COAL POWER & COMBUSTION

QUARTERLY REPORT

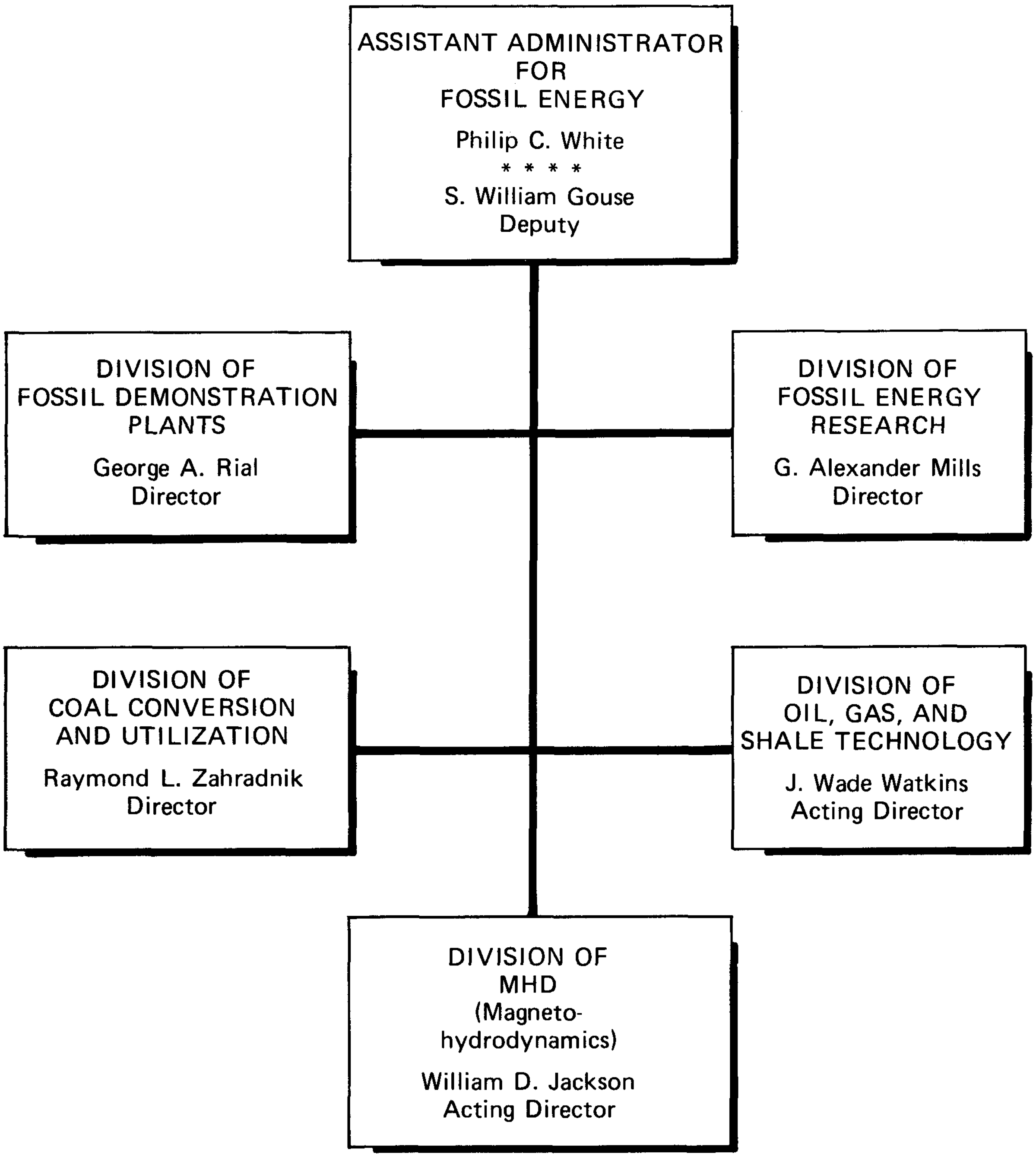
JANUARY-MARCH 1976

Philip C. White
Assistant Administrator
Office of Fossil Energy

Raymond L. Zahradnik
Director
Division of Coal Conversion and Utilization

Office of Fossil Energy
Energy Research and Development Administration
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

CONTENTS


ASSISTANT ADMINISTRATOR FOR FOSSIL ENERGY
Philip C. White
* * * *
S. William Gouse
Deputy
DIVISION OF FOSSIL DEMONSTRATION PLANTS
George A. Rial
Director
DIVISION OF FOSSIL ENERGY RESEARCH
G. Alexander Mills
Director
DIVISION OF COAL CONVERSION AND UTILIZATION
Raymond L. Zahradnik
Director
DIVISION OF OIL, GAS, AND SHALE TECHNOLOGY
J. Wade Watkins
Acting Director
DIVISION OF MHD (Magneto-hydrodynamics)
William D. Jackson
Acting Director

EXECUTIVE SUMMARY

The United States has more energy available in coal than in petroleum, natural gas, oil shale, and tar sands combined. Nationwide energy shortages, together with the availability of abundant coal reserves, make the use of coal vital to the nation's total supply of clean energy. In response to this need, the Office of Fossil Energy of the Energy Research and Development Administration (ERDA) is conducting a research and development program to provide technology that will permit rapid commercialization of processes for improved direct combustion of coal, for advanced coal-burning power equipment, and for converting coal to synthetic fuels. These fuels must be suitable for power generation, transportation, storage, aand residential and industrial uses.

The technologies selected for development—gasification, liquefaction, combustion, and advanced power systems—satisfy an urgent need for a particular type of fuel and final energy form, are potentially feasible both technically and economically (in terms of the cost of research and development and the final product) and will not exceed the air, water, and solid pollution standards established by the Environmental Protection Agency (EPA). The emphasis given each technology varies, depending on such things as technical complexity, development stage (laboratory research, including bench-scale tests and experiments with process development units, and pilot plant design construction, and operation), variety of uses for the fuel produced, and urgency of the need that the technology is designed to satisfy.

ERDA's coal combustion and power program, started by the Office of Coal Research (OCR) of the U.S. Department of the Interior (merged into ERDA in January 1975), has focused on two major areas: direct combustion of coal and advanced power systems. For direct combustion systems, emphasis is on (1) development of atmospheric and pressurized systems capable of burning high-sulfur coals of all degrees of rank and quality in fluidized-bed combustors, (2) development of the ability to burn coal-oil slurries in substitution for oil-fired combustors, and (3) improvement in the efficiency of present boilers. Compared with conventional coal-fired systems, fluidized-bed combustion systems, when generating steam for conventional turbine systems, give higher power generation efficiencies and cleaner exhaust gases, even when burning high-sulfur coals. If the fluidized-bed system is pressurized, additional economies in capital costs (because of lower construction expenses) and in operating costs (because of increased efficiencies) may be realized. The benefits from high-pressure combustion are a reduction of furnace size because of decreased gas volume and heat transfer characteristics and better sulfur removal. High-pressure combustion, however, requires the development of equipment to clean the hot combustion products so that they are suitable for direct use in power generation turbines.

