature fuel cell, for instance. It is not a modular device and must be developed on large scale. There are many component technologies not yet established. One can conclude that for what is likely to be a billion dollar - 20-year effort, the measures to be taken are to (a) encourage and support the continuation of work already started with redirection to blend with other work; (b) establish a national laboratory to engage in research on the fundamentals and to guide the government's participation; and (c) proceed with large scale integrated experiments only after confirmation on components testing.

d. The present program in the government probably runs (excluding military) eight million dollars. The present ERDA plan combines MHD and potassium vapor funding. The MHD program support should be ten to twelve million dollars per year.

The tentative conclusions that have been drawn relative to the closed cycle MHD conversion system are the following:

a. Closed Gas Cycle MHD -

(1) The closed cycle (He, Cs) MHD is a competitor to the closed cycle gas turbine. It needs a He temperature of approximately 2500 to 3000°F, which is probably an easier duty than the 2500°F gas turbine. It appears to have an ultimate potential for about 55% efficiency in a combined steam plant and would require combustion gas to He/Cs heat exchanger to use "dirty" fuels. It probably requires a ceramic heat exchanger. Feasibility has been demonstrated for a linear generator in a program conducted to General Electric and apparently by others in shock tubes. This cycle needs low pressure to achieve unequilibrium excitation of electrons.

(2) This work is in the early technology phase and should be continued in that mode. Since there is much commonality with open cycle devices, but without the slag and extremely high temperature problems in the ducts, a decision to proceed with development of the closed cycle system at some future time could rely heavily on open cycle

technology in many areas. Use of "dirty" fuel again is heavily dependent on conductor research and heat exchanger research carried in other programs.

b. Closed Cycle Liquid Metal MHD -

Liquid metal MHD may ultimately obtain an overall cycle efficiency as high as 55% but at much lower temperatures ($\sim 1500^{o}F$) than any other MHD system. Its heat exchanger problems, etc., are therefore correspondingly simpler. However, knowledge of performance is presently cursory - glowing predictions aside. This technology is also in its early stages and should be continued as such to let it run its race with closed cycle MHD and thermionics. Decisions between those candidates and open cycle MHD can probably not be made in less than several years.

4. Fuel Cells

The Ray and conversion subpanel reports propose a fuel cell program which augments an ongoing industrial development effort at a level of roughly 30% of the total industrial investment in this technology. This latter effort is primarily one being conducted at Pratt and Whitney Aircraft Company under a broadly based combined utility and company-funded program at about $15 million on the acid hydrogen fuel cell concept. In addition, EPRI is sponsoring advance fuel cell research at a level of about $2 million per year. The subpanel report also cites a methyl alcohol cell effort being carried at about $2 million per year.

Based on the overall high potential of fuel cell technology to make major contributions in many energy conversion applications, this appears to be a very modest program. An important contribution which ERDA could make to this effort would be to provide a centralized and coordinated balanced development effort on the more advanced and higher performance systems. Overall, the program recommended by the subpanel seems well-structured. The primary problem areas on which research and development should focus in implementing this program are:

- o prohibitively high cost of low temperature electrodes because of the need for an expensive platinum catalyst.
- o application and materials problems of high temperature fuel cells using molten salt or solid electrolytes.
- o corrosion and heat removal problems associated with high temperature cells.

- alcohol diffusion through the air electrode in the low temperature methanol fuel cell.
- system engineering problems to eliminate the need for complicated operating control and regulation systems.
- sensitivity of the electrodes to small amounts of fuel and air impurities.
- increased operating life.

Tentative conclusions which are drawn for fuel cell development efforts are:

a. The current low temperature, H_2 - air, acid electrolyte fuel cells require clean H_2 which can currently only be obtained by reforming CH_4 or cracking NH_3. The overall efficiency for the total system apparently is limited to less than 40%. Therefore, these cells as developed in the Target and FCG-1 programs cannot play a major role in conservation unless their efficiency can be improved. The availability of clean synthetic fuel from coal would be a big step towards this. They do, however, have a potential for dollar savings because of reduced cost of pollution control if they can be provided at 150$/Kw and last five years.

Platinum is a big problem here. Successful development of the low temperature alkaline hydrogen cell may increase these efficiencies to about 55%.

b. If methanol becomes widely and cheaply available (at prices and resource consumption competitive with coal, natural gas, etc.), the low temperature alcohol-air, electrolyte fuel cell can be a large contributor to conservation because its potential efficiency would be above 60%, pollution costs are nil, and catalysts relatively cheap (silver perovskites). This will require the development of methods to prevent alcohol/air electrode reactions.

c. To use "dirty" fuels, much more exotic and difficult fuel cells are required. These, if they could be developed, might have a tremendous effect on conservation because they could be upwards of 80% efficient and use coal or cheap hydrocarbons. They will have no catalyst problems because of high temperatures, but several materials problems will require extensive effort. This is very tough technology to develop since it requires high temperature cells (1000 - 1500°F), means to use waste heat for reforming of "dirty" fuel, molten carbonate electrolytes and/or solid electrolyte designs with means to remove heat, and containments.

5. Advanced Power Conversion Concepts (Thermionics, Feher CO_2 Cycle, etc.)

The conversion subpanel report recognized the high potential for a variety of advanced conversion cycles to make important contributions to relieving long range energy conservation problem severity. It selected the Feher CO_2 system as the one which would be given priority in this category of conversion system because of its good potential to make a relatively near term contribution. It appears that this may be a premature conclusion. Recent studies which have been performed clearly indicate that thermionic conversion offers very good potential as a topping cycle for central system steam plants with relatively low development costs. This is because the technology can be established on small modular units to the point where it can be applied to conventional designs with high confidence of success. The possibility of achieving this is considered very good based on recent data evolved in ongoing research programs. It appears that 48 to 50% overall plant thermal efficiencies can be realized with modest extensions of current technology and 55 to 60% with further improvements.

The tentative conclusions which have been drawn for the advance concept developments are the following:

a. Thermionics -

Thermionics have at least an equal chance to be a major contributor as these other unrealized technologies. The background data are superior to MHD and equivalent to potassium topping or 2500^{O}F long-life gas turbines. The data base is perhaps a little less well established than for 50% efficient fuel cells. Its modular nature may make it possible to bring to practical application with relatively modest investment. These systems should be compatible with any fuel but will require low NO_xSO_x combustors. Ultimately, combined cycles may be developed that will be in the 60% efficiency range.

b. Feher CO_2 Cycle -

The supercritical Feher cycle may achieve 50% overall conversion efficiencies with more compact and therefore somewhat more economical equipment than will be possible with high temperature ($\sim$ 1500^{O}F) gas turbines. It requires significant advances in technology for high temperature compact heat exchanger and CO_2 gas bearings and a demonstration of the high efficiencies that have been projected.

c. Helical Screw Topping Cycle Turbine (Lysholm Expander) - Lawrence Livermore Laboratory has proposed the adaptation of the Lysholm turbo compressor to use in a coal burning gas turbine topping cycle - believing that this type unit may be less sensitive to damage from dirty combustion products.

B. OVERVIEW OF SIGNIFICANT EFFORTS UNDERWAY WORLDWIDE

In the area of energy conversion technology, our knowledge of foreign activities is quite incomplete. Much of the work in this field is conducted by private industry and details of the technology are kept proprietary. Therefore, there are significant gaps in our knowledge of the scope and relative merits of energy R&D in foreign countries. The following information has been obtained from various sources and is recounted here to give some perspective to the extent of certain energy activities outside the United States. For the United States government supported activities, see Appendix 4.

1. Magnetohydrodynamics

a. Soviet Union MHD Program -

Extensive technical staff and facilities at the Soviet High Temperature Institute have been devoted to MHD materials development over the past ten years. The Russians have designed, built and since 1971 are operating on natural gas a 25 MWe experimental open cycle MHD pilot plant in the outskirts of Moscow. It is tied into the city's electric grid network and, therefore, is the first commercial MHD pilot plant in the world for network service. The plant (U-25) is complete except for the steam turbine of the bottoming unit. The power plant components are widely separated and housed in a large building devised so that experimental changes can be made with ease. The U-25 is so designed that a number of trial channels can be placed within its conventional magnet and tested in succession. Soviet scientists have recently claimed excellent performance of zirconia electrodes in the U-25 facility at temperatures to 2000°C with operating times greater than 100 hours. The Moscow group claims 99.9 percent seed recovery and successful operation of boiler tubes for long periods of time in a potassium seed combustion gas. It has been estimated that there are about one thousand people at work in this MHD project.

b. The Japanese MHD Program -

A very extensive effort directed toward open cycle MHD power generation with experiments on all phases of MHD central station power plants is being conducted in Japan. A number of generator channels have been tested and a number of pre-heater designs have been run. Japan has already built and combined a superconducting magnet with an MHD generator. An MHD Power Generator Study Team exists at the University of Tokyo.

c. Other Countries -

Numerous other open-cycle MHD efforts exist in other countries such as Poland and Canada. In the British Isles, France and the Federal Republic of Germany, the MHD efforts have been terminated. Liquid metal MHD systems are under study by the USSR, Czechoslovakia and Austria. Closed-cycle plasma research is ongoing in the USSR, common market countries, and Japan.

2. Fuel Cells

There is reported ongoing research in a number of European countries - France, Germany, Switzerland on hydrogen, hydrazine and hydrocarbon fuel cells.

a. The largest is a joint effort between France's Alsthom and Jersey Interprises, Incorporated, which is a subsidiary of Standard Oil of New Jersey (EXXON). This five-year, $10 million effort is aimed primarily at developing methanol-fueled fuel cell systems for small power application in the 5 to 25 KW range.

b. At the Battelle-Institute, Frankfort, Germany, there are industry funded programs in solid oxide electrolytes, organic cathodes, methanol catalysts, and hydrogen and methanol fuel cells, and electrodes.

c. At the Institute Battelle, Geneva, Switzerland, there are industry funded programs in hydrazine fuel cells, hydrocarbon fuel cells, electrocatalyst, high temperature solid electrolytes.

d. At the Laboratorire d'Electrolyse, Bellevue, France, basic research is being conducted in the electrochemical oxidation of hydrocarbons at low temperature.

The major effort to develop commercialized fuel cells in the USA is by Pratt and Whitney Aircraft (PWA) using hydrogen-air fuel cells. PWA has one major program with the gas industry (TARGET) to provide fuel cells or part of a total energy system for apartments, commercial use, and possibly individual residences. A number of 12 KWe demonstrator power plants are presently in operation. A second major program is with the electric utility companies to develop dispersed fuel cell generator stations of 20 MW(e) capacity for operation in parallel with an electric utility distribution system. These two programs are probably being supported with a total of $15 million/year.

3. <u>Gas Turbines</u>

We have not found a good source of information on foreign gas turbines; however, pertinent domestic activity is discussed. The major gas turbine manufacturers are currently developing larger size and higher specific power (KW/lb/sec of gas flow) open-cycle gas turbines. This is a general uprating of performance by increasing the gas turbine inlet temperature through incorporation of advanced design features derived from aircraft gas turbine engines. The improvement in specific power is expected to result primarily from increased cycle temperatures. When the gas turbine inlet temperature is increased to 2500^{O}F, combined gas/steam cycles are projected with thermal conversion efficiencies of over 50%. The large capacity gas turbines currently under development are in the range of 100 to 150 MW(e), and they will produce combined gas/steam cycle modules varying from 150 to 500 MW(e) which is a more desirable size range for most electric utilities. The existing large gas turbines are in the 50 to 80 MW(e) capacity range. Three large capacity COGAS systems with outputs ranging from 85 to 250 MW(e) have been installed in the United States Southwest.

IV. PROGRAM MANAGEMENT AND R&D INTERFACES

A. THE ANTICIPATED PERFORMERS

Without exception, all of the technologies being considered in this area have a background of past or past and current performers. It appears that, as might be expected, this background has created considerable polarization among the parties concerned, and it is evident from review of proposals submitted to the Ray panel, comments on the Ray report and other documents that polarization has often dominated objectivity. Substantial political pressure centers evidently exist that would make it difficult to exclude major areas of technology from future support. The following Table 6 summarizes partially the past and present participants in their approximate roles so far as can be determined by study of documents available. The subsequent Table 7 summarizes areas of future interest to potential performers as evidenced by their proposals to the Ray panel.

Although these tables are not complete, it is evident that there is both a substantial government, industry, and university base, and that they are generally desirous of advancing the work in their areas of interest. The existence of substantial and widely distributed present and past involvement poses a considerable future ERDA management problem in conducting future programs in an organized and logical fashion, while at the same time preserving

TABLE 6.

PAST AND PRESENT PERFORMERS ROLE

Area of Work	Management	Execution Major Programs	Supporting Research
Potassium Topping Cycle	OCR	GE	AEC-ORNL
	NASA EPA	NASA Centers AEC	
Gas Turbine	Utilities NASA DOD	P&W GE Westinghouse	NASA Centers WPAFB
MHD	OCR Elect. Res. Council EPRI	AVCO Univ. of Tenn. Westinghouse	MIT Stanford Several Other Universities
	DOD	B of M	Several Res. Institutes
	OSR ONR NASA AEC	NASA Centers WPAFB GE	ANL GE NSF
Fuel Cells	NASA	P&W	State Univ. of New York
	DOD	Army Centers	Univ. of Colorado
	Utilities	GE	Energy Res. Corporation
	AEC	NASA Centers	RPI ANL TYCO NSF
Thermionics	NASA AEC EPRI	GGA TECO Rasor	Many universities and contractors NASA Centers JPL NSF

TABLE 7

FUTURE PARTICIPANT INTEREST FROM PROPOSALS

Area of Work	Management	Execution of Major Programs	Supporting Research
Potassium Topping Cycle	NASA OCR AEC	GE AEC-ORNL	
Gas Turbine	NASA DOD HUD EPA AEC (HTGR Turbine) ANS (HTGR Turbine)	UAC (P&W) Westinghouse Garrett Corp GE GGA	B of M NBS
MHD	NASA OCR DOD ONR TVA Utilities AEC	Aerojet Nuclear TVA AVCO Westinghouse NASA Centers GE Univ. of Tenn. ANL JPL	B of M Ga. Tech. NBS ANL
Fuel Cells	NASA Utilities (Target - Team to advance research for energy transportation) EPA OCR	P&W GE	NASA Centers NBS
Thermionics	AEC NASA		

as far as possible the continuity in expertise and facility utilization.

It should be pointed out that facilities for carrying out future R&D are not available in many instances. The interests of Government agencies and industrial organizations do not signify that the basic facilities are available at those locations nor necessarily that a trained nucle us of technical and managerial talent is available to perform the work.

B. PROGRAM MANAGEMENT

No single prescription for program management may be applied to all situations, of course. This is particularly true when complex structures of management involving shared responsibilities for management and execution exist such as between utilities, manufacturing industries, and Government. However, the program elements, objectives, methods of execution and intrinsic work content in this area are sufficiently similar to past AEC, DOD, NASA, and non-Government development efforts that the ERDA management approach can be decided in principle by studying the alternatives within a standard management structure which has been proven by experience. For this preliminary examination, that structure has been assumed to be as follows:

Level I - Overall Program Management

Functions: Budget, plan, scope, monitor, coordinate, and integrate other efforts.

Assigned to: Government headquarters or utilities

Level II - Lead Center or Office

Functions: Project management, planning, feedback, contract, execute, perform some SRT

Assigned to: Government laboratories, offices

Level III - Contributing Laboratories, Centers, Universities, etc.

Function: Perform or contract for supporting research or major components or elements of program

Assigned to: Technically able and ready government or contractor organizations

Level IV - Executing Contractors, Laboratories, Centers

Function: Perform the work

Assigned to: Technically able and ready contractors and government laboratories

Using this assumed management arrangement, a study was performed of each sub-program to determine the level and role of organizations participating in the areas of work in the past and present and to examine various future options and select a tentative future management arrangement for ERDA.

This process served to approximate the arrangements needed to preserve continuity and to determine the ERDA and other budget allocations. An example of one such study is given in Appendix 5.

A summarization of the results is given in Table 8. The program assumed is that presented in the Ray report.

Scanning the table shows that with the incorporation into ERDA of the Office of Coal Research and the Bureau of Mines, it becomes feasible to concentrate the Level I and Level II management roles in ERDA without destroying continuity, assuming that the FY 75 NSF funding can be properly allocated between NSF and ERDA, with a few exceptions. These are the continuing role of the utilities in the ongoing fuel cell and MHD programs, and the future role of the utilities in assuming all or partial responsibilities with the Government for major pilot plant and demonstration programs. In addition, HUD would share or assume the top management role for dispersed plants in some cases. In the case of Level II responsibilities, it is logical to assign ERDA laboratories, offices or centers the role of project management with one exception. That is, that gas turbine project management most likely should be carried by NASA because of their traditional role and expertise in these matters and the close relationship to the HTGR helium gas turbine program.

TABLE 8

TENTATIVE ROLE ASSIGNMENTS

Area of Work	Level I	Level II	Level III	Level IV
Potassium Topping Cycle	ERDA (Possibly utility for demo plant)	ERDA Lab (Office)	ERDA Labs (B of M, Labs, NASA)	Competitive GE, P&W Westinghouse, etc.
MHD	ERDA EPRI with ERDA Support for AVCO program	ERDA Lab (Office)	NASA AEC Labs ERDA Labs (B of M) NSF	Many competitors See Table 7 AVCO U of Tenn for continuing work
Fuel Cells	ERDA Utilities with ERDA Support for Target	ERDA Lab (Office)	ERDA Labs US Army NASA NBS	P&W for target Many competitors for balance. See Table 7.
Gas Turbine	ERDA HUD for dispersed demo	NASA	ERDA Labs NASA NBS NSF	Competitive. See Table 7.
Thermionics	ERDA Utilities for pilot plant	ERDA Lab	NASA JPL TECO Rasor NSF	Competitive
Feher Cycle	ERDA (Possibly utility or HUD for demo plant)	ERDA Lab	ERDA Labs	Competitive

C. MAJOR ISSUES

As has been discussed in previous sections of this report, the Ray report recommends a broad approach to advanced cycles encompassing four major areas of sub-programs and a modest effort on advanced programs. The Ray report identifies FY 75 funding of approximately $18 million for the combined combustion gas turbine program and the HTGR helium turbine program, and an additional approximately $18 million for all other advanced cycles. The corresponding runout costs through 1979 are $315 million and $210 million, respectively, or if one subtracts about $200 million for the HTGR turbine, then there is available about $115 million and $210 million, respectively. As discussed in the budgetary analysis section of this report, the actual amounts available in FY 75 within the President's energy message, as far as we can decipher it, are very much less, approximately $6 million and $12-15 million, respectively. As a consequence, it will not be possible to perform the program outlined in the Ray report in FY 75. In addition, even with optimistic assumptions of contributions by the private sector, it will not be possible to perform the program outlined in the Ray report in subsequent years. This situation, deplorable as it may be, needs rapid resolution.

D. OPTIONS AND STRATEGIES

It is difficult to summarize the situation in a few words without omitting some major considerations, but with that qualification the following is an overview. At present it is not possible to rationally select between the various potential advanced cycles with high confidence that any one or two development programs will meet the needs of the country in the next ten to thirty years. The reasons such a selection cannot be made are many, but dominantly they are that (a) substantial technical uncertainties exist in all of the attractive technical options, (b) large uncertainties remain in development costs and ultimate capital costs, and perhaps most important (c) the systems of choice depend very heavily on the ultimate resolution of the magnitudes and types of fuels that the country chooses to develop and supply in the next few decades. In view of this situation, a number of optional strategies may be considered.

1. Elect to fully fund the across-the-board program suggested in the Ray report. This would require increases in FY 75 funding and in the FY 75-79 total.

2. Continue all programs at a low level until some future date when funding and other issues are resolved. This would require reductions in ongoing programs (principally MHD) or an increase in FY 75 funding, and would entail postponement of commercial utilization probably on a nearly year-for-year basis.

3. Arbitrarily select one or two major thrusts and continue the others on low level until the issues are resolved. This would require properly coping with the resultant political problems and an increase in FY 75 and in subsequent years.

4. Accept the current level of the President's budget allocation and do the best you can with it. This would probably mean no focused effort toward advanced systems except those that are already in being, namely, MHD open cycle funded by the OCR and utilities and the hydrogen-air fuel cell funded by utilities and industry. The balance of the program would be miscellaneous small R&D programs.

There are, of course, many other options. Those given above cover the practical range. It seems likely that if resolution of this issue is postponed until the establishment of ERDA that only Option 4 will remain.

V. SUMMARY AND CONCLUSIONS

The USA past efforts on advanced power cycles have been largely directed toward objectives other than commercial power station applications. The work with few exceptions has been piecemeal and sporadic, and responsibilities have been scattered throughout various government and private sector organizations. Based on incomplete information available, this situation persists today. The Ray report adopts the approach that it is not possible at this time to eliminate candidate systems and, therefore, major thrusts in parallel should be immediately undertaken to reduce at least four advanced cycles to commercial practice, and secondary programs should be undertaken on several others. The reasons that eliminations are not possible at this time are a combination of organizational, political, technical, and economic factors for which we do not currently have an integrated and comprehensive mechanism and organization to resolve on any reasonable time scale. The President's energy message and the FY 75 budget are not sufficient to support this approach. Therefore, the recommendations of the Ray report cannot be executed in the present circumstances.

It seems unlikely, therefore, that the broad across-the-board simultaneous approach will be supported, and several options are presented for consideration. Even crude analysis, however, strongly indicates that from the conservation and economic viewpoints, it is important to introduce advanced cycles in an effective manner as rapidly as is feasible. Some such analysis is presented.

It is apparent that we have not adequately completed our homework in advanced cycles. It is urgent to develop a realistic plan for the next 10 to 20 years. The ERDA energy analysis efforts, as well as the cadre assigned to every systems analysis, should include a strong emphasis on advanced cycles.

APPENDIX 1

CONVERSION TECHNIQUES

R & D PROGRAM

FY 75-79

Submitted by Subpanel VI
November 13, 1973

Panel Members

Robert E. English, NASA (Chairman)
Winfred M. Crim, Jr., Army
James L. Powell, DoI
Samuel J. Schneider, DoC
John Smith, EPA
Donald K. Stevens, AEC
Patrick A. O'Riordan, AEC (Executive Secretary)

Prepared for the Chairman, AEC, in support of her development of a comprehensive Federal energy R & D program to be recommended to the President on December 1, 1973.

1. GOALS AND OBJECTIVES

The importance of improved techniques for energy conversion is reflected in the following statistics: At present, U. S. residents spend about $40 billion a year for electric power. Our energy-use rate for production of power is $2x10^{16}$ BTU per year, the equivalent of nearly 1 billion tons of coal or 20,000 tons of uranium each year. Of this input energy over half (about 10^{16} BTU/yr) is wasted and adds to thermal pollution of our waters; the quantity of rejected heat is more than sufficient to heat every residence in the Nation. In addition, construction of new power plants is estimated to total $1000 billion during the remainder of this century.

Fossil steam power plants are the product of a very mature technology that has plateaued at an efficiency of 40 percent. Clean fuels for these power plants are growing scarce, and our means for burning coal are not yet socially acceptable. Present nuclear power plants are 32 percent efficient and are therefore large thermal polluters.

Therefore, improved energy conversion techniques for the reliable generation of electric power and for energy conservation are of great importance to our Nation, and the goals of this R & D program are to (1) increase the efficiency of use of indigenous energy supplies (coal and uranium as well as new, alternate energy sources), (2) to reduce the environmental impact of this power production, and (3) to reduce the capital cost for construction of new power plants.

For the purpose of reaching these goals, the following eight objectives were established:

(1) Coal Gasification. To develop processes for the production and use of clean low-BTU gas from coal in central power stations.

(2) Gas Turbines. To increase the overall efficiency and reliability of power generation by developing high-temperature gas-turbine systems.

(3) MHD. To increase the overall efficiency and reliability of power generation by developing MHD power systems.

(4) Potassium Topping Cycle. To increase the overall efficiency and reliability of power generation by developing potassium-vapor topping systems.

(5) Fuel Cells. To develop efficient and economical fuel cells for power generation.

(6) Use of Waste Heat and Fuel. To develop power systems for economical use of heat and fuel presently wasted.

(7) Advanced Concepts. To evaluate, to investigate, and ultimately to develop advanced concepts for energy conversion.

(8) Enabling Technology. To evolve the basic constituent technologies that enable the substantial improvement of various power systems or that make feasible entirely new concepts for power generation.

An implicit constituent of these objectives is to minimize the environmental impact of power generation.

These eight objectives represent a significant narrowing of the range of options considered. Under the pressure of severe budgetary constraints, the R & D originally proposed on Low-Temperature Cycles was deferred and converted instead to a study under Advanced Concepts. Further, the Use of Waste Heat and Fuel was confined to the use of solid waste for power generation.

Among energy conversion techniques in these eight objectives, the following three priorities were assigned:

First Priority:

Low-BTU Gasification of Coal

Gas Turbines

Second Priority:

MHD

Potassium Topping Cycle

Fuel Cells

Third Priority:

Use of Waste Fuel

Advanced Concepts

Enabling Technology

2. INDUSTRIAL CONTRIBUTION

In these programs, the level of industrial contribution will vary over the program's life, depending on the degree of technical risk, on the amount of investment required, and on the time required for financial return on the investment. Until technical feasibility has been demonstrated, little, if any, industrial contribution is likely. Based on discussions with industrial representatives and on past experience, industrial contribution to the pilot stage will be approximately 25 percent, for by this stage the risks and time to financial return are diminishing.

The demonstration plants will be built at sites selected by a consortia of electric utilities. One of these utilities will operate the plant and market the power generated. The cooperating utilities are anticipated to make large contributions toward the construction of the plant, approximately 50 percent.

If a large advance in technology is to be achieved that involves both long time to financial payoff and substantial technical risk, the Government must be a heavy financial contributor. For those technology programs affecting public welfare (such as pollution reduction) rather than financial gain for the power industry, the Government must carry the major share of the financial burden.

3. PROGRAM BUDGET

The energy conversion R & D budget amounts to $755 million for FY (75-79) with the FY 75 expenditure totaling $89 million. The $89 million includes $50 million for the low BTU gasification subprogram which has been already obligated. Table 1 (attached) summarizes details for each subprogram.

4. SUBPROGRAMS - DESCRIPTION, BENEFITS AND BUDGET

GASIFICATION (LOW BTU)

Each commercial power generation plant or industrial application of low BTU gas from coal will release current premium fuels such as natural gas or oil for other higher priority usages.

The goal is for low BTU gasification pilot/demonstration size (20 to 50 MWe) combined cycle systems utilizing present technology and consuming all ranks of coal which are scheduled for operation in the 1978-1979 time period operating in a non-polluting mode. These plants will supply operating and economic data so that participating utilities can proceed with the construction of a multiplicity of plants with confidence. At least 3 improved technology pilot scale gasification reactors for inclusion in future improved systems will be constructed and operating by the end of this time period.

Selected sub-process improvements for incorporation in later systems will be developed. Improved gas turbine efficiency increases are anticipated from other energy initiatives. This total effort is based on continuing cooperative funding by industry (2/3 Federal - 1/3 industry) and those major program elements not so funded will be deemphasized or eliminated.

This is a reasonable program of high impact on future electric power generation with no known major technical obstacles. The plant combined cycles systems will operate at initial efficiencies over 40% as compared to 35% conventionally and produce power later at efficiencies approaching 50%; however, the relative economics and growth potentials of such systems can only be proven by early construction and operation at pilot/demonstration scale plants.

Commercial exploitation of the developed low BTU system is expected to proceed at a rapid pace after successful demonstration and the estimated benefits of this program to the nation are:

	1985	2000
No. Plants	10 Commercial Plants	210 Commercial Plants
Electrical Power	32.9×10^{6} MWH e	1150×10^{6} MWH e
Q energy released for priority uses	0.28×10^{15} BTU	9.8×10^{15} BTU
Q saved by high efficiency	0.014×10^{15} BTU	$0.49 - 0.9 \times 10^{15}$ BTU

Budget ($ Millions)

	1975	1976	1977	1978	1979	Total
Federal	50	60	80	35	25	250
Industrial	(15)	(25)	(35)	(25)	(25)	(125)

Construction of pilot/demonstration plants shape the funding towards early heavy expenditures tapering toward 1979 with the peak in 1977. Lag in cooperative funding capability of industry tends to front load the Federal contribution.

HIGH TEMPERATURE GAS TURBINES

For fossil-fueled gas turbines, two programs are planned, viz., (1) high-temperature gas and steam turbine combined cycle and (2) closed gas turbines to supply waste heat.

The combined cycle is entering utility service this year and will achieve an efficiency of 40 percent. The crucial improvement needed for the system is to raise system efficiency to 50 percent by increasing turbine-inlet temperature to 2500°F. Improved air-cooling of the turbine and, in particular, liquid-cooling must be investigated and developed. Ceramic materials for turbines will be also investigated under the Enabling Technology subprogram (q.v.). Low-pollution combustion will also be investigated as well as the use of a pressurized furnace for the steam boiler as a way to both reduce system cost and increase efficiency. The higher temperature turbines will be tested in the laboratory and demonstrated in 1979 in a 100-MW demonstration plant at a utility's power plant; a system efficiency of 50 percent is anticipated.

This gas-turbine development will be carried out by industry under contract to the Government. Industrial contribution to the 100-MW demonstration plant is expected to be 50 percent. Power plants incorporating this advanced technology will enter service in the mid-1980's. Energy savings in the year 2000 will amount to 2×10^{15} BTU per year, having a value of $2 billion a year at $1 per million BTU.

1975-77 Design, build and test high-temperature turbines.

1975-76 Design, build, test catalytic, surface, and reformed-fuel low-pollution combustors.

1976 Economic study of pressurized furnace.

1976 Design 100-MW demonstration power plant.

1977-79 Build 100-MW power plant.

At present, high-grade fuels are burned and electric power is consumed in various applications solely for the purpose of providing heat. Integration of power generation with the supply of heat can yield enormous energy savings. Because the total demand for heat is beyond what power generation can provide, the market for waste heat can, from the point of view of power generation, be considered limitless.

In realization of this goal, the problems are (1) to minimize the cost of distributing the waste heat by generating the power near the site at which the heat is required, and (2) to heat the transport fluid (water) to 400°F while maintaining a high efficiency of power generation. The closed fossil-burning gas turbine is well suited to this service because of its suitability to produce powers from 1-100's MW close to the site of heat use, its constant, high efficiency at part power, its ability to burn various fuels (including municipal or industrial waste), its maintenance-free operation, and its ability to heat water to 400°F without a penalty in efficiency. The potential energy savings are 4-8 x 10^{15} BTU/yr in the year 2000, depending on the speed of entry into the marketplace.

The schedule of events and funding are given below:

1975 Design 1-MW power plant

1976-77 Build test models of components and power plant

1978 Test the power plant

1979 Continue power plant tests. Procure additional power plants for use by HUD in energy-conserving housing developments.

Cost in Millions

FY	1975	1976	1977	1978	1979	Total
Funds	15	65	53	50	42	225

MAGNETOHYDRODYNAMICS (MHD)

There are three MHD concepts: 1) open cycle, 2) liquid metal closed cycle, and 3) closed cycle plasma. An open cycle generation system is ideally suited for fossil fuel operation (including coal) while the closed cycle systems are better adapted to nuclear heat sources. All systems when combined with conventional cycles, offer significant benefits which include:

- high efficiencies (55-60%)
- fuel and dollar savings*
  - 1×10^{15} BTU in year 2000
  - 1 billion dollars in year 2000
- direct coal-fired systems
- non-polluting systems
  - NO_x - 1/9 EPA standards
  - SO_x - 1/20 EPA standards
  - Water - nil

The goal of the MHD program is to accelerate the development of these highly efficient, non-polluting systems. The open cycle segment of the program (the largest) will lead to the construction of a coal-fired demonstration plant in the 1980's and operation in about 1987. Smaller program elements are planned for the closed cycle systems but will

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* Assuming 28.9×10^{15} BTU total electric demand from fossil sources in 2000; and fuel costs of $\$1/10^6$ BTU.

lead to the proof of technical feasibility and design of prototype systems. During the FY 1975-1979 period the program will be devoted to: 1) component and materials development and testing, 2) system analysis and design, and 3) facilities design and construction (large scale generator and long endurance materials test facilities). The generator and materials test facilities amount to about 60% of the FY 75-79 costs and are key features of the program. In effect, they replace many aspects of a conventional pilot plant. Also there will be considerable emphasis on the utilization of existing USSR MHD facilities (25 MW and 250 KW plants) and expertise through the ongoing US-USSR Cooperative Program.

Under Government management, the FY 75-79 program will be implemented by contract to a mix of national and university laboratories and industrial organizations already involved in MHD R & D. Scientific and engineering expertise and manpower are readily available for the design, construction and operation of test facilities. As evidenced by previous support ($8 million), industry can be expected to provide a significant portion of the funds necessary to bring about commercialization of MHD. Early industrial involvement will amount to some $20 million through FY 79 by the Electric Power Research Institute and expand to at least 30-50% of the cost of a demonstration plant (utilities).

The following table summarizes the suggested Government R & D budget:

FY Cost in Millions

1975	1976	1977	1978	1979	Total 75-79
10	19	22	22	22	95

POTASSIUM TOPPING CYCLE

Potassium vapor generated at 1400-1500 °F is expanded in a turbine and then condensed at 1100 °F, the heat of condensation being the heat input to a conventional steam power plant. Overall efficiencies of 50-55 percent appear practical, about a 30 percent increase over the best fossil plants today. Both energy consumption and thermal pollution would be reduced accordingly.

The low operating temperatures of this power plant might make feasible the direct combustion of coal without atmospheric pollution. In a fluidized bed, the combustion temperatures might thereby be limited to maximum values of 1600-1700 °F, thereby both avoiding NO_x formation and permitting limestone or dolomite to capture the sulfur. Competitive concepts using clean fuel must exceed 60 percent efficiency in order to achieve the same efficiency between coal pile and busbar.

Operation of a complete potassium-vapor system fired with natural gas for over a year has already demonstrated the feasibility of the concept. The following sequence and timetable of events are planned:

1974	Power plant preliminary design and economic assessment by an architect-engineering firm.
1975-1979	Design and build a 30 MW potassium power system as a pilot plant demonstration using clean fuel.
1979-1981	Operate the 30 MW pilot plant.
1980-1984	Build two additional 30 MW potassium modules and add them to the pilot plant. Build and add steam power-generating equipment. Demonstration plant output, 300 MW; potassium output, 90 MW.

1985 Start full commercial operation of the 300 MW plant.

1977-1981 Build and test a pilot-scale fluid-bed furnace for later incorporation into the demonstration power plant.

The following budget is required:

Fiscal Year	75	76	77	78	79	75-79
R&D	3	7	7	7	7	31
Pilot Plant (C of F)	0	8	14	9	3	34
Total	3	15	21	16	10	$65M

This entire program will be performed by industry under government contract. Both the pilot plant and the demonstration plant would be installed at the site of a cooperating utility. Although the government would pay for the plant design and its economic assessment, both the equipment manufacturer and the cooperating utilities are expected to pay 25 percent of the pilot plant cost and one-half the cost of the demonstration plant.

Following demonstration in 1985, the installation of this class of power plant would begin and could reach 150,000 MW by 2000. Accordingly, fuel savings would amount to 10^{15} BTU per year and $1 billion* a year at that time.

*Based on fuel cost of $1 per million BTU.

CONVERSION SYSTEMS - FUEL CELLS

Fuel cells are simple devices which convert chemical energy directly to electrical energy with efficiencies which are presently about 60% and ultimately may approach 80% with essentially no environmental pollution. They are modular in nature and may be supplied in a variety of sizes varying from fuel cells for use in individual houses (5 KW giving "total energy" capability) to fuel cells for use in substation power plants (150 MW). Fuel cells are quiet and have essentially instantaneous response to load variation, high efficiency at partial load operation, heat rejection to air and automatic operation. Fuel cells, an emerging technology with demonstrated technical feasibility, require R & D to solve three major problems: cost, life, and limited fuel flexibility.

The proposed program is aimed at solving these problems for the following five promising fuel cells systems: acid hydrogen, basic hydrogen, methyl alcohol, solid electrolyte and molten carbonate. The envisioned program is broad based with a simultaneous pursuit of a number of fuel cell concepts because of the high risk nature of the approach and the realization that no one fuel cell concept is clearly superior at this time. Greatest funding will be placed in the acid hydrogen area because of the maturity of ~~the~~ program and possibility ~~of~~ early commercialization. Basic hydrogen has been supported because it has the potential of being 15% more efficient than acid hydrogen with simultaneous use of less expensive electrocatalysts. The methyl alcohol cell is attractive because of its potentially high thermodynamic efficiency plus the use of a pure, cheap, easily available liquid fuel. The solid electrolyte and molten carbonate cells operate at high temperature and have the potential for using dirty fuels with good efficiency.

The program provides the following by the end of 1979:

1. Build and test one 7 KW methyl alcohol prototype fuel cell.
2. Build and test dispersed power plants (2 to 5 MW, 1976; 20 MW, 1977).
3. Commercially demonstrate the acid-hydrogen fuel cell on site system (40 KW Field Unit).
4. Pilot test hydrogen fuel cells in the integrated total energy system.
5. Build 10 KW basic hydrogen prototype fuel cell.
6. Build a 10 KW solid electrolyte fuel cell and begin testing.
7. Limited search for new concepts.

At present, industry is supporting the acid hydrogen cell development at a rate of about 15 million dollars per year and the methyl alcohol cell at a level of about 2 million dollars per year. The Electric Power Research Institute (EPRI) is spending about $2 million per year in fuel cells. The other concepts are being supported at low levels by a number of organizations. The projected developments on this program are predicated on the assumption that industry (which has solicited Government participation) will contribute at least $2 for every $1 that the Government furnishes.

Progress in the fuel cell area is limited only by the availability of funding. If platinum is required as the electrocatalyst in fuel cells, then large scale fuel cell production will require low platinum loadings. However, the development of less expensive and more available electrocatalysts is an integral part of this program.

The proposed budget is:

1975	1976	1977	1978	1979	75-79
5.5	9.5	17	22	26	80

Fuel cells are applicable to the whole spectrum of sizes varying from use in the home to use in power plants. Fuel cells may replace the internal combustion engine in many applications, thus the following energy savings are projected:

Q (10^{15} BTU) (Savings)

	Residential	Commercial	Power Plants	Cars	Total
1985	1.2*	0.3	0.3	0.3	2.1
2000	9.0*	2.5	1.0	4.0	16.5

Integrated system.

CONVERSION SYSTEMS - USE OF WASTE FUELS

Half of the energy generated in the United States is wasted; this contributes to accelerated depletion of our energy resources, thermal pollution of our waters, and degradation of air quality. In addition, municipal, industrial, agricultural, forestry, and mining wastes are posing solid waste disposal problems which are increasingly difficult to solve. Much of the solid waste can be burned directly to produce clean energy or can be converted to clean fuels. Programs to develop and utilize these energy sources are described below:

Processes will be developed and demonstrated to economically recover clean energy from municipal, industrial, agricultural, forestry, and mining wastes. The processes considered include waste combustion, gasification, liquefaction, and biochemical conversion.

The following program will be carried out: (1) processing and combusion of wastes as auxiliary fuels in commercial, industrial and utility boilers - 1978, (2) processing and combustion of waste fuels in fluid bed combustors with gas turbine-electrical energy recovery - 1978, (3) thermochemical conversion of wastes to clean gaseous, liquid or solid fuel - 1980, (4) biochemical conversion of wastes to liquid fuels - 1981. These technologies will be demonstrated under joint programs with industry and local governments, who are developing new waste disposal processes. Emphasis will be placed on equipment development and process modifications which are needed to optimize energy recovery.

Budget

Fiscal Year	75	76	77	78	79	Total
Cost in Millions	1.5	2.6	2.3	1.9	1.7	10.0

There are indications of wide support of waste disposal-energy recovery processes by both industry and local government. In fact, the success of the above programs is predicated on the assumption that they will put in at least $2 for every $1 of Federal funds. At least 5 utilities have firm plans for firing municipal wastes as an auxiliary fuel in their boilers. However, the newer, higher level development cost processes (fluid bed combustion, thermochemical conversion and biochemical conversion) will probably require partial support by Federal funds through at least pilot scale operation. Many localities face critical solid waste disposal problems. If development of new technologies are not implemented by Federal funds, older processes which do not recover energy will be installed and the energy which could have been recovered will be lost during the 15 to 20 plant year life.

Benefits of the proposed developments would include: (1) recovery of over 10^{15} BTU/year of energy by 1985, (2) economically and environmentally acceptable disposal of solid waste and, (3) a reduction in air pollution.

ADVANCED CONCEPTS

A five year experimental and analytical program to conduct applied research and engineering development on a number of promising advanced energy conversion methods and concepts for eventual use in high efficiency central station, decentralized and smaller power plants. A number of energy conversion methods and concepts including Feher (CO_2) cycle, thermionics, thermal oscillator, thermogalvanic cells, advanced thermoelectric materials and low temperature cycles have been identified as having the potential for higher energy conversion efficiencies compared to existing systems.

Feher (CO_2) cycle and thermionic conversion would receive the highest priority for investigation because of their impact on large power systems. Other conversion techniques such as thermal oscillators, thermogalvanic cells and advanced thermoelectric materials are more applicable to increasing the conversion efficiency of small power plants and hence would receive a lower priority. Other advanced cycles such as the organic Rankine would receive analysis and assessment for use as low temperature/bottoming cycles.

The application date of these energy conversion methods to commercial power production in central station plants would be no earlier than the mid-1980's due to their advanced nature. It is possible that new small power plants would be commercially available in the late 1970's. All of the potential advantages of these new technologies cannot be anticipated and therefore, the specific time of application for the small power plants is difficult to determine.

The CO_2 cycle system appears to offer efficiencies for central station power plants in the mid-40% range for temperatures of about 1200 °F. If the potential of thermionic conversion is achieved, topping cycles can be added to centralized power plants that will raise conversion efficiencies from present values of 30 to 40% to the range of 40 to 50%. The efficiency of a thermionic conversion system is relatively independent of power level, thus thermionics may be applied to various size energy conversion systems. The other conversion methods have demonstrated efficiencies, in laboratory scale experiments/devices, of as high as 30%.

Industry has made only a minimal investment in this area due to the advanced nature of and long time to payoff for these conversion methods. It is believed that this situation will continue to exist until more specific development results are available from the proposed investigations.

This program does not involve large pilot or demonstration plants but rather applied research, engineering development and analysis of new energy conversion cycles and methods therefore does not involve any roadblocks to implementation.

The recommended funding levels are as follows:

Cost in Millions of Dollars

	FY 75	FY 76	FY 77	FY 78	FY 79	Total
Advanced Concepts	2.0	2.0	2.0	2.0	2.0	10.0

Each of the above energy conversion systems posses unique characteristics and attributes that, if successfully developed, could make significant contributions in the future toward the nation's developing energy crisis. The investment risks are minimal compared to the potential return.

ENABLING TECHNOLOGY

This subprogram has two major thrusts: (1) the development of a 100 MW ac generator using superconductor technology, and (2) a continuing undergirding materials R&D program which is focused on high temperature aspects of materials performance in specific applications and is intermediate between short-term development and multi-directional basic research.

Industry has already constructed 5MW laboratory scale ac generators. The next step is to go to 100 MW before advancing to 600-1000 MW machines. No scientific breakthroughs are required; however, considerable engineering development is necessary. The development of electrical machinery using conventional approaches appears to have been maximized and with the advances now being made in superconductor technology, e.g., higher temperature superconductors, this approach is increasingly attractive.

The proposed effort to construct and test a 100 MW ac generator will be carried out primarily by contract with industry from which substantial cost sharing can be expected. The benefits to be derived from this system's development are: increased conversion efficiency (up to 1% for large installations), circumvention of size limitations of components which may be shipped from factory to installation site, and avoidance of foreign competitors from capturing future markets for electrical machinery. The principal risks/uncertainties center around the complexity of the envisioned system and thus its acceptibility to industry and the utilities.

In most new technologies, the development of new materials is the key to eventual success. Advanced conversion concepts (higher power, higher temperature) will require materials which are now beyond the current state-of-the-art. For example, gas turbines with 2500 °F inlet temperatures will require new vane and first row blade materials. MHD will require special materials for ducts, electrodes, and insulators. High temperature heat exchangers will require high strength materials resistant to thermal shock and cyclic fatigue and which will minimize inter-diffusion of contaminants from one working fluid into the other. The effect of micro impurities in hot working fluids on the long term properties of high temperature materials is poorly understood and in some cases not at all. There is a need not only for new materials but also a more complete bank of engineering data on existing materials to allow prediction of long-term reliability. This is a level-of-effort activity to permit study of only the most obviously important problems and will be conducted in those institutions wherein the expertise lies. The benefits to be derived include increased efficiency, increased reliability, and reduced down time of existing systems, reduction of environmental problems (e.g., inter-diffusion of contaminants), and in the case of new technologies, possibly a go-no-go determination. The budget for the program is:

FY Cost in Millions

75	76	77	78	79	Total 75-79
2	3	5	5	5	20

TABLE 1

ENERGY CONVERSION TECHNIQUES R&D BUDGET

(cost in millions)

Subprogram	FY 75	FY 76	FY 77	FY 78	FY 79	Total FY75-79
1. Coal Gasification (Low-BTU)	50	60	80	35	25	250
2. High Temperature Gas Turbines	15	65	53	50	42	225
3. MHD	10	19	22	22	22	95
4. Potassium Topping Cycle	3	15	21	16	10	65
5. Fuel Cells	5.5	9.5	17	22	26	80
6. Waste Fuel	1.5	2.6	2.3	1.9	1.7	10
7. Advanced Concepts	2	2	2	2	2	10
8. Enabling Technology	2	3	5	5	5	20
Total	89.0	176.1	202.3	153.9	133.7	755.0

APPENDIX 2

1. Gas Turbines

The conversion of heat energy into mechanical work, as performed in a power plant using turbines occurs essentially in three steps. Heat from burning fuel produces a high-temperature, high-pressure gas. The compressed, high-temperature medium then expands in suitably shaped nozzles, producing a high-velocity jet. The stored or thermal energy of the fluid is thus converted into kinetic energy. Finally, the kinetic energy is converted into rotational mechanical energy when the jet, impinging on the blades of the turbine, moves the turbine wheel against the torque exerted by the load. This is the basic conversion process of any turbine.

In the gas (or noncondensable) turbine, air enters a compressor which is an integral part of the arrangement, and its pressure is raised sufficiently so that, after heating, it can expand in the system's turbine and produce power. In the combustor, the air is heated by burning fuel in the airstream. The resulting high-temperature air and combustion gases expand through the gas turbine, drive the compressor, and in addition produces useful power in a device such as a generator or pump.

The temperature of the gases supplied to the turbine must be sufficiently high to permit the power developed by the gas turbine to exceed that required by the compressor. The temperature of the air and gases leaving the combustor and entering the turbine is a critical factor, for the efficiency rapidly increases as the temperature of the turbine inlet gas is raised. Because it is a major factor in the output and thermal efficiency of the gas turbine and, in turn, strongly influences unit cost per kilowatt, firing temperature has progressively increased, averaging a rise of about 15° F per year. Present levels for natural-gas firing are in the range of 1600 to 1700°F for equipment in continuous service without blade cooling and up to 1800 to 2200°F for equipment with blade cooling.[1]

The gas turbine can operate on either an open or closed cycle. In the open cycle, the air that passes through the compressor is used in the combustion process, and the air and combustion gases expand and produce work in the turbine. The gases, still at high temperature, then are exhausted to the atomosphere. The closed cycle differs in that the air and combustion gases exhausted by the turbine are recirculated through the compressor. One advantage of the open system is that the atmosphere acts as the

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[1] Technological and Economic Feasibility of Advanced Power Cycles and Methods of Producing Nonpolluting Fuels for Utility Power Stations. UAC Research Laboratories. F. L. Robson et al Dec. 1970. (National Technical Information Service No. PB 198-392)

thermodynamic sink of the system and usually no cooling water is required; also the working medium, air, is available in unlimited quantities. In the closed cycle, the pressure in the system is not related to atmospheric pressure and hence can be arbitrarily fixed. This is advantageous in that the work produced in terms of the gas density within the system can be varied by regulating pressure in the cycle. With increased operating pressures, the system can be smaller. Moreover, the closed cycle can use gases other than air as the working fluid.

The high specific fuel consumption of gas turbines in general can be considerably improved with regenerative heat exchangers, which essentially extract the heat intrinsic in the exhaust gas to preheat the incoming combustion air.

The thermal efficiency of the simple-cycle (non-regenerative) gas turbine, which is the most widely used within the United States, has been progressively increased through higher firing temperatures and continual improvements in the mechanical efficiency of the turbine and the compressor; it now approaches 30 percent. The mechanical efficiency of these components is about 90 percent, so that further internal-efficiency improvements probably will be in small increments and of relatively minor significance to overall cycle efficiency. The performance of the system is also a factor of the pressure ratio through which the air is compressed which, in turn, must be related to the inlet temperature. The compressor used may be axial flow, centrifugal, positive displacement, or a device such as the free-piston engine discussed previously.

A number of smaller regenerative-cycle gas turbines have been built, with thermal efficiencies about 10 points higher than the simple-cycle unit; larger sizes up to around 100 MW are now being built.

A wide variety of fuels has been used in gas turbines. Natural gas has been the primary fuel in most installations, but process gases and liquid fuels ranging from kerosene to residual oil have been burned in some. Gas fuels are most generally applicable since they are usually lower in cost and are free of corrosive and erosive elements. Most higher grade liquid fuels are equally satisfactory, but their cost is often prohibitive. While residual or Bunker C fuels are inexpensive and can be burned successfully, residual oils reduce the permissible firing temperature, and the low fuel cost may be offset by the cost of equipment required to remove certain corrosive elements in the oil.

For the electric power industry, several hundred gas-turbine generators are in service within the United States, totaling several MW of generating capacity. These units are predominantly in the 10,000-kw range, but several are rated up to nearly 30,000 kw. On order are two very large (100,000 to 120,000-kw) units employing 8 and 10 aircraft jet engines, respectively, which discharge hot gas into a single load wheel driving an electric generator. In addition, several hundred additional gas turbines are in nonutility use, serving industrial plants, pipelines, and railroads. The smallest gas-turbine size is about 100 hp, the low limit being determined by efficiency onsideration.

The majority of the gas-turbine generators in service are used primarily for peaking purposes, although in some instances they also serve other functions such as area protection. There is growing interest in the combined steam/gas-turbine cycle as a means of reducing the cost of base-load generation. Broad application of the combined cycle, burning natural gas, requires no specific technical development, and design and operation of plants such as the 238-Mw Horseshoe Lake No. 7 unit have demonstrated its technical feasibility.

2. Potassium Topping Cycles

The potassium topping cycle is comprised of two interconnected power conversion systems. Heat from the combustion of the fuel would be transferred to boiling potassium. The potassium vapor exits the boiler and expands through a turbine. The mechanical energy of the turbine is converted to electrical power by means of a conventional generator attached to the turbine shaft. The vapor discharged from the turbine is condensed and recirculated to the inlet of the boiler by a pump. The waste heat of the potassium cycle, evolved during the condensation process, is transferred to a coolant, in this case, boiling water. The steam generated in cooling the condensing potassium then flows through a conventional steam power plant to produce additional electric energy. The potassium vapor entering the turbine in the proposed program would be at a temperature of approximately 1500^{o}F.

This cycle could convert the energy of coal to electricity with a calculated efficiency of from 50 to 55%. As a result of these relative high efficiencies the costs of the power plant on a per kilowatt basis and of the electric power that it produces may be substantially less than that of a conventional steam power plant.

3. Magnetohydrodynamic Generators

A magnetohydrodynamic (MHD) generator converts mechanical into electrical energy by using the motion of a fluid conductor in the presence of a magnetic field to generate power. It does so by expanding a heated, electrically conducting fluid in a channel so that the fluid passes through a transversely oriented magnetic field. In its simplest form, the channel has electrical insulators on two opposite walls and power-removing conductors or electrodes on the other two walls.

The functional principle of the MHD generator is similar to that of a conventional electrical generator which operates by moving a conducting wire through a magnetic field; the conductor in the MHD generator is replaced by the moving fluid itself. Similarly, the MHD generator operates like the turbine part of a conventional turbogenerator system in that the working fluid in both cases is heated and then expanded against a resistance to do useful work. The resisting force for the MHD generator is provided by the interaction of the currents induced in the gas with the magnetic field. The MHD generator thus combines in a single unit the functions of the turbine and generator portions of a conventional turbogenerator system.

The primary technical advantage of the MHD generator is that it has no moving parts exposed to high temperatures and hence can use higher fluid temperatures than a conventional turbine, with an attendant gain in thermal efficiency. Theoretically, estimated energy-conversion efficiencies for MHD generator plants are in the range of 40 to 60 percent, and these potential gains are the main motivation for current work on commercial MHD generators.

Among commercial energy-conversion schemes for the future, MHD holds a uniquely promising position because of several factors. Since the efficiency and performance of MHD generators increase as the size of the device (the power generated) increases, these devices are best suited for central station power generation. Yet, in contrast to most direct-conversion schemes, MHD generators have relatively compact systems comparable to and even exceeding those of conventional generation plants. Theoretically, an MHD generator can be used with any fossil-fuel energy source (including powdered coal), with fission-derived energy, or even (eventually) with fusion-power sources.

At the same time, most MHD generators have been designed for operation at pressures not too far from atmospheric, in order to achieve higher power densities. Under this combination of pressures and temperatures, combustion products and/or noble gases would by themselves be essentially electrically non-conducting; at 1 atmosphere and 3,000°K, the gas will be essentially non-ionized; that is, the gas has insufficient free electrons to carry a useful current. The simplest solution has been to add to the parent gas a small amount of easily ionized "seed" material which readily gives up electrons upon impact with other gas particles ("impact" is in fact, the mode of ionization). If all the particles that make up the gas have approximately equal energies--that is, if the gas is in thermodynamic equilibrium--the process is known as thermal ionization, which is certainly the situation that holds in combustion-product gases at atmospheric pressure. Suitable seed materials are the alkali metals, cesium, potassium, sodium, etc., which normally are added as compounds such as K_2CO_3. Cost can be a major consideration in choosing a seed, for the amount of seed may aggregate 1 to 2 percent of the fuel weight in a coal or oil burning plant.

In closed gas-cycle MHD, the working fluid is continuously recirculated through a closed loop. The heat source in such a loop presumably will be a nuclear-fission reactor. Since current reactor technology does not countenance outlet coolant temperatures even approaching 1,400°K (much lower than the 3,000°K encountered in open-cycle generators), and since even seeded gases do not exhibit appreciable electrical conductivity below about 2,000°K, it is apparent that electrical conductivity in the gas must be achieved by some nonthermal approach if an MHD generator is to work in such a system. Note that the closed-cycle system has an inherent advantage over the open-cycle system in that the total recovery of seed permits use of cesium rather than potassium as a seed element, despite cesium's high cost. Thus, to achieve the same level of thermal ionization as with potassium, gas temperatures may be several hundred degrees lower. The key to successful, closed-cycle, nuclear-powered MHD, thus, is an efficient means of achieving electrical conductivity in the working fluid under conditions that are reasonably compatible with foreseeable reactor technology.

While theoretical analysis indicates that efficiencies in the range of 40 to 50 percent are possible with reactor-powered MHD units, the fundamental operating parameters of MHD generators in the "hot electron" regime have not yet been determined experimentally, although system studies have been made. One study considered a closed-cycle 500-Mw plant of which 315 Mw were to be supplied by an MHD generator and the rest by a turbogenerator. The cycle used seeded helium, an axial-flow compressor, and a gas-cooled reactor with unclad fuel elements (a coolant outlet temperature of 1,900°K) and exhibited an estimated overall plant efficiency of 47.1 percent.

Higher temperatures would result in correspondingly higher efficiencies. The use of a 100,000-gauss superconducting magnet was assumed for the MHD generator, but this field-strength magnet will be both very difficult to develop and costly for a megawatt plant. Such a system would likely have to be maintained by remote control, since the fission products would probably diffuse from the fuel elements and be carried by the helium throughout the primary system.

a. Liquid Metal MHD

Closed loop liquid metal MHD power conversion devices can be used as a topping cycle for the conventional Rankine steam cycle or as a bottoming cycle with high temperature systems such as open-cycle plasma MHD. One concept employs thermal energy (heat) to accelerate a conductive working fluid (the liquid metal) so that it can pass through the generator duct where it interacts with an electromagnetic field to produce electric energy. Other approaches for accelerating the liquid metal are being evaluated. Using thermal energy to accelerate the working fluid involves a two component system where the heated liquid metal is mixed with an inert gas to form a homogeneous two-phase mixture which is expanded through the MHD generator. The phases are then separated and the liquid pumped back to the heat source. The gas is passed through a regenerator, to conserve the internal energy of the gas, and through a heat exchanger which allows the waste heat to be rejected at any arbitrary temperature above the ambient surroundings. The cooled gas is compressed and passed back to the mixer via the regenerator.

4. Fuel Cells

A fuel cell is an electrochemical device capable of converting into electrical energy part of the free energy of the reactants, which are stored outside the cell itself. Its four basic components are fuels, oxidants, electrodes, and electrolytes. The human body is itself a fuel-cell system: the fuel (food), in an electrolyte (blood), is oxidized catalytically (enzymes) to produce energy, part of which is electrical.

A successful fuel cell (hydrogen-oxygen) was first operated in England in 1839 by Sir William Grove. In 1959, in England, a fuel-cell power unit and, in the United States, a fuel-cell-driven tractor were demonstrated. At this point, the fuel cell ceased to be a laboratory curiosity and became a significant device for energy conversion and power generation. Too, the number of institutions concerned with fuel-cell technology mushroomed, so that hundreds of government, industrial, and university laboratories now are engaged in basic and applied research in this area. NASA's recent specification of fuel cells for auxiliary power in certain space projects recognizes the coming of age of the fuel cell.

Predominant among the many potential advantages of primary fuel cells, relative to other devices, is the direct-conversion feature: they are not subject to the Carnot-cycle efficiency limit that is imposed on all heat engines. The theoretical limit to the efficiency of fuel cells is the thermal or ideal efficiency. $\Delta F/\Delta H$, the ratio of the changes in free energy to total energy of the chemical reaction. Though this might be more than 90 percent, practical fuel cells are expected to operate at 40- to 75-percent efficiency. Higher numbers are unlikely because the voltage drops as more and more current is drawn from a fuel cell, necessitating a compromise between efficiency and power obtained per cell.

In contrast to thermal powerplants, the efficiency of fuel cells is independent of size, although overall system efficiency will be affected by the possible need for parasitic power (e.g., to drive pumps) and by the efficiency of DC-DC converters or DC-AC inverters if these are required.

For part-load use, they have a lower relative fuel consumption than at full load, whereas engines consume relatively more fuel under such conditions. Thus, fuel cells will be particularly advantageous when power profiles vary widely --as for frequent stop-and-go or on-off cycles.

The fuel cell itself has no moving mechanical parts, although most fuel-cell systems will need pumps and valves.

The reaction products of fuel cells using conventional fuels and air are expected to be mainly carbon dioxide and water (although they may emit some "unburned" reaction intermediates); nitrogen and other inert constituents of the air will be ejected unchanged. Such innocuous products are a necessity for powerplants operating in closed areas. Because they minimize the noxious products and release them in more highly concentrated streams which are more easily purified, fuel cells could contribute toward solving the problem of air pollution from exhaust fumes in urban areas.

Power densities cannot compare with those of engines, for a gasoline engine can develop about 20 kw per cu ft, compared with perhaps 1 to 5 kw per 3 cu ft for present fuel cells.

Fuel cells can be classified by any of several criteria:

a. By electrolyte, which designates either basic or acid systems. Many different acids and bases have been studied.

b. By form of electrolyte. This would include free liquids, restrained liquids (contained in a membrane, mat, or matrix), pastes, solids, or pseudo-solids.

c. By fuel. Hydrogen, alcohol, and coal are representative examples.

d. By fuel form -- gaseous, liquid, or solid.

e. By temperature, although the boundaries are arbitrary and not sharply defined. Low, up to about 300°F; intermediate, to about 750°F; high, to 1,470°F; and very high, above 1,470°F.

Oxidants for fuel-cell use are generally limited to oxygen, air, and hydrogen peroxide. The electrodes employed depend on the form of the reactant and may be porous, nonporous, or even consumable.

5. Thermionics

Thermionic conversion produces electrical energy directly from heat energy without use of moving mechanical parts. Electron emission from metals heated to high temperatures is known as the Edison effect. In the conventional vacuum tube, heat applied to an emitter (the cathode) causes electrons to "boil" off its surface; a positive voltage applied to the collector (the anode) pulls the freed electrons across the vacuum gap. In a thermionic converter, the thermal energy of the free electrons is raised by heating the emitter to a high temperature (1,000^{o} to 1600^{o}C) so that the electrons travel to the collector without the aid of an applied voltage.

A thermionic converter has a theoretical upper limit on its efficiency, as given by the Carnot equation. The thermodynamic cycle is the transport of electrons (the working fluid) from emitter to collector, through an externally connected electrical load, and back to the emitter. The electron gas is electrically charged, and therefore its passage through the interspace between the electrodes constitutes a current flow generated directly by the heat supplied to vaporize the electron fluid from the emitter. This current, returning to the emitter through the external circuit, may thereby deliver power to an electrical load.

A typical converter of this type comprises emitter and collector electrodes, separated by a narrow gap filled with cesium vapor. The function of the cesium is to reduce re-sistance to the electron flow and thereby raise electrical output, the interelectrode spacing is filled with ionized cesium vapor at pressures ranging between 0.1 and 10 mm Hg.

In the early work on vacuum converters, the currents were extremely small because a cloud of electrons formed a space-charge barrier between the electrodes, limiting the number of electrons that could flow to the current collector. If space-charge effects are not eliminated, it is impossible to get current densities greater than 1 to 2 amp per sq cm of emitter surface to flow from emitter to collector, even in diodes with electrode spacing of the order of 0.0005 inch. At a normal output voltage of 0.5 volt, the maximum power-output density obtainable for such a vacuum device is less than 1 watt per sq cm.

The recent upsurge of interest in thermionic conversion began around 1957 with several investigations of ways to neutralize the space charge in order to obtain useful power output; i.e., current densities of 5 to 10 amp per sq cm. Almost all present-day thermionic converters may be categorized according to the techniques used for overcoming space charge effects between the electrodes.

Four basic types of converters have evolved from studies of techniques to neutralize space charge:

a. A vacuum converter with extremely close electrode spacing (of the order of 0.00025 to 0.001 inch).

b. A high- or low-pressure cesium-vapor-filled converter in which positive cesium ions are formed by thermal ionization at a hot electrode surface. These are also known as Langmuir, surface-ionization, or contact-ionization devices.

c. A high-pressure cesium-vapor-filled converter in which all or most of the cesium ions form as a result of volume ionization (electron impact, photon excitation, multiple collisions, etc.) in the interelectrode space. These devices are also known as arc-mode or ignited-mode devices.

d. Triode devices, in which a third electrode is inserted between the main emitter and collector. This third electrode within the thermionic converter produces ions and injects them into the space between the emitter and collector. The advantage is the freeing of the emitter from its dual role of ionizer and electron emitter. The disadvantage is the additional mechanical complexity, as well as the necessity of providing the third electrode with the energy for ionization.

All direct-conversion techniques have certain clear-cut advantages over conventional electric-power generators, primarily silent operation, greatly increased operating life, and low maintenance. Thermionic conversion, because it is an ultrahigh-temperature phenomenon, offers the additional benefit of extremely high power density. The predicted advantages of thermionic conversion over other systems are reduced weight, compactness, high-temperature heat sink for radiation in space, and a minimum number of moving parts. The heat that thermionic devices reject at relatively high temperature may be used for practical purposes in terrestrial applicatins, such as topping cycles, space heating and air conditioning, and in industrial processes requiring large amounts of heat.

6. Feher Supercritical CO_2 Cycle

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

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

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

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

APPENDIX 3

MHD PROGRAM (AS OUTLINED IN DOI ADVANCED POWER CONVERSION TASK FORCE REPORT DATED DEC. 13, 1973)

Magnetohydrodynamics (MHD). Specific milestones, program funding and program analysis charts of the National MHD Program are referenced as Figures 1 and 2. This national program has been developed cooperatively with EPRI and is the recommended program for cosponsoring with EPRI.

1. Description. MHD is a system for generating electricity whereby a moving conductor (ionized gas) is used in a magnetic field rather than the rigid conductor in the conventional generator. The system is particularly suitable for use with a coal gasifier since the high heat content of the MHD exhaust can be used in the gasification process, producing a net gain in efficiency.

2. Benefits.

a. Increased efficiency in the utilization of fuel. Efficiencies of 60% or more are theoretically possible.

b. Can be adopted for use with other thermodynamic cycles using coal or coal derived fuels with no additional environmental impact above that of the cycle with which it is combined.

3. Problem areas. The major identifiable problem areas at this time are:

a. Channel materials and construction techniques must be improved.

b. Air preheaters--additional development required.

c. Seed recovery--methods and materials for the recovery of seed material injected into the gas stream to enhance conductivity must be perfected.

d. Electrode development--electrode technology must be advanced.

4. Plan of action. The recommended plan of action to be accomplished in two phases involves the following six areas of effort (Reference Figure 1):

(1) Basic Technology Development
(2) System Engineering and Plant Design
(3) Component Design
(4) System Testing
(5) Large Scale Generator Development
(6) US-USSR Cooperative Program

a. Phase I. Using AEDC's MHD facilities, tests will be conducted to demonstrate 65% to 70% energy extraction by a MHD channel. Using the USSR U-25 MHD facility, it will be demonstrated that a large scale channel can be built and operated at reasonably high power level for 100 hours or more. The cost of this phase will be minimal since existing facilities will be utilized.

b. Phase II.

(1) Operate a large scale high performance facility at 50 MW_e output for 500 hours to demonstrate the feasibility of large scale components.

(2) Demonstrate the feasibility of integrated operation of MHD systems on the smaller scale test facility by 500 hours operation followed by 2000 hours operation.

c. The individual areas involved in the above.

(1) Basic technology development. This category provides the basic development studies needed to support component design work. It includes tasks such as (a) coal use technologies, (b) materials development, (c) generator diagnostics, and (d) combustion processes, and will include other basic technologies which become identified in time and are required as input to component development. In general then, guidelines for this work category will be set by component development requirements.

(2) Systems engineering and plant design. This task will define systems requirements for commercial size MHD powerplants. Guidelines will be set for component design and systems testing. Continuing efforts will be carried out to design components, evaluate systems, conduct economic studies, and seek help from industry in addressing component design from a practical engineering standpoint.

Efforts will be directed toward developing mathematical models to permit scale-up of equipment and to correlate these models with data obtained in other tasks. Further efforts will be directed toward designing a 250 to 350 MW demonstration plant for construction in FY 80. Environmental impact studies will be carried out to assure compliance with Federal and State regulations.

(3) Component design. The principal components to be designed in this test are channels, burners, high temperature heat exchangers and gas cleaning-seed recovery systems. The three superconducting magnet designs are covered under categories Generator Development, US-USSR Cooperative Program, and System Testing. The work will involve following on with the U.S. MHD program as it exists today to advance the state-of-the-art in the major component design categories. Three principal testing sites exist, namely, UTSI, Avco, and Westinghouse. It is expected that these will form a basis for continued development. Analytical work will be done to support experimental development of components and design of scaled-up components for testing and evaluation in the Generator Development and US-USSR Cooperative Program.

Development information obtained in component design test will support also the Systems Engineering and Plant Design tasks and will provide guidelines for the Basic Technology task.

(4) Systems testing. An intermediate scale 50-60 MW thermal MHD system is proposed which is large enough to provide significant tests and small enough to incur only reasonable costs. This system will include all components of a total power system with a MHD topping cycle (including burner, channel, superconducting magnet, air heater), a steam bottoming cycle, seed recovery, and exhaust gas cleanup. The testing facilities will be used to: (a) identify and permit solving of system problems, (b) identify and permit solving of problem concerning auxiliary equipment in MHD unit, and (c) verify compliance with EPA regulations. It is planned that this system be built as soon as possible in Phase I so that it will be available for testing at the earliest date.

(5) Large Scale Generator Development. Two separate large scale generator development projects are considered: one which has started in FY 74 involves the testing at AEDC using the existing MHD facility with modified burner, and magnet and new channels to establish that high enthalpy extraction at high turbine efficiency is technically feasible. The other large scale high performance demonstration test to be run at a high overall efficiency will be conducted in a MHD facility specifically designed for the test.

The primary difference between the second facility and the existing AEDC facility as modified is that the second facility will use: coal or coal gas burners, superconducting magnet, advanced channel design, air preheaters and inverters. The advanced large scale demonstration facility will be designed specifically to establish that it is possible to build a MHD system to operate over a long duration of 50% or higher efficiency and thus to justify the construction of a large demonstration plant of the order of 250-350 MW of electric power from the MHD generator starting in FY 80.

In addition to the primary objective stated above, the large scale demonstration plant, built in Phase II, will be used to test advanced component designs for burners, heat exchangers, inverters and channels using a range of fuels including direct combustion of coal. Finally experimental measurements can be made to investigate plasma flows and to correlate performance with scaling parameters.

(6) US-USSR Cooperative Program. The U.S. is committed to provide: (a) a generator channel for testing on the USSR U-25 MHD facility, (b) a superconducting magnet for installation on the USSR U-02 MHD facility, (c) a coal combustor for test on the USSR ENN II facility, and (d) candidate channel electrode and insulator materials to be tested on the U-02. The principal advantage to the U.S. is experience gained in testing a channel design and candidate materials for a reasonably long duration at moderate power levels in a large MHD facility at moderate cost to the U.S. The secondary advantages to the U.S. are the materials test results gained in testing U.S. candidate materials

in the U-02, diagnostic results from the U-25, results of superconducting testing on U-02, and coal combustor experimental results from the ENN II.

5. Funding (Reference Figure 2).

Figure 1. Schedule and Milestones (For MHD Cycle Only)

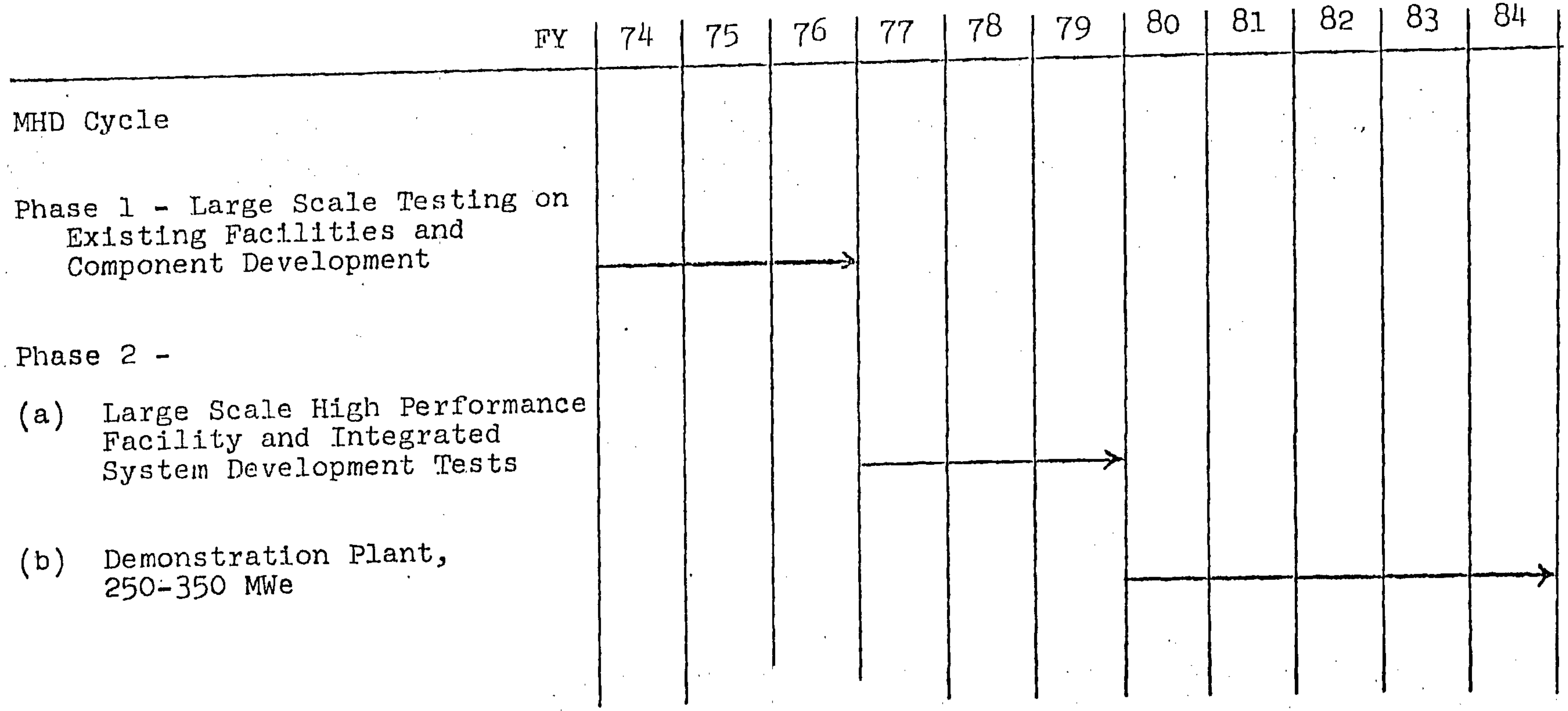

Figure 2. Program for Advanced Energy Conversion Systems

	FY 74	Proposed Program	FY 76 - FY 79
Magnetohydrodynamics	5.30	20.00	
Fuel Cells	0.50	1.50	
Potassium Topping	1.00	7.00	
Feher Cycle	0.50	2.00	
Gas Turbine	*	1.50	
Engineering Evaluations	0.30	1.0	
Bottoming Cycles	-	0.50	
Totals (Advanced Energy Conversion System)	$7.60	$33.5	$250.00**

* Low B.T.U. Program is supporting some Gas Turbine development (mainly in the area of particulate and sulfur removal).

** This assumes that only one system will eventually be carried through to completion.

Fuel Cell PIC Briefs

PIC #	Title	Proponent	FY 73 $K
1466	Mass Transfer in Fuel Cells (Physical properties of electrolyte solutions)	NASA-Lewis	35.0
1509	Electrochemical Cells with Fused-Salt Electrolytes (Thermally regenerative cells)	AEC-ANL	50 (1 Mn-Yr)
2198	The Hydrogen-Deuterium Exchange of Hydrocarbons at a Fuel Cell Electrode (hydrocarbon reactions at electrode)	Ft. Belvoir U. S. Army inhouse	60 (1.2 Mn-Yr)
2200	Mechanism of Hydrocarbon Oxidation on Fuel Cell Electrodes (how hydrocarbons react at electrode)	U. S. Army Ft. Belvoir inhouse	20 (0.4 Mn-yr)
2246	Electrochemical Power Sources (Themis 840) (Basic research)	U. S. Army Ft. Monmouth RPI	73.0
2314	Family of Open Cycle Fuel Cell Power Plant Development (1.5 Kw, 0.5 Kw, 3 Kw and 5 Kw power plants)	U. S. Army Ft. Belvoir P&W	182.0
2409	Hydrogen Generator for 0.5 Kw Fuel Cell System (design, construct and test)	U. S. Army Ft. Belvoir Energy & Research Corp.	6.8
2522	High Power Density Fuel Cell for Aircraft High Power (hydrogen-oxygen cell)	Air Force WPAFB P&W	250.0
2524	Regenerative Fuel Cell Follow-On for Satellite Secondary Power (development of energy storage system, program completed)	Air Force WPAFB P&W	116.0

PIC #	Title	Proponent	FY 73 $K
2529	Fuel Cell Technology Program (Acid) (fabrication and testing of a 5 Kw fuel cell module, program completed)	NASA-Houston G.E.	420.0
2530	Fuel Cell Technology Program (Alkaline) (5 Kw fuel cell on life test 3500 hours as of January 5, 1973, program completed)	NASA-Houston P&W	327.0
2533	Rotating Ring Disk Electrode Studies Applicable to Corrosion Prevention, Fuel Cells, & Batteries (deposition of metals)	Air Force OSR State U. of N.Y.	68.4
2538	Absorption of Molecules at the Electrodes of Batteries and Fuel Cells (Basic research)	Air Force OSR U. of Colorado	?
2606	Fuel Cell System Experiments (applied research on controls)	NASA-Lewis internal	235.0
2608	Advanced Technology Fuel Cell Systems (Life testing - system design for Space Tug power plant)	NASA-Lewis P&W	500.0
2661	Electrolytes for Hydrocarbon/Air Fuel Cell (seeking new electrolytes)	U. S. Army Ft. Belvoir ANL	28.0
2667	Electrolytes for Hydrocarbon/Air Fuel Cell (seeking new acid electrolytes)	U. S. Army Energy Research Corp.	27.0
2685	Hydrogen/Nickel Regenerative Fuel Cells for Satellite Energy Storage (build 6-50 ampere-hours cells)	Air Force WPAFB TYCO Labs.	31.6

PIC #	Title	Proponent	FY 73 $K
2690	Inplantable Biological Fuel Cells (eventually for artificial heart system)	NIH TYCO Labs.	109.4
2702	High Voltage Fuel Cell Assembly (inter-connected groups of small fuel cells)	U. S. Army Energy Research Corp.	
2715	Alkaline Fuel Cell Decay Mechanisms (predicting degradation)	NASA-Lewis Internal	10.0
2718	Radiolytic Preparation of Powered Metal Catalysts for Use in the H_2-O_2 Fuel Cell (new electrode catalyst)	NASA-Lewis internal	15.0
2720	Advanced Membrane Fuel Cell Studies (new design evaluation)	NASA-Lewis G.E.	75.0

Gas Turbine PIC Briefs

PIC #	Title	Proponent	FY 73 $K
1054	Turbine and Compressor Performance (testing BRU compressor and turbine) program completed	NASA-Lewis	25 (.5 mn-yr)
1179	Experimental Study of Brayton Cycle System (to develop an integrated Brayton Cycle System)	NASA-Lewis	400 (8 mn-yr)
1763	A GT-1500 Gas Turbine Development (to develop a 1500 HP vehicular turbine)	U. S. Army Tank Command AVCO	2,734.0
2014	Materials Development for Second Generation Navy Shipboard Gas Turbines (to improve the efficiency, life and reliability)	U. S. Navy R&D Center Md. internal	255.0
2283	Turbine Powered Generators (development of 10 Kw turbo-alternators)	U. S. Army Ft. Belvoir International Harvestor Corp.	?
2434	Reactor Brayton Heat Exchange and Ducting Assembly (HXDA) (to develop above for a power system producing from 15 to 80 Kw_e).	NASA-Lewis Air Research Corp.	74.9
2436	Airborne Auxiliary Power Unit (APU) (design and component testing of hydrazine turbine) N_2H_4	Air Force Rockwell International	61.3
2579	Heat Transfer Problems in Advanced Gas Turbines for Naval Applications (fundamental investigations of cooling turbine blades)	ONR U. of Minnesota	18.0

PIC #	Title	Proponent	FY 73 $K
2584	Space Shuttle Auxiliary Power Unit (APU) (design, fabrication, development and endurance testing of a 400 HP hydrogen-oxygen turbine engine)	NASA-Lewis Air Research Co.	87.0
2612	Investigation of Gas Bearings for Gas Turbines (develop a gas lubricated main rotor shaft and bearing system for small turbo-alternator)	U. S. Army Ft. Belvoir Franklin Institute	13.7
2636	Small Turbine Advanced Gas Generator (STAGG) for Army Aircraft (integrate compressor, combustor and turbine into a self-sustaining gas generator)	U. S. Army P&W	875.0
2637	Small Turbine Advanced Gas Generator (STAGG) for Army Aircraft (see above)	U. S. Army Ft. Eustus AVCO	1,231.0
2638	Small Turbine Advanced Gas Generator (STAGG) for Army Aircraft (see above)	U. S. Army Ft. Eustus Air Research	805.0
2639	Small Turbine Advanced Gas Generator (STAGG) for Army Aircraft (see above)	U. S. Army Ft. Eustus William Research Corp.	718.0
2680	Investigate Techniques for Fabrication of Small Radial Turbine Components from Silicon Carbide (turbine wheels from Silicon carbide using a CVD process)	U. S. Army Ft. Belvoir Energy Research Corp.	8.4

MHD PIC Briefs

PIC #	Title	Proponent	FY 73 $K
562	MHD Generator Study (studying the operation of non-equilibrium MHD generators)	ONR GE	200.0
1066	Investigation of MHD Power Generating Devices (evaluate the feasibility of generating MHD power with a cesium seeded argon gas through the use of non-equilibrium ionization)	NASA-Lewis	450.0 (9 Mn-Yrs)
1518	Non-Equilibrium Phenomena in Flowing Plasmas for MHD Power Generation and Propulsion Systems (basic research in plasma phenomena)	Air Force OSR Stanford Univ.	68.6
2020	MHD Plasma Investigations (basic research in plasma phenomena)	ONR Colorado State University	33.0
2058	MHD Power Generation Research for Advanced Plasmadynamic Electric Power Sources (theoretical and experimental investigations of combustion driven MHD generators)	Air Force OSR Univ. of Tennessee	?
2186	Non-Continuous Magnetofluidynamic Flows (plasma research)	Air Force OSR Tel Aviv University of Israel	?
2323	Experimental Airborne MHD Generator Research (test at APL produced 210 Kw MHD Power)	Air Force WPAFB Systems Research Lab.	93.6

PIC #	Title	Proponent	FY 73 $K
2354	Production of High Density Uniform Plasmas for Advanced MHD Generators (plasma research)	Air Force OSRO AVCO	67.2
2355	Interaction of Forced Convection and Magnetic Fields with Arc Plasmas for Advanced MHD Power Generators (plasma research)	Air Force New York State University	?
2356	Non-Linear Time-Dependent Phenomena Applicable to Advanced MHD Power Generators (analysis of the operating characteristics of MHD generators)	Air Force OSR STD Research Corp.	60.0
2419	Disk Geometry MHD Generator for High Voltage, High Power Aircraft Requirement (feasibility tests completed)	Air Force WPAFB AVCO	200.0
2420	Multi-Burst, High Power MHD Generator for Aircraft (to obtain criteria for MHD channel design)	Air Force WPAFB AVCO	162.0
2452	Limiting Mechanisms in Aircraft Generator Performance (investigate limitations of the Hall field in combustion MHD generators)	Air Force WPAFB Stanford Univ.	137.4

PIC #	Title	Proponent	FY 73 $K
2492	Solid Fueled MHD Generator for Aircraft High Power (demonstrate operation of a 50-Kj, explosive MHD generator)	Air Force WPAFB Hercules Inc.	191.0
2493	Liquid Fueled MHD Generator for Aircraft High Power (demonstrate operation of a 20 Kj/pulse repeating pulse generator)	Air Force WPAFB AVCO	194.0
2587	Liquid Metal MHD (experiments on two phase MHD generators)	ONR ANL	130.0
2589	Colloidal Plasma Study (study the enhancement of electrical conductivity by dust suspensions in noble gases)	ONR India Institute of Technology New Delhi	30.0
2669	MHD Laser (determine the capability of a MHD generator to operate as a MHD laser)	ONR GE	92.3
2670	Two-Phase MHD Generator (to design and construct a two-phase MHD generator)	ONR ANL	350.0
2683	Superconducting MHD Magnet Testing (performance test a 40-kilogauss superconducting magnet)	Air Force WPAFB Magnetic Corp. of America	30.0

PIC #	Title	Proponent	FY 73 $K
2684	Extended Duration MHD Power (design, construction, installation, and testing of a one-minute duration MHD power generator)	Air Force WPAFB Systems Research Lab. Inc.	120.0
2701	Dynamic System Study for Two-Phase Liquid Metal MHD Reactor System (analysis of the transient behavior of a liquid metal MHD power system)	ONR Applied Dynamics Research Corp.	60.0

Advanced Concepts PIC Briefs

PIC #	Title	Proponent	FY 73 $K
886	ISOTEC Technology Program (to develop and improve specific thermoelectric materials for space applications)	AEC GGA	270.0
214	Transport Properties of TI and MHD Converters (basic research in plasmas)	Air Force CRL Internal	50.0
747	Thermoelectric Generator Systems (to establish the feasibility of utilizing modular thermo-electric power source units to power forward area communications and surveillance equipment)	U.S. Army Ft. Monmouth Internal	25.0
135	Energy Mechanisms in Plasmas (plasma research)	Air Force WPAFB Internal	10.0 (0.2 Mn Yr.)
223	Electrofluidynamic Energy Conversion (basic research	Air Force WPAFB Internal	250.0 (5 Mn Yr.)
275	Piezoelectric Energy Converter Systems (to develop a piezoelectric driver for an artificial left ventricle of the heart)	NIH Physics International Company	201.0

[illegible] C #	Title	Proponent	FY 73 $K
2[illegible]45	Thermoelectric Materials Evaluation Program TPM-217	AEC	300.0
2[illegible]99	Eleven Hundred Watt Thermoelectric Power Source (exploratory development model thermoelectric generator for use in forward area tactical operations)	U.S. Army Ft. Monmouth 3M	20.0
2[illegible]54	Thermoelectric Generator Testing and Evaluation Program (life tests, performance tests and analysis of thermoelectric modules and generators)	AEC JPL	200.0
2[illegible]14	Feasibility Evaluation of D-Cycle for Power Generation (investigation of using an organic working fluid in thermodynamic cycle)	U.S. Army D-Cycle Power Systems Inc.	20.0
2[illegible]74	Investigations of Two Fluid EFD Alkali Metal Processes for Aerospace Vehicles and Ground Based Power Generators (basic research in gas vapor mixtures)	Air Force MIT	62.5
2[illegible]87	One Hundred and Twenty Watt Manportable Thermoelectric Power Source (develop the above for use in forward combat areas)	U.S. Army 3M	93.0
2[illegible]89	Electrofluid Dynamics Power Generation (to determine the performance characteristics of axisymmetric EFD channels)	Air Force WPAFB TRW	30.0

APPENDIX 5

SAMPLE ALLOCATIONS OF MANAGEMENT AND EXECUTION ROLES

Fuel Cells (First Trial)

TASKS		PRESENT PROGRAM	FY-73 $K
Task 1. SRT			
	a.	Mass transfer in FC - NASA LeRC	35K
	b.	Electrochemical cells with fused salt electrolites - AEC, ANL	50K
	c.	H_2-O_2 exchange at electrode USA inhouse	60K
	d.	Hydrocarbon reactions at electrode USA inhouse	20K
	e.	Basic Research on electrochemical power sources - USA - RPI	73K
	f.	Rotating ring electrode corrosion USAF, State University of New York	68.4K
	g.	Adsorption of molecules at electrode USAF, University of Colorado	?
	h.	Fuel cell controls - NASA LeRC inhouse	235K
	i.	Search for new electrolytes for H_2/air - USA, ANL	28K
	j.	Search for new acid electrolytes - USA, Energy Research Corporation	27K
	k.	H_2 nickel regenerative fuel cells for satellites - USAF, TYCO Labs	31.6K
	l.	High voltage fuel cell assembly - USA, Energy Research Corporation	?
	m.	Alkaline fuel cell decay mechanism - NASA LeRc inhouse	10K

TASKS	PRESENT PROGRAM	FY-73 $K
n.	Radiolytic preparation of powdered metal catalysts for H_2/O_2 cells - NASA LeRC inhouse	15K
o.	Advanced membrane FC studies - NASA LeRC-GE	75K
Task 2.	Open-Cycle Power Plant Development Family .5, 1.5, 3, 5 FW - USA - PW	182K
Task 3.	Design, Construct, Test H_2 Generator for .5KW Plant - USA - PW	6.8K
Task 4.	High Power Density Fuel Cell for Aircraft and regenerative Fuel for Satellites - USAF - P&W	366K
Task 5.	5KW acid FC module (completed) and 5KW alkaline - NASA, Johnson - GE - P&W	747K
Task 6.	Advanced (space training) FC testing NASA LeRC, P&W	500K

(From here on they are from P&W presentation.)

Task 7. Demonstrate commercial for MW unit by 1978 - P&W, industry, utilities

Task 8. Demonstrate 26MW unit at $185/KW by early 80's - P&W, industry, utilities

Future Programs (Ray Report)

Task 9. Build and test 7KW alcohol cell

Task 10. Build and test 2 to 5MW by 1976

Task 11. Build and test 20MW by 1977

Task 12. Commercial demo 40 KW field unit

Task 13. Pilot tests H_2 cell

Task 14. Build (and test?) 10KW H_2 prototype

Task 15. Build and test 10KW solid electrolite

Task 16. Continued SRT

PRESENT

Task No.	Level I	Level II	Level III	Level IV
Task 1				
a.	NASA	LeRC	-	LeRC IH
b.	AEC	ANL	-	ANL IH
c.	US Army	Ft. Belvoir	-	Ft. Belvoir IH
d.	US Army	Ft. Belvoir	-	Ft. Belvoir IH
e.	US Army	Ft. Mommouth	-	RPI
f.	USAF OSR	-	-	State Univ. of New York
g.	USAF OSR	-	-	Univ. of Colorado
h.	NASA	LeRC	-	LeRC IH
i.	US Army	ANL	-	ANL IH
j.	US Army	?	-	TYCO Labs
k.	US Army	-	-	Energy Research Corporation
l.	US Army	-	-	Energy Research Corporation
m.	NASA	LeRC	-	LeRC IH
n.	NASA	LeRC	-	LeRC IH
o.	NASA	LeRC	-	GE
Task 2	US Army	-	-	P&W
Task 3	US Army	-	-	P&W
Task 4	USAF	WPAFB	-	P&W
Task 5	NASA	Johnson	-	GE, P&W
Task 6	Utilities (Target)	P&W	Many Contractors	P&W
Task 7	Utilities (Target)	P&W	Many Contractors	P&W
Task 8	Utilities (Target)	P&W	Many Contractors	P&W

FUTURE

Task No.	Level I	Level II	Level III	Level IV
Task 9	ERDA	NASA LeRC (ERDA Center)	NASA LeRC ANL	P&W, GE
Task 10	P&W, industry, utilities, ERDA subsidy	P&W	ERDA Center NASA LeRC	P&W
Task 11	oe	oo	oo	oo
Task 12	Utility ERDA subsidy	P&W, GE	-	P&W, GE Construction Contractors
Task 13	ERDA	NASA LeRC (ERDA Center)	NASA LeRC ANL	P&W, GE Energy Research Corporation
Task 14	ERDA	NASA LeRC	-?	oo
Task 15	ERDA	NASA LeRC	-	oo
Task 16	ERDA	NASA LeRC	NASA LeRC ERDA Centers	GE, P&W, Energy Research Corp., TYCO, RPI, Ft. Belvoir

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Technology Administration
National Technical Information Service
Springfield, VA 22161 (703) 605-6000