FOSSIL ENERGY: ADVANCED POWER SYSTEMS

by
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Mr. Crim initiated his technical career in the Norfolk Naval Shipyard and the Rebuild Facility for small boat diesel and gas turbines. After a tour in the Army Corps of Engineers, he returned to the Shipyard, completed his apprenticeship and enrolled in the Virginia Polytechnic Institute. After graduation Mr. Crim was assigned in the U.S. Army to the Engineering School to set-up a new fabrication training school. Upon returning to the civilian community, he set-up new groups for the Corps of Engineers to provide production engineering ability on research projects. At the Engineering Research and Development Laboratory, he designed & supervised construction & tested specialized heavy equipment. Mr. Crim joined the U.S. Army Engineering Reactor group at Fort Belvoir, where his primary mission was establishing a viable research and development program for the development of the first closed cycle nuclear gas turbine system in the world. He was Manager of this organization, which had the responsibility of some 125 projects including material reserach, heat transfer, both direct and indirect energy conversion and the operation of the first closed cycle gas turbine experimental facility in the United States.

Mr. Crim has acted as Consultant in the area of power systems, open cycle gas turbine, closed cycle turbine systems, gas reactors and energy conversion systems in general to the Air Force, Army, Navy, AEC and industry. Until 1974, he acted in the capacity of Technical Director of the U.S. Army Engineers Power group at Fort Belvoir, Virginia. The ENPG was engaged in the operation of both nuclear and non-nuclear power plants, the training of power plants operators and the research and development of advanced power systems. Since June 1974, Mr. Crim has been Head of Advanced Power Conversion for the Office of Coal Research, which in January 1975, became the fossil energy element of the Energy Research and Development Administration. Mr. Crim has been in advanced power conversion for some 35 years. He has advanced degrees from Catholic University and the University of Florida including completion of advanced work under the Oakridge School of Reactor Technology.

Marco Polo reported that the Chinese used "black rocks" for fuel, and recent studies indicate that the Chinese may have used coal in small amounts for two or three millennia previously. The use of coal as a major source of energy however, did not begin until about the twelfth century, when the inhabitants of the northeast coast of England discovered that certain black rocks found along the seashore — and thereafter known as "sea coles" would burn.

Since this initial discovery, coal has been mined continuously, first in England and shortly thereafter in present Belgium, France, and Western Germany, and finally in all coal-bearing areas of the world, in ever increasing amounts.

The production of coal in the United States began about 1820, when 14 tons were reportedly mined. Since that time the production of coal increased steadily until about 1907, after which the rate has fluctuated between the extremes of about 400 and 700 million tons per year.

Bituminous coal and lignite production was 590 million tons in 1974. Value of production was $8.9 billion. Anthracite production was 6.3 million tons with a value of $157.5 million.

The vast coal reserves of North America offer a potential source of energy far into the future. In the United States, coal represents 73 percent of the total known resources of fossil fuel, whereas petroleum, natural-gas liquids, and natural gas together represent only 9 percent. Yet, the consumption of coal annually represents only 21 percent of the energy demand, with the other forms of fossil fuels supplying some 75 percent. In the future, the nation will continue to demand energy in its cleaner and more convenient forms. Bringing the consumption pattern into harmony with the availability of fossil fuel reserves will require development of technologies for conversion and utilization of the plentiful types of fossil fuels to replace those types whose reserves are limited.

ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

On October 11, 1974, President Ford signed the Energy Reorganization Act of 1974 establishing an "Energy Research and Development Administration to bring together and direct Federal activities relating to research and development on the various sources of energy, to increase the efficiency and reliability in the use of energy and to carry out the performance of other functions" — ERDA officially began business on Jan. 19, 1975. It is organized into six major units — one of which is Fossil Energy.

The Fossil Energy Program in ERDA is an ongoing program that principally originated in the Department of Interior's Office of Coal Research, and the U.S. Bureau of Mines. It involves work on coal, oil shale, petroleum and natural gas.

The overall objectives of the Fossil Energy R&D Program are to assure that the nation's fossil fuel resources can be developed with economic efficiency, social and environmental acceptability by developing the technology to convert domestic fossil fuels into the various energy forms which satisfy market demand.

A major element under Fossil Energy is in the area of Coal Conversion and Utilization.

COAL CONVERSION AND UTILIZATION

Coal is our most abundant domestic fossil fuel resource and reserve. Because of numerous delays in bringing nuclear electric plants on line, limited domestic supplies of oil and gas, insecurity of supplies of imported oil and gas, and the size of projected import requirements to close the demand-supply deficit. The country now has no alternative but to accelerate its investment in making coal available as a major energy source.

Increasing quantities of coal or coal-derived products will be needed for electric utility and industrial boilers, refinery feedstocks, and pipeline gas distribution systems. Reliable projections indicate that coal production will have to double by 1985.

However, accelerated use of coal requires resolution of many potential problems. The knownledge base for most aspects of the process of coal conversion and utilization is not adequate for the fossil fuel industry in all its parts to meet the challenge before it, even though some technologies are ready for immediate implementation.

The overall program goal is to provide the knowledge for the economic environmentally sound utilization of our vast coal resources to help meet national energy needs. This goal includes developing and demonstrating technical methods and processes for:

- The production of clean gaseous and liquid fuels from coal suitable for power generation, transportation and residential and industrial uses.
- Direct combustion of coal in an environmentally acceptable manner.

I would like to address the subject of advanced Power Systems that could utilize coal or coal derived fuels in the future.

This preliminary R&D plan is viewed as a dynamic plan that will likely require revision on the basis of further studies and technological developments presently being pursued by government and industry. Results of the government-sponsored Energy Conversion Alternatives Study (ECAS), which will assess the relative merits of advanced energy conversion techniques, will aid in future revisions of the APC R&D Plan.

An *advanced power cycle* is defined as one that can:

- utilize coal and/or coal-derived fuels in an environmentally acceptable manner,
- achieve overall conversion efficiencies (raw fuel to electric power) of at least 40 percent, and
- provide reliable electric power at central station capacities.

Among the anticipated benefits of commercialized advanced power cycles are savings in fuel usage, the possibility of reduced cost of electric power, and improvement in the United States balance of trade. The potential advantages of advanced power cycles, compared with conventional steam plants, warrant their accelerated development so that the nation's energy resources can be more effectively utilized and its dependence on imported fuel minimized.

The major APC candidates were evaluated with respect to their capabilities for attaining commercial-scale technical and economic feasibility within both near-term and mid-term intervals. Near-term objectives are defined as those that can be realized by 1985, while mid-term objectives can be achieved during the 1985-2000 time frame. Long-term objectives apply to the year 2000 and beyond.

The cycles considered are:

- open cycle gas turbines
- closed cycle gas turbines
- open and closed cycle magnetohydrodynamics (MHD)
- metal vapor topping cycles
- low-temperature bottoming cycles
- fuel cells
- thermal/electric processes
- electro-gas dynamics (EGD)

A number of factors including present development status, research and development requirements, critical needs, technical risks, beneficial features, growth potential, and feasibility of retrofit to presently planned steam plants were considered in the evaluation of the advanced power cycles. Table I presents a synopsis of the results for the power cycles under consideration and also contains preliminary conclusions as to the R&D emphasis and funding priority that should be associated with each candidate cycle.

For achieving near-term objectives, highest R&D emphasis is associated with APC's that appear to have the greatest potential for development as the best possible advanced power system, even at the expense of increased technical and economic risk and longer development time. Factors which enter into the consideration of the "best possible advanced power system" are energy conversion efficiency, construction cost, siting flexibility, and life-cycle cost. The program funding priority is based upon a need to perform R&D on APC for both near- and mid-term objectives. A major factor influencing the R&D program funding priority is the need to resolve quickly whether the high-risk development problems are amenable to solution within the time period required for the APC to meet its stated objective.

On the basis of available data and the systems analysis, the highest R&D emphasis should be assigned to open cycle gas turbines, closed cycle gas turbines, metal vapor topping cycles, and open cycle MHD.

The closed cycle gas turbine (CCGT) is an APC candidate for meeting the near-term program objective of demonstration by 1985 of a topping cycle which can be combined with a low-temperature bottoming cycle or a state-of-the-art steam plant that will provide an overall plant efficiency of 45 percent or better. Thus, the CCGT merits high priority in the R&D program. The use of coal or coal-derived fuel poses far less of an ash carry-over problem than for the open cycle, but a development effort to design a primary heat exchanger, capable of providing a relatively high working fluid temperature (TIT of 1500°F to 1700°F or higher) at a high operating pressure, is required. There is a moderate risk associated with the development of this heat exchanger for operation at a turbine-inlet temperature (TIT) in excess of 1500°F. Failure to succeed in this effort would require a reduction in operating temperature with an attendant performance penalty.

The open cycle gas turbine (OCGT), especially at the high temperatures* necessary for good efficiency, is very sensitive to the ash carry-over from the coal combustion process; this

*Achieving a TIT of 2800°F has been proposed as a near-term objective.

TABLE I
ADVANCED POWER CYCLES R&D STRATEGY SUMMARY

	CURRENT STATUS AND PROGRESSION OF DEVELOPMENT					GENERAL ASSESSMENT CRITERIA				PRELIMINARY CONCLUSIONS	
	Theoretical Feasibility	Engineering Feasibility	Engineering Development: Tech.	Engineering Development: Econ.	Present Industry Involvement	Technical Risk	Commercialization Target Date (1) (2)	MarketPotential After Commercialization	Technical Compatibility With Steam Plants	R&D Emphasis (Relevance to OCR Objectives)	OCR Funding Priority
GAS TURBINE											
Open (2800°F TIT)	√	√	X	X	high	high	1985	high	high	high	high
Closed (1500°-1700°F TIT)	√	√	X	X	moderate	moderate	1985	moderate	moderate	high	high
Feher (Supercritical CO_2)	√	X			low	high	unknown	unknown	low	low	low/none
METAL VAPOR TOPPING CYCLE	√	√	X		low	moderate	1985-1995	moderate	high	high	moderate
LOW-TEMPERATURE BOTTOMING CYCLE	√	√	√	X	moderate	low	1970	moderate	moderate	low	low/none
FUEL CELLS	√	√	X	X	moderate	moderate	1982-1985	low	low	moderate	moderate
EGD	X				low	high	2000+	unknown	unknown	low	low/none
THREMAL/ELECTRIC	X	X			low	high	2000+	unknown	moderate	low	low/none

√ = Established
X = Work Under Way
N.A. = Not Applicable
TIT = Turbine-Inlet Temperature

(1) Assumes R&D program proceeds according to schedule

(2) Commercialization is defined by *industrial acceptance of a contract* to design, build, and install an APC system in an operational utility plant.

(3) Funding & emphasis beyond next 3 years to be contingent on successful passing of life and performance milestones (see text)

carry-over can cause excessive fouling and erosion of the turbine blading. This problem must be overcome before the open cycle gas turbine can meet the near-term (1985) objective of providing full-sized coal burning plants with higher conversion efficiencies and lower life-cycle costs than present steam plants. The open cycle gas turbine can be expected to evolve, over the long-term, toward an ultra-high temperature (UHT) turbine, operating at turbine-inlet temperatures as high as 3500°F, if significant technological advances in ceramics, composite materials, blade cooling, and other currently costly techniques, now under development, can be achieved.

The metal vapor topping cycle (MVTC) should receive high R&D emphasis because of its potential for meeting mid-term objectives. From the standpoint of conversion efficiency and fuel utilization, this cycle is highly attractive, but it requires development of a liquid metal boiler/superheater that can provide the desired peak metal vapor temperatures within acceptable materials corrosion limits. Additional problems regarding turbine design and fabrication and potential hazards in using liquid metal need to be resolved before this system can become commercially feasible. While there is moderate risk associated with the development of the metal vapor topping cycle, the potential benefits of this cycle are significant.

For all advanced power systems, there is a need for an integrated approach to the development effort which will encourage participation and cooperation by industry, the utilities, and responsible governmental organizations. Long-term continuing programs for assessing system reliability, advanced power system commercialization potential, and retrofit capability of power cycle advancements in existing and planned power plants need to be inaugurated. Power-plant designers should be made aware of probable advancements in power systems so that the design process can allow for their eventual incorporation.

In addition, environmental considerations associated with the utilization of advanced power cycles need to be explored thoroughly to identify those problems unique to the individual APC that must be solved during APC development.

Finally, since there are many uncertainties and risks in APC development, a balanced program strategy, in which several APC candidates are developed, should be pursued. In this way, the program goals are not jeopardized by the failure of a single APC to meet its objectives.

PRELIMINARY CONCLUSIONS

It appears desirable that, with regard to hardware development:

Open cycle gas turbines receive high priority in program funding, with emphasis on achieving a turbine design capable of operation at high TIT and compatible with moderately clean, coal-derived fuels.

Closed cycle gas turbines receive high priority in program funding, with emphasis on development of a primary heat exchanger capable of providing peak working fluid temperatures in the range of 1550°F to 1750°F.

Metal vapor topping cycles receive moderate priority in program funding, with emphasis on development of a liquid metal boiler/superheater capable of providing peak metal vapor temperatures in the range of 1400°F to 1600°F.

Certain high-potential/high-risk areas, including fuel and combustion products compatibility with advanced open-cycle gas turbines, turbine materials development, and high-temperature and corrosion-proof heat exchangers, be considered high priority.

Priorities associated with the other candidate advanced power cycles be assigned in accordance with Table I.

The advanced power cycle program place added emphasis on overall system considerations so that important interrelationships among advanced power system elements receive appropriate attention.

Regarding implementation, it appears desirable that:

a. Long-term continuing programs on advanced power systems potential marketability and retrofit capability of power cycle advancements in existing and planned power plants be established.
b. Detailed investigations of the environmental impact of advanced power systems be given strong emphasis.

Definition of Advanced Power Cycles and Systems

An advanced power cycle is defined as one that can:

- provide reliable electrical power at central station capacities,
- achieve conversion efficiencies of at least 40 percent* , and
- utilize coal and/or coal-derived fuels in an environmentally acceptable manner.

An advanced power system (APS) is a combination of at least two cycles which meets the criteria established in the definition of an APC. In addition, an APS must be economically competitive (low mills/kWh) with conventional coal-fired steam plants. This is a working definition in which the overriding criterion is the ability or potential for economical utilization of coal and coal-derived fuels in an environmentally acceptable manner.

The 40 percent conversion efficiency baseline cited in the APC definition was selected since it is the maximum efficiency level that utilities will strive to attain in present-day power-plant operation due to a balance of economic and reliability factors. The conversion efficiency of existing plants is between 30 and 35 percent with new plants achieving 35 to 38 percent.

Need for an Advanced Power Cycles Program

Role and Importance of Coal

Coal, our most abundant domestic fuel resource**, is expected to regain its former status as a major national energy source. To a great extent, its reinstatement can be attributed to the inadequacy of domestic petroleum supplies and the lack of dependability of foreign petroleum sources.

Currently, coal provides the major source (45 percent) of energy for the generation of electrical power in the United States. About two-thirds of all the coal consumed in the U.S. during 1974 was used for this purpose. Increased quantities of coal can be expected to become available to fulfill anticipated energy demands. Electric power generation can contribute to greater use of coal if appropriate methods of converting coal to electricity can be developed which permit operation whitin imposed environmental constraints.

The major emphasis of Project Independence is to reduce our dependence on petroleum imports. Since significant impacts from renewable energy sources (e.g., solar, geothermal, wind, tidal power) are unlikely to occur before the year 2000, and, since nuclear power plants alone cannot fill the gap, coal will have to play an increasingly important role during the forseeable future.

The Use of Coal for Electric Power Generation

Existing coal-fired plants for the generation of electric power are major sources of pollution. Emission control devices for particulate matter, oxides of sulfur and nitrogen, and thermal pollution have decreased overall plant operating efficiencies and increased installation and operating costs of these plants. In addition, coal-fired steam plants have reached a high degree of perfection and require a significant increase in capital expenditures to produce a small increase in steam cycle efficiency. These limitations have led to the search for other (advanced) power cycles and systems utilizing coal and/or coal-derived fuels that can be made commercially feasible.

In addition, advanced power cycles are needed by the utilities to provide greater flexibility in the use of fuels and to minimize siting constraints (e.g., enable electricity generation in semi-arid areas of the United States where coal is abundant and cooling water is scarce).

The Government Role in APC Development

On the basis of the potential advantages of advanced power cycles and the need to resolve critical energy issues in a short time period, it is imperative that the United States increase its R&D activity in the APC area. The technology base that will permit the development of advanced power cycles using coal or coal-derived fuels needs to be established.

However, both the anticipated cost and technical risk associated with APC development efforts are high. Consequently, it appears appropriate and necessary for the government to take a leading role in advanced power cycle development by encouraging participation and cooperation by industry and utilities and providing economic support for development of the most promising advanced power cycles. In this way, the development risk will be shared, the APC effort will be executed in a coordinated manner, and the government will serve as a catalyst for the commercial development of the most promising advanced power cycles.

Anticipated Economic Benefits of APC

The expected economic benefits of the APC program include savings in fuel usage, reduced cost of electric power, and improvement in the United States balance of trade.

It is estimated that if advanced power cycles with conversion efficiencies of 50 percent are introduced beginning in 1985, over 25 percent of the presently projected coal consumption for electric power generation during the succeeding 30-year period can be saved. The coal saved would amount to approximately 6 billion tons. The 30-year interval was selected

*This figure is based on direct coal firing. When fuel conversion losses, attributable to the use of coal-derived fuels, are taken into account, the cycle conversion efficiency must be correspondingly higher to achieve an overall process efficiency of 40 percent.

**U.S. DOI, Bureau of Mines, estimates domestic reserves (as of Jan. 1, 1974) to be about 434 billion tons.

TABLE II
OBJECTIVES OF ADVANCED POWER CYCLES R&D PROGRAM

1) Develop and demonstrate by 1985 an APC that is capable of operating as a topping cycle in combination with a state-of-the-art steam power plant or with a low-temperature bottoming cycle and achieving an overall plant efficiency of 45 percent or better.
2) Develop and demonstrate by 1985 an APC that is capable of being retrofitted as a topping cycle in a present-day steam power plant (efficiency well below 40 percent) and achieving an overall plant efficiency of 40 percent or better.
3) Develop and demonstrate by 1985 advanced power systems for peak-load and/or dispersed power-plant applications that operate on coal or coal-derived fuels and achieve an overall plant efficiency of 40 percent or better.
4) Develop and demonstrate by 1990 an advanced power system for mid-load and base-load central station electric power generation that operates on coal or coal-derived fuels and achieves an overall plant efficiency of 50 percent or better.
5) Advance the state-of-the-art of technology in the areas of materials, high-performance heat exchangers, and systems integration by maintaining a continuous engineering technology program related to advanced power conversion systems and concepts.
6) Identify and evaluate candidate advanced power cycles for further development by performing basic research on advanced energy conversion concepts which may be capable of using coal and coal-derived fuels for electric power generation.

since it represents an estimated average plant lifetime. The fuel savings that can be realized from the use of advanced power cycles can be expected to reduce the cost of electric power.

It also appears reasonable to assume that, as the United States develops marketable advanced power generation equipment, exports of this equipment will grow substantially. For this reason, as well as the expected decrease in oil imports, the development of APC technology may provide for a significant improvement in the balance of trade. A conservative estimate is that APC technology exported to developing countries alone could provide a net addition of $2 billion to the United States balance of trade during the period 1985 to 1990.

The Role of OCR

General Responsibilities

The Department of the Interior, through the Office of Coal Research, has the primary responsibility for the development of new technology to provide for the increased utilization of coal in an environmentally acceptable manner. This task is quite extensive and interacts with all phases of coal technology from extraction to final utilization. In accomplishing this task, coordination with other governmental programs and with the efforts of private industry is to be maintained.

This report specifically addresses one aspect of OCR's coal-related R&D program — i.e., the development of advanced power cycles for centrally generated electrical power.

APC Program Goal and Objectives

The goal of the OCR Advanced Power Cycle Program is to develop and demonstrate clean, efficient, reliable, economically feasible methods of converting coal and coal-derived fuels to electrical energy in commercial-size central station power plants at the earliest practical date.

This goal will be met through:

- coordination of the national effort in the development of alternative advanced power cycles,
- identification and promotion of solutions for technical problems,
- establishment of a technology base for advanced power cycles,
- development of realistic estimates of benefits to be derived from the utilization of advanced power cycles, and
- OCR acting as the catalyst for commercial development and utilization of advanced power cycles.

The specific objectives of the APC Program are presented in Table II. Accomplishment of Objectives (1), (2), and (3) will provide the means for more effective utilization of coal in present and new electric power plants by the year 1985. In addition, it is anticipated that other coal-utilizing processes, such as fluidized-bed combustion, coal liquefaction, and gasification processes, which may both support and depend on APC utilization, also will be commercially available by that time. Therefore, meeting these near-term APC objectives is considered critical to the integration of advanced power cycles into present and new utility power plants.

The timing of Objective (4) is somewhat flexible since it is envisioned to be a new power-plant design from the ground up.

Objective (5) represents a continuing effort with specific milestones and decision points being dictated by the common technology developments required by specific advanced power cycles and by basic research areas identified from work accomplished under Objective (6).

Objective (6) is seen as a continuing low-level effort to ensure that all possible technologies related to advanced energy conversion concepts are identified and evaluated.