The advanced power systems program is directed toward developing electric power generation systems that operate on coal or coal-derived fuels. These systems involve the use of high-temperature gas turbines burning low-Btu gas and turbine systems using inert gases and alkali metal vapors. These systems will have lower electricity costs than those that can be obtained using medium- and high-sulfur coal in new steam power plants built using today's technology.

To develop direct combustion and advanced power systems as quickly as possible, ERDA is sponsoring research and development projects. Responsibility for designing, constructing, and operating a 30 Mw, atmospheric pressure, fluidized-bed boiler at the Monongahela Power Plant in Rivesville, West Virginia, was contracted to Pope, Evans and Robbins, Inc. This improved combustor design is to be used to produce steam for conventional power generation. The novel features of this system include sulfur removal during combustion and the use of modular "cells" to facilitate construction and increase reliability and maintainability. The Lewis Research Center, National Aeronautics and Space Administration. through contracts with General Electric Company, Westinghouse Electric Corporation, and others, is conducting an energy conversion alternatives study whereby performance and economic comparisons are being made of advanced power generation technology. Both Combustion Power Company, Inc., and Argonne National Laboratory are studying pressurized fluidized-bed combustion. The former is developing a hot-gas cleanup system for an open-cycle gas turbine for an electric power generation system utilizing coal rather than oil and combining desulfurization with combustion. The latter is evaluating the engineering and scientific aspects of fluidized-bed combustion and sulfur dioxide absorption at elevated pressures. Oak Ridge National Laboratory is developing an externally fired gas turbine power generation system for use in a modular integrated utility system, with each module having a capacity of about 0.5 Mw. Such generating systems can be economically practical only by efficient recovery of heat from the turbine exhaust gases. The Pittsburgh Energy Research Center is conducting a coal-oil slurry combustion program and a Solvent-Refined Coal (SRC) combustion test program, and Morgantown Energy Research Center is conducting a program on anthracite refuse utilization in a fluidized-bed combustor. The National Research Development Corporation is researching the combustion science features of pressurized fluidized-bed furnaces. Other projects include studies of high-temperature dust control by the Construction Engineering Research Laboratory of the U.S. Army Corps of Engineers; analysis of applications of fluidized-bed combustion technology by Exxon Research and Engineering Company;

R&D planning assistance services provided by The MITRE Corporation; and technical and engineering services provided by Gilbert Associates, Inc.

During the first quarter of 1976, general construction for the ***Multicell Fluidized-Bed Boiler*** focused on coordinating deliveries with erection requirements. Supplementary technical information was prepared to assure that the systems are being installed correctly and according to the sequence and procedures recommended. Final copies of the operating and maintenance manual and of the test and instrumentation program plan for the multicell fluidized-bed steam generator were issued. Laboratory research included:

- Limestone evaluation. Cheney limestone, which has a different impurity content from limestones used previously, was tested to determine its effectiveness as a sulfur sorbent. While not as efficient as Greer limestone, Cheney limestone performed better than Germany Valley limestone.
- Horizontal tube bundle tests. Alternatives for installation of a superheater in the fluidized-bed module were evaluated.
- Investigation of conditions that promote bed agglomeration. Six tests were run to study agglomeration during light-off and two to study agglomeration during emergency shutdown.
- Study of spent bed material to determine whether it can be used as a supplemental source of nutrient sulfur and as a soil neutralizing agent.

Another major activity during the quarter involved engineering, purchasing equipment, and starting construction required for converting the fluidized-bed module to a carbon-burnup cell. Also, three new computer programs were put into operation.

The final report on Task I—Parametric Analyses required for the ***Energy Conversion Alternatives Study (ECAS)*** was prepared. The technical effort for Task II—Conceptual Designs was completed, and the results of the work were presented to the Interagency Steering Committee, Technical Advisory Panel, and Utility Advisory Panel, comprising personnel from ERDA, National Aeronautics and Space Administration, and National Science Foundation. The results are being evaluated and the results obtained for similar systems analyzed by different contractors are being compared. Where appropriate, the Task II results are being compared to results obtained in Task I. Task III—Implementation Assessment was started during the quarter.

Work on the ***Pressurized Fluidized-Bed Combustor and Turbine Power Generation*** process development unit involved modifying the moving-bed granular filter. The louver panels and their supporting structure were redesigned, for example, and a new method for controlling the amount of filter media in the reactor bed was developed. A 1,000-hour test (started in November 1975) in the model combustor was completed in January.

Samples of alloys placed in the model were analyzed to determine their resistance to corrosion by sulfidation; Inco 713C was the most resistant of the samples tested. Another 1,000-hour test was started, and, by the end of the quarter, the model combustor had operated for 515 hours. Preliminary examination of alloy samples indicated that conditions in the model combustor were not severe enough to enable differentiation in the extent of attack on the various samples. The temperature in the combustor was therefore increased to induce greater differences. The results of other research during the quarter showed that sodium chloride (used to help dolomite react with the sulfur in the fluidized bed) cannot be introduced in a combustor driving a hot exhaust gas turbine because it would cause excessive corrosion. Other tests, however, showed that Burgess pigment, when added to the dolomite, is very effective in removing sodium and potassium from the exhaust gases. Studies of particulates present in the process development unit show that a more effective separation system is needed to remove large particles from the gas stream before the gas strikes the turbine.

Supportive Studies of Pressurized Fluidized-Bed Combustion continued throughout the quarter, and included research on combustion, sulfation and regeneration, trace element analysis, mathematical modeling, and new equipment design. Emphasis in combustion studies was on the effects of recycling and regeneration of sorbents on performance in the fluidized-bed combustor. Sulfation and regeneration studies covered a wide range of activities and topics: the effect of changing the size of the oxidizing and reducing regions in the fluidized bed, agglomeration of ash and sorbent, sulfur distribution inside a sorbent pellet, new candidate for sorbent materials, the effects of temperature on sorbent support materials, and one-step and two-step regeneration studies. Analysis was made for trace elements in coal and their volatility. New equipment is being designed to permit continuous combustion-regeneration experiments. Mathematical modeling of the combustion process inside a coal particle was begun.

Work on the ***Externally Fired Gas Turbine For Modular Integrated Utility System (MIUS)*** focused on reviews of the turbine evaluation study, specifically, the evaluation of ways to adapt an AiResearch engine to MIUS. It was decided that the engine could be modified and that a speed of slightly less than 80 percent of the original design speed would be optimum for the closed-cycle system. Drawings for a bid package for the furnace assembly were completed, and ERDA approved a request to proceed with procurement and construction. Laboratory research involved investigating three alternatives for coal handling and transport: flow splitter type of system, vibrator-eductor coal transport system, and Iron Fireman feeder. In addition, the cold-flow model was used for three tests on the mixing rate of coal in a fluidized bed of limestone. Supplemental studies were started during the quarter, and include planning of corrosion and heat transfer tests on air-cooled tubes in a fluidized-bed furnace, and preparing information on problems associated with handling solids.

In the ***Coal-Oil Slurry Combustion Project*** work involved preparing for and starting a 1,000-hour test in the 100 hp firetube boiler. The purpose of this test is to record data for determining combustion and boiler efficiency. Control problems occurred after 250 hours of operation. New parts were obtained and are being installed. The facility bid package specification for the 700 hp watertube boiler was completed and reviewed. To expedite construction of the facility, it was decided to hire a contractor to do the detailed design and be construction manager, and to start buying equipment with long lead times.

Work on the ***Solvent-Refined Coal (SRC) Combustion Test Program*** focused on several tests firing SRC from the Wilsonville, Alabama, pilot plant. The fuel and ash from the tests are being analyzed, and the emission of nitrogen oxides and carbon conversion values are being determined. Combustion tests were also made using Pittsburgh seam coal and Illinois No. 6 coal. The purposes of these tests were to characterize the combustion of these coals and to study the emission of nitrogen oxides. The emission is apparently related to the intensity of combustion.

Work on the ***Anthracite Refuse Utilization*** program involved a test in the Morgantown Energy Research Center fluidized-bed combustor, using Mid-Valley Bank refuse. Analysis of the results of the test showed that:

- The emission of nitrogen oxide was about 0.27 pound per million Btu.
- The emission of sulfur dioxide was 440 parts per million, which is close to the emission standard limits.
- The constituents of the ash in the spent bed material and material collected from cyclones and bag filters was basically the same.

Pressurized Fluidized-Bed Combustion Research involved modification of test equipment. The equipment is being altered so that three fluidized-bed tests can be conducted.

Test sections required for evaluating a device for ***High-Temperature Dust Control*** were fabricated during the first quarter of 1976. The overall dimensions of each section are the same, but the shape of the dust collecting rods varies, as does the angle that the rods make with the vertical lines of the bottom panel. All equipment, instruments, supplies, test sections, and dust hopper were delivered to the ERDA test facility, and much of the equipment was placed in position. Ducts were added to the roof of the facility and tested; problems were resolved. Meetings were held to coordinate test runs with the operation of the facility's fluidized-bed boiler.

Studies of ***Applications of Fluidized-Bed Combustion Technology*** included an evaluation of the requirements for classifying or screening hot bed materials and of the commercial potential for retrofitting coal-fired fluidized-bed combustion technology. The incremental costs of adding single new oil- or coal-fired boilers to existing boiler systems were calculated. The results generally show that, if a new boiler is added to an existing coal-fired boiler plant, the use of existing facilities for receiving and storing coal makes a significant reduction in steam cost. A large quantity of statistical information was received from the Federal Energy Administration. The information is being analyzed and tabulated to form a data base for determining the potential for industrial coal-fired fluidized-bed combustors. Other activities during the quarter included contacting companies that use industrial boilers to determine their attitudes toward applying coal-fired fluidized-bed combustion to the boilers.

R&D Planning Assistance Services provided to ERDA during the first quarter of 1976 included work on projects related to both advanced power systems and direct combustion systems. Activities pertaining to advanced power systems included work on the draft of an overall program plan as a background document for a workshop on advanced power systems, the feasibility of various turbine blade cooling concepts, analysis and development of various technological concepts (including coal cleaning technology, ceramics technology, and primary heat exchangers), and an analytical review of Task I results of the energy conversion alternatives study. Work on direct combustion systems included updating a program plan of the national fluidized-bed combustion program, support work and engineering assistance for the component test and integration facility, review of the program for staffing and training at the multicell fluidized-bed boiler at Rivesville, West Virginia, and planning of a workshop on the commercialization of fluidized-bed combustion. In addition, cost-benefit analyses were done for both the advanced power and direct combustion systems.

Technical and Engineering Services in support of ERDA's combustion program included continuing technical surveillance of the multicell fluidized-bed boiler project being developed by Pope, Evans and Robbins, Inc., and technical consulting services on the pressurized fluidized-bed combustion process development unit of Combustion Power Company, Inc. The Morgantown Energy Research Center was helped with the preparation of a conceptual design and cost estimate for the component test and integration facility. Work on cleanup systems for use with fluidized-bed combustion systems included studies of new sorbents and their regeneration, and of high-temperature and high-pressure particulate-removal systems for combustion gases. Methods of cleaning coal and measuring particulates in combustion gases were also investigated.

Work on the ***Boiler Tube Bundle and Burner Module Tests With Potassium*** was started with emphasis on completion of preparations for conducting a test of the module with water as a substitute for potassium. In addition, work on the design of the piping and equipment for operating the boiler with potassium was resumed. Arrangements for purchasing long-lead-time items were initiated.

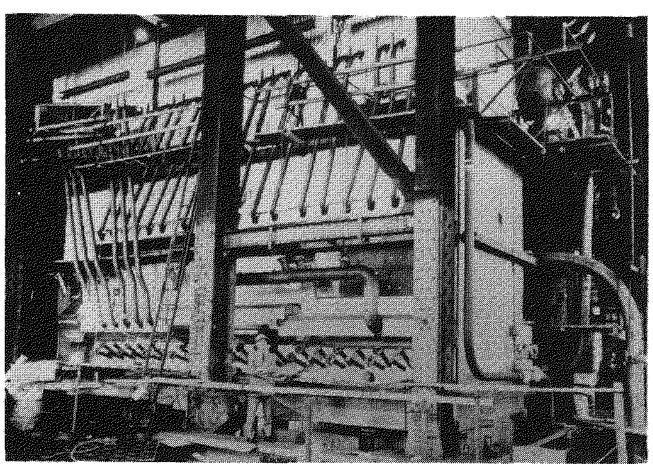
I. MULTICELL FLUIDIZED-BED BOILER

POPE, EVANS AND ROBBINS, INC.
NEW YORK, NEW YORK

Contract No. E(49-18)-1237 Total Funding: $14,300,000

INTRODUCTION

A multicell fluidized-bed boiler is being developed by Pope, Evans and Robbins, Inc. (PER), under the sponsorship of ERDA. The objective of this program is to design, construct, and operate a prototype multicell fluidized-bed boiler at an electric utility power station as a method of burning high-sulfur or corrosive coals in an environmentally acceptable manner and without excessive maintenance problems. The system is to have a capacity of 30 Mw and is to be operated under typical electric utility conditions. In addition to developing the boiler, PER is conducting a laboratory research program to optimize certain boiler and operational features. Experience gained from designing and operating the boiler and from laboratory research will be used as the basis for scaling up to a 200 Mw multicell fluidized-bed boiler system. The schedule for development of the fluidized-bed boiler is provided in Figure I-1.



PROCESS DESCRIPTION

The fluidized-bed boiler is 12 feet wide, 25 feet high, and 38 feet long; has conventional water tube walls and a convection economizer; and has a capacity of 300,000 pounds of steam per hour. However, the boiler is unique in that it has horizontal tube bundles submerged in the bed of fluidized coal, ash, and limestone, which is the combustor. The unit is divided into separate cells, three of which are almost equal in size. The fourth cell, the carbon burnup cell, is smaller in width due to its own design requirements. The dimensions of the cells were influenced by shipping limitations, duty requirements, and the anticipated function of each cell. The design of the cells was based on the intended heating function:

Cell A, the primary superheater, has a horizontal superheater tube bundle submerged in the bed, with two additional horizontal bundles, the evaporator, and economizer

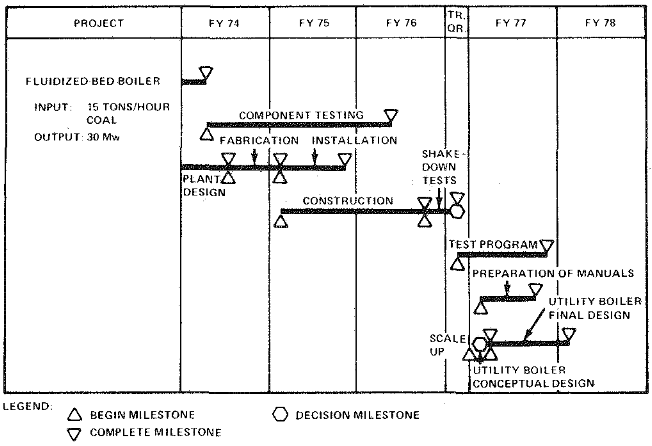


Figure I-1. MULTICELL FLUIDIZED-BED BOILER PROGRAM SCHEDULE

located in the convection zone (freeboard).
Cell B, the finishing superheater, has a horizontal bank of finishing superheater tube bundles in the bed zone with horizontal boiler and economizer surfaces in the convection zone.
Cell C, has a horizontal boiler tube bundle in the bed zone and boiler and economizer surfaces in the convection zone.
Cell D, the carbon burnup cell, contains only horizontal economizer tubes in the convection zone.

The fluidized bed is located approximately where the grate would be in a conventional coal-fired boiler. The bed thickness would be 4 feet with a 6-foot free zone above it and a 6-foot deep, convection heat transfer volume above that. The partition walls between the cells are the membrane type, i.e., finned tubes without refractory protection.

Coal and limestone are fed to cells A, B, and C, and are fired with air containing oxygen 3 percent in excess of the stoichiometric quantity. Approximately 0.1 pounds of carbon per pound of coal feed are elutriated from these cells and collected in a mechanical dust collector. This material is then sent to Cell D and burned with 25 percent excess air. The coal is burned in an inert ash or sulfur-absorbing limestone fluidized bed at nominal bed temperatures of 2,000° F in the carbon burnup cell and 1,550° F in cells A, B, and C. The mixing tendencies of the fluidized bed are controlled by using boiler tubes as baffles and walls. Movement of the particles from one portion of a cell to another is caused by the inherent fluid-like behavior of a fluidized bed.

One of the advantages of the multicell fluidized-bed boiler is that sulfur dioxide and nitrogen oxide emissions are well within EPA standards; expensive and energy-consuming flue gas cleaning equipment is not required. The sulfur dioxide is controlled by the use of limestone, which acts as an absorber. The limestone will be kept reactive by regeneration to recover concentrated sulfur dioxide and by the addition of fresh limestone. Emissions of ash particles, which are removed from the flue gas using conventional gas cleanup equipment, are also low because the coal is not pulverized, resulting in a mean dust-particle size of 100 microns compared to 20 microns for conventional coal preparation equipment.

There are several other advantages to the fluidized-bed boiler:

- Low-quality, high-sulfur coal can be burned without danger of slagging because of low combustion temperatures.
- The heat release and heat transfer coefficients are high, which reduce boiler size, weight, and cost. Cost analyses indicate that the 200-Mw-size fluidized-bed boiler will weigh 2,760 tons, compared to 6,000 tons for a conventional 200-Mw-size boiler, and will cost $5.9 million less.
- The multicell design lends itself to mass production assembly of the major components, facilitating shipping and saving plant building time.
- It is anticipated that use of the fluidized-bed boiler, rather than a conventional coal-fired boiler requiring a flue gas cleanup system, will result in an overall cost savings for the boiler of up to 35 percent.
- The overall operating efficiency of the multicell fluidized-bed boiler power plant is projected to be 39 percent, compared to approximately 37 percent for a conventional coal-fired plant with stack-gas cleanup operating with the same coal and at the same steam pressure and temperature.

HISTORY OF THE PROJECT

In February 1965, OCR (now part of ERDA) awarded PER a contract to build and operate a small atmospheric fluidized-bed boiler. The ability to meet the most rigorous air pollution standards while burning high-sulfur coals was demonstrated, and ash fouling and slagging problems common to other types of boilers were greatly reduced. Furthermore, the boiler promised improved power plant efficiency and cleanliness when burning chars, anthracite, or conventional coal and eliminated the need for pulverization of the coal feed.

Under another OCR contract, initiated in May 1972, PER (in its Alexandria, Virginia, laboratory) performed additional experimental work using a small-scale (0.5 Mw) unit. Four types of fuels (two high-sulfur bituminous coals, North Dakota lignite, and a petroleum coke) were burned to demonstrate the feasibility of fluidized-bed combustion and to examine the effect of lignite's high sodium content. The results of this work indicated that the addition of small quantities of common salt to the fluidized bed was a useful method for increasing limestone utilization, that chloride emissions were low, and that corrosion due to the addition of salt did not occur. Sulfur oxide emissions were reduced to levels well below the emission standards of existing and proposed federal and local regulations.

Because the previous work indicated a high probability of success, work under the current contract was initiated, in October 1972, to design, construct, and operate a 30-Mw-size multicell fluidized-bed boiler under typical utility conditions. For proper design development sizing of the 30 Mw boiler, a concept for an 800-Mw-size fluidized-bed boiler was developed, consisting of four modules, each containing seven vertically stacked fluidized-bed cells. The modular construction results in a four-to-one turndown ratio plus a two-to-one turndown ratio for each module, resulting in an overall plant turndown capability of eight to one. Steam pressure and temperature conditions of the boiler were designed to meet the requirements of the site at which the boiler was installed—the power plant of the Monongahela Power Company at Rivesville, West Virginia. Responsibility for constructing the 30 Mw boiler was awarded to Foster Wheeler Energy Corporation. Foster Wheeler is also responsible for (1) preparation of the designs, technical specifications, arrangement drawings, bills of materials, etc., for the boiler and the pumps, valves, and burners directly attached to the boiler; (2) preparation of a fluidized-bed boiler test program; and (3) design, construction, and testing of a cold model. Champion Construction and Engineering Company, Inc., was awarded responsibility for general construction work at the plant site and for scheduling shipments of structural steel, motors, pumps, etc. Champion and PER jointly review and approve structural drawings prior to fabrication.

Shop fabrication of the 30 Mw boiler was completed in 1974, and field erection of the boiler in the Monongahela Power Company power plant was started. Auxiliary systems and plant general construction (including boiler and plant controls) and laboratory construction were also started in 1974. Field erection of the boiler was nearly completed during 1975. Completion of the steam generator was delayed, however, because accessory equipment was received late. Almost all the general construction at Rivesville, such as pouring foundations, erecting structural steel, removing old equipment, and installing laboratory equipment, was also done. Because conditions in some parts of the plant, which was built about 60 years ago, were different from those originally indicated on the drawings, 60 contract change-orders were issued, thus delaying progress somewhat. An operation and maintenance manual was written, and development of a test and instrumentation program was started.

Laboratory research during 1975 included:

- Studies of fuel injection, bed renewal, local fluidization, and fly-ash injection using a cold-flow model.
- Comparison of the sulfur absorption properties of Germany Valley limestone, which is available near the Rivesville plant, and Greer limestone, which has been used frequently in fluidized-bed combustion. The results show that, for coal containing more than 2.5 percent sulfur, Greer limestone is more efficient for sulfur capture; Germany Valley limestone is more efficient for coal containing less than 2.5 percent sulfur.
- Studies of salt's effect on sulfur absorption and fluidized-bed combustion. Generally, the results show that the use of a salt additive can result in significant economy of limestone usage, especially with high-sulfur coal, from which a large amount of sulfur dioxide must be removed.

Among other laboratory research projects were tests of horizontal tube bundles to study the effects of bed depth on heat flux to the bundle and of gas velocity at both constant and varying preheat, and to obtain heat transfer coefficients. Tests to verify component design were also made, with emphasis on a prototype air distributor.

PROGRESS DURING JANUARY-MARCH 1976

Boiler Design and Construction

General construction by Champion Construction continued throughout the quarter. Coordinating equipment deliveries with erection requirements was emphasized. Champion was also involved in supplying supplementary technical information to assure that the systems are being installed correctly and according to the sequence and procedures recommended.

By the end of the quarter, about 99.5 percent of the scheduled contract work was completed. The engineering design work was 100 percent complete; 100 percent of the materials ordered for delivery at Foster Wheeler's manufacturing plants was received; 100 percent of the shop work was completed; and the erection work was 60 percent complete. The erection of the steam generator was about 96 percent completed, and the remaining work, such as the installation of the recirculating pumps, the large check valves, the fluidization grid plate, and other miscellaneous items, is expected to be finished early in the coming quarter.

The piping fabricator, B. F. Shaw, delivered all prefabricated piping during March. Field installation of the boiler feed and main stream piping is progressing. The main stream and boiler feed lines were tied into the Monongahela power plant in late March.

Most of the miscellaneous metals have been fabricated and delivered, except a few items, such as ladders and handrails. All of the grating has been ordered, two-thirds of it was delivered to the shop, and a portion was fabricated and delivered.

About 98 percent of the equipment has been received from Allen-Sherman-Hoff. The equipment not yet received, although minor in value, is creating difficulties in assembly. Furthermore, Allen-Sherman-Hoff has not given Champion the internal wiring diagrams needed for checking the electrical system drawings. As a result, field wiring has been more difficult than necessary.

Champion's expeditor has been monitoring material procurement, fabrication, and delivery schedules at Pullman. By the end of the quarter, all the ductwork and expansion joints had been shipped to the site and erected. Also, Champion has received the balance of the miscellaneous metals, grating, and silencers, and all of the duct hangers approved for fabrication are on-site.

Carpenter and Paterson of New York, Inc., is designing and fabricating the pipe hangers for the materials handling lines. Champion is assisting them in obtaining required information.

Buffalo Forge, the manufacturer of the auxiliary force draft fan, is no longer on strike but the scheduled delivery date will cause a delay in the scheduled start-up date of about 30 days.

The operating and maintenance manual for the Rivesville multicell fluidized-bed steam generator and associated equipment supplied by Foster Wheeler was completed and copies were issued in this quarter. Preparation of the test and instrumentation program plan was also completed and copies issued.

Laboratory Research

Because the high purity Germany Valley limestone had proved to be a less efficient sorbent for sulfur than the lower purity Greer limestone, an unexpected result, it was thought that the presence of certain impurities, particularly sodium, might significantly affect the limestone's physical structure and thus its sulfur sorption effectiveness. Accordingly, another high purity limestone—Cheney, from Bellevue, Michigan—of different impurity content from those used previously was obtained and two tests conducted. The Cheney limestone (95.2 percent calcium carbonate, 1.4 percent magnesium carbonate, and 0.9 percent sulfur) is nearly as pure as Germany Valley limestone, but has a calcium carbonate content between that and the Greer limestone. During the first run, the limestone bed was calcined and sulfated without bed removal or limestone makeup to generate a bed composition representative of steady-state operation. A second run consisted of a 5-hour approach to steady state, followed by operation at steady state for 3.5 hours. There was no supplementary catalyst addition and Sewickley coal containing 4.1 to 4.5 percent sulfur was used.

Partial analysis of the flue gas shows the presence of 800 parts per million sulfur dioxide, which is about 200 parts per million higher than allowed for new coal-fired boilers, and corresponds to 70 percent sulfur retention in the sorbent with a calcium-to-sulfur molar feed ratio of 3.7. The operating conditions of the test were less than ideal:

- The bed temperature was cooler than the 1,500° F to 1,600° F optimum range, and sulfur capture efficiency decreases significantly as the temperature drops below 1,500° F.
- The gas velocity was more than 20 percent higher than the Rivesville design condition of 12 feet per second, and the bed depth was lower than the design value of 24 inches. This high velocity, combined with the low bed depth, resulted in a gas residence time that was half of that of the Rivesville design conditions.
- The Cheney limestone had a higher than desirable fraction of very fine particles, which appear to have been elutriated from the bed before they could act as sulfur absorbent.

Despite these operating conditions, Cheney limestone performed fairly well as a sulfur sorbent; while not as efficient as Greer limestone, it did perform better than Germany Valley limestone, thus confirming the earlier result that less pure limestones are more efficient sulfur sorbents for high-sulfur coal.

To test the superheater performance in the fluidized-bed module, three alternatives were considered for installing a heat transfer tube bundle to simulate a superheater section in the multicell fluidized-bed boiler. The existing tube bundle removes too much heat, and to operate the fluidized-bed module under design conditions, a reduction of 21 percent in the heat removed is required. The three alternatives considered were:

- Use steam generated in the fluidized-bed module for the operation of a superheater section.
- Use an external source of steam for operation of the superheater.
- Reduce the size of the superheater to enable the use of steam generated in the fluidized-bed module.

PER concluded from the preliminary calculations that none of these alternatives would satisfy requirements under the terms of the current testing program.

Work was done to determine how the quality of fluidization relates to heat transfer. Heat transfer data collected for the horizontal tube bundle revealed that the overall heat transfer coefficients, calculated over various conditions, are lower than reported in the literature for similar situations. In some cases, data revealed temperature gradients in the bed that were larger than expected. This may indicate that the bed is not uniformly fluidized and that the circulation of solids may be poor. To determine how well the bed was fluidized for the conditions under which it was operated, the resistances of the grid and the bed were determined from the measured pressure drops across the grid and bed. The results indicated that the entire bed was not fully suspended. This behavior is usually associated with channeling beds suggesting incomplete contacting and partial fluidization.

Since the quality of fluidization is strongly influenced by the design of the gas distributor plate, the grid design was examined. Calculations indicated that the velocity of the gas fluidizing the bed was sufficiently high so as to cause severe channeling. A series of tests was then carried out, and at first glance the results indicated normal fluidization with no evidence of bed channeling. The calculated values of the limiting dimensionless pressure drop were low, however. When the bed material was removed from the combustor, PER observed that large leaks had developed along the periphery of the distributor plate. These leaks could allow a substantial amount of air to bypass the bed, thereby causing a reduction in pressure drop across the bed. Thus, the results of these tests are inconclusive, and further investigation is required.

A program to investigate and define conditions that promote bed agglomeration was started during the quarter. The results will be used to define operating procedures that will minimize or eliminate the conditions for bed agglomeration during operation of the multicell fluidized-bed boiler.

Bed agglomeration may result from coal melting or coal ash melting, which may occur in the main cells if reducing zones develop during quick start-up, after an emergency shutdown, during a shutdown operation, or in unfluidized regions in the bed. In the carbon-burnup cell, conditions causing melting would be most likely to occur during fluctuations of temperature or oxygen concentrations. Several parameters influence bed agglomeration in each of the conditions, and the effect of each parameter is to be investigated in these tests.

Six test runs were carried out to study bed agglomeration during ignition. The first three tests were carried out with an insufficient flow of air during the start of ignition. Only in the case of the lowest flow obtainable in the fluidized-bed module were agglomerates formed. They were soft, easily breakable, and differed considerably in appearance. The larger agglomerates appeared to be mostly melted coal with bed particles adhering to the surface; the smaller were mostly bed particles stuck together. Chemical analyses of these agglomerates are being performed.

The next three runs were carried out to test the situation when there were insufficient increases in air flow as the coal combustion rate increased. The tests were carried out with the same air flow rate, but with excessive amounts of coal in the bed. In the first test, no agglomerates were found. In the second, a soft easily breakable agglomerate was formed. The agglomerate was in the bed for only a short time before the test was terminated. In a later run, it was put back into the bed, and it disappeared. Hence it seems that such agglomerates are not stable at steady operating conditions and should pose no difficulty. During the run with the greatest excess of coal, numerous hard agglomerates about 1 inch in diameter were formed. They appeared to be melted coal ash clinkers; they were stable and did not break apart after extended exposure to the fluidized-bed environment.

Three tests investigated the conditions that might promote bed agglomeration in the event of the failure of the forced draft fan and subsequent collapse of the operating bed. In the first run, the fan was shut off, but the induced draft fan was left on. The bed was allowed to remain in the slumped condition until it had cooled to ambient temperature. A large agglomerate, soft on top but very hard on the bottom, comprising about 70 percent of the bed, was found in the unit. In the next test, both fans were turned off at the same time. No agglomerate was found when the unit was examined the next day. The forced draft fan was shut off for only 15 minutes in the third test, while the induced draft fan was left on. The fan was then turned on and the bed refluidized and brought back to operating conditions. No agglomerates were found when the bed was later examined. Thus it appears that, if a small flow of air is maintained through the bed after an emergency shutdown, agglomerates may form. Also, if the bed is collapsed for up to 15 minutes, no agglomerates will form even if a small flow of air through the bed is maintained. Further, agglomeration may be avoided if all air is shut off to the bed after emergency shut down.

During the last seven of these tests a plate was installed on the air distributor to create an unfluidized region along the wall of the vessel. No agglomerates were formed on the plate even though agglomerates were found elsewhere in the bed. This indicates that an unfluidized region in the bed of the size formed by a 5-inch by 5-inch plate should pose no problem with respect to bed agglomeration.

As part of a study of commercial recovery of by-products, PER sent a sample of spent bed material from the fluidized-bed module to the Tennessee Valley Authority, Office of Agricultural and Chemical Development. The material, generated from Greer limestone and Sewickley coal with no salt addition, was tested to determine whether it can be used as a supplemental source of nutrient sulfur for growing corn and as a soil neutralizing agent. The results of the tests showed that the bed material performed better than elemental sulfur, but not as well as sodium sulfate, as a source of nutrient sulfur. During the testing as a neutralizing agent, it was shown that the relative liming value of the −6+60 mesh bed material is 10 percent and the value of the −100 mesh bed material is 47 percent that of pure calcium carbonate. These preliminary tests also showed that the bed material is not toxic to the crop tested even at high application rates. Among agricultural applications being investigated for the use of sulfated bed material is peanut growing.

Another major activity during the quarter involved engineering for converting the fluidized-bed module to a carbon-burnup cell. Detailed engineering design work was completed, and all the major equipment and systems for the carbon-burnup cell was purchased. Construction done during the quarter for this conversion included such things as pouring foundations for the propane storage tanks, fly ash hopper, silos, and coal and limestone preparation systems; erection of the fly ash hopper and dust collector on the fly ash silo; installation of load cells on the fly ash silo; and installation of all piping for the propane tanks.

Three new computer programs were put into operation. One calculates the overall heat transfer coefficient, the internal coefficient, and the external coefficient for the horizontal tube bundle. The second calculates the moisture content of the flue gas based on barometric pressure and the amount of water collected from the sample gas during a test time period. The third calculates and/or fits a curve to a set of input points using the least square method.

II. ENERGY CONVERSION ALTERNATIVES STUDY (ECAS)

LEWIS RESEARCH CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
CLEVELAND, OHIO

Contract No. E(49-18)-1751 Total Funding: $2,600,000

INTRODUCTION

The Energy Conversion Alternatives Study (ECAS) is being managed by the Lewis Research Center under the sponsorship of ERDA and the National Science Foundation, each of which is providing approximately one-half of the funds for the project. The studies are being conducted by General Electric Company, Westinghouse Electric Corporation, and a team of Burns & Roe and United Technologies, Inc., supplemented by Lewis Research Center laboratory personnel.

The overall objective of this project, initiated in August 1974, is to study advanced power generation techniques that can use coal or coal-derived fuels and to evaluate their relative merits and potential benefits. ECAS is to be conducted using a comparable basis of technology and materials performance and to evaluate these technologies in light of current conditions. In addition, ECAS is to define development plans or the various advanced systems, providing estimates of both cost and risk, and is to provide a basis for establishing needed technology or development programs. The evaluation of alternative systems on a comparable basis is needed so that cost-benefit analyses may be performed and the preferred systems selected for further development.

PROGRAM DESCRIPTION

Accomplishment of the ECAS objective requires a review of the technical claims, designs, performance, materials selection, development needs, and costs of each power generation system being studied. To determine the relative performance, economics, natural resource requirements, environmental impact, and development requirements and risks of the various advanced power generation systems, a *Conversion Systems Evaluation* is being used. This will be coupled with an *Energy Systems Evaluation* to assess the benefits and impacts of widespread implementation of these advanced energy conversion systems in electric utility applications. Basically, the project comprises four tasks:

Task I—Parametric Analyses
- 25 to 3000 MWe of generating capacity
- Variety of coal or coal-derived fuels
- Variety of heat rejection methods
- Variety of combustors/furnaces
- Variety of working fluids and thermodynamic cycles
- Variation of major power generation parameters
- Materials and performance related to technology status

Task II—Conceptual Designs
- Component conceptual designs
- Plant layouts
- Detailed estimates (performance, economics, environmental impact, natural resources for selected cases)
- Construction requirements
- Operating characteristics
- Technology advancements required

Task III—Implementation Assessment
- Preliminary research and development plans
- Time and resources required to bring system to commercial service
- Commercial acceptability
- Special problems and limiting factors

Task IV—Reports

A preliminary outline for reporting on the output of Tasks I, II, and III is shown below:

- Output of Parametric Analyses
  - Efficiency
  - Economics
    - Capital cost
    - Cost of electricity
  - Natural resource requirements
    - Coal
    - Water
    - Land
  - Environmental impact
    - Emissions (sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, particulates)
    - Thermal pollution
    - Wastes
- Output of Conceptual Designs
  - Plant layouts
  - Improved evaluation of plant characteristics
    - Efficiency
    - Economics (capital cost, cost of electricity)
  - Natural resource requirements
    - Coal
    - Water
    - Land
    - Critical materials
  - Environmental impact
    - Emissions (sulfur dioxide, nitrogen oxides, carbon monoxide, hydrocarbons, particulates)
    - Trace elements
    - Thermal pollution
    - Wastes
- Output of Implementation Assessment
  - Development time and funding requirements
    - Preliminary research and development plans
    - Assessment of uncertainties and risks
    - Identification of key experiments and common technology
  - Factors affecting implementation
    - Economic viability
    - Environmental impact
    - Natural resource conservation
    - Reliability potential
    - Safety
    - Ease of operation, control, and maintenance
    - Limiting factors

The parametric analyses were completed during the second quarter of 1975, and involved studying a variety of advanced energy conversion systems based on combinations of combustors, power cycles, and fuel cells. Among other tasks, construction materials were selected, components sized, and costs estimated. Preliminary results of the parametric analyses indicate that potentially large dollar benefits may be possible for full-scale use of some of the advanced systems.

Conceptual designs are being developed for 10 coal conversion systems. Tasks include selecting design basis and configurations for the conceptual designs, establishing the arrangement of system components, and determining plant layouts. There were some delays, however, in receiving fuel samples for determining semiclean fuel specifications. An energy model is being used for analyzing the costs and benefits of the systems being studied, by geographic region, for each decade from 1980 to 2020.

PROGRESS DURING JANUARY-MARCH 1976

Parametric Analyses

Reports on Task I—Parametric Analyses were completed by General Electric and Westinghouse during February. The reports were reviewed by Lewis Research Center, and a final ECAS Task I report was written.

Conceptual Designs

The technical effort for Task II—Conceptual Designs was completed during the first quarter of 1976. A design review meeting was held with General Electric, covering the specifications for the high-temperature closed-cycle gas (helium) turbine system and for the air-cooled combined gas-turbine steam-turbine cycle with the integrated low-Btu gasifier system. The operation and maintenance costs for all seven systems assigned to General Electric for the development of conceptual designs were also reviewed. The results of General Electric's work were presented at a meeting of the Interagency Steering Committee (ERDA, NASA, National Science Foundation), Technical Advisory Panel (ERDA, NASA), and Utility Advisory Panel on February 17-18 in Washington, D.C.

Westinghouse Electric Corporation presented the results of its conceptual design efforts at the February meeting in Washington. Sections of the final report on the conceptual design effort are being prepared.

The conceptual design of a molten carbonate fuel cell system done by Burns & Roe and United Technologies was completed, and the results were presented at the February meeting in Washington. Final reports on the design are being prepared.

Two baseline scenarios were developed for the energy model being used to evaluate the impacts and benefits to the country resulting from the introduction of advanced stationary power conversion technology. The energy model was run for every decade from 1970 to 2020 for Scenario 1, which considers "business-as-usual" conditions and oil at $7.00 per barrel. The second scenario, for which the energy model was also run, assumes deregulated oil and gas prices. The results for both models are being analyzed and prepared for presentation. The required annual addition of coal plants, allowing for the replacement of retired plants as well as new installations to increase the total energy generating capacity, has been computed for both scenarios.

The program to analyze revenue, capital, and fuel requirements has been completed. Data from EPA on existing fossil fuel plants is currently being processed.

Two scenarios of future electric power demand, one reflecting relatively low growth and the other reflecting relatively high growth, have been developed in detail with a view to bracketing the potential impact of the new energy technologies. From this study, a framework will be constructed for identifying the relative benefits and impacts of specific energy technology developments. Work is continuing on assessing the impacts within the context of the developed scenarios.

Samples of H-Coal fuel obtained from Hydrocarbon Research, Inc. (HRI), were analyzed. The results indicated that the samples provided were not representative of a typical HRI residual fuel (viscosity, vanadium and alkali metal content, flash point, pour point, etc.). Additional samples were requested for further analysis.

Lewis Research Center personnel began working on Task II results. The results of conceptual designs are being examined to compare and evaluate those of all systems and to compare those of similar systems analyzed by different contractors. Where appropriate, the Task II results are being compared to those obtained in Task I. The possibilities for improvements in system configurations are also being studied.

Implementation Assessment

Task III—Implementation Assessment of the conceptual designs developed in Task II was started during the first quarter of 1976. Lewis Research Center held meetings with General Electric and Westinghouse to discuss the work required.

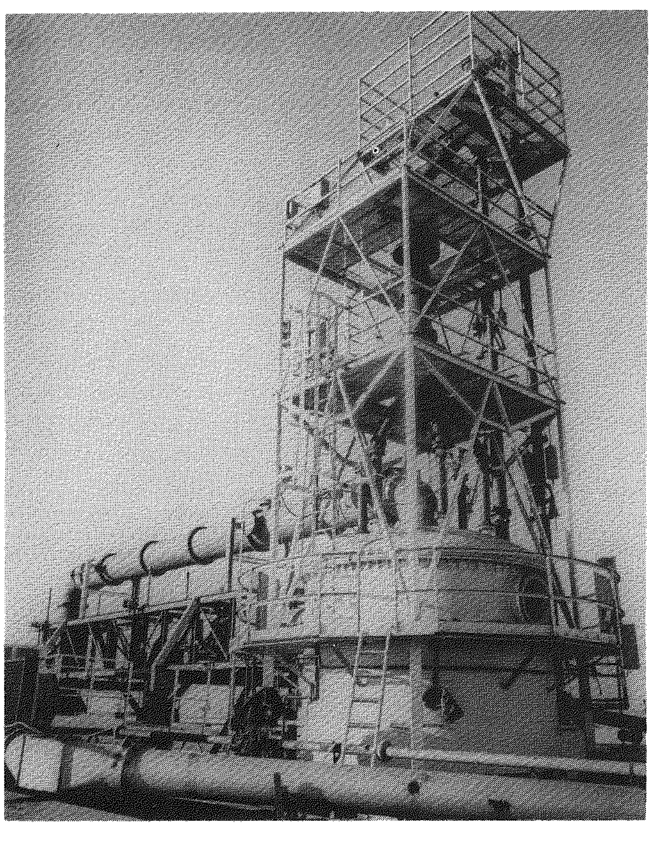
III. PRESSURIZED FLUIDIZED-BED COMBUSTOR AND TURBINE POWER GENERATION

COMBUSTION POWER COMPANY, INC.
MENLO PARK, CALIFORNIA

Contract No. E(49-18)-1536 Total Funding: $3,465,780

INTRODUCTION

A combustor-gas turbine system is being developed by Combustion Power Company, Inc.



(CPC), under the auspices of ERDA. This contract is an extension of an earlier research and development contract between CPC and EPA, in which municipal solid waste was burned without pollution in CPC's CPU-400 pressurized fluidized-bed combustion and gas turbine system. The overall objective of the current program is the development of a process to generate electrical energy from coal by applying technology based on pressurized fluidized-bed combustion of solid wastes and subsequent power generation. Specifically, CPC is tasked to expand existing CPU-400 technology to evaluate the combustion of high-sulfur coals mixed with dolomite, using a gas turbine directly on line for power generation, through laboratory research and long-duration testing of the process development unit. The schedule for development of this combustor-gas turbine system is provided in Figure III-1.

PROCESS DESCRIPTION

A schematic of the CPC combustor-gas turbine system is provided in Figure III-2. In this process, the coal is crushed to a size smaller than 1/4 inch. Dolomite is then added to the coal and the mixture is carried into the fluidized-bed combustor by means of a stream of compressed air. Fluidization is maintained by air from the turbine compressor.

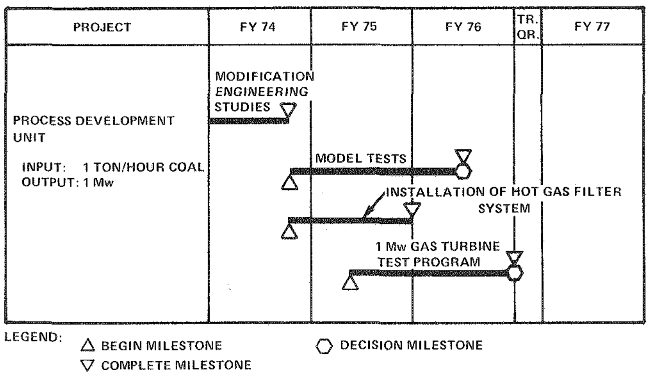


Figure III-1. COMBUSTOR-GAS TURBINE DEVELOPMENT SCHEDULE

In the fluidized-bed combustor, the coal is burned to produce gas; the sulfur compounds in the gas are absorbed by the dolomite. The gaseous products are passed through a three-stage system of separators to remove the solid particles. Stages 1 and 2 each consist of a pair of cyclone separators that remove particles down to 5 microns in size. The third stage, originally a system of inertial impactors, now consists of a moving-bed granular filter to remove particles down to 2 microns. The cleaned gas is then expanded in a gas turbine driving a 1 Mw generator.

To facilitate start-up, fuel oil is used initially to heat the fluidized-bed combustor to reaction temperature and is also used in an oil combustor during turbine start-up. The various transient modes of operation during start-up are controlled by a process control computer, which also records all process operating conditions.

There are several advantages to the CPU-400 system:

- Sizing is the only pretreatment of coal needed.
- High-sulfur caking coal can be burned without exceeding current EPA standards for sulfur dioxide and nitrogen oxide emissions.
- The only stack gas treatment necessary is removal of particulates.

HISTORY OF THE PROJECT

For the past seven years, CPC has been conducting a research and development program, under the sponsorship of EPA, to convert the heat energy of solid waste to electrical energy through the use of the CPU-400 system. With the cooperation of EPA, OCR contracted with CPC in June 1973 to conduct a research and development program to demonstrate the combustion of high-sulfur coal using CPU-400 technology.

Under the current contract, CPC has conducted parametric evaluations of coal combustion in a model of the CPU-400 combustor, using caking and noncaking high-sulfur coals. The caking coal used was Lower Kittanning seam; the noncaking coal used was Illinois No. 6. The coals were burned under varying conditions: superficial velocities of 4, 7, and 10 feet per second; bed temperatures of 1,400° F, 1,600° F, and 1,800° F; calcium-sulfur ratios of 1.5, 3, and 5; and three additives for absorbing sulfur compounds (two types of dolomite and one type of limestone). Each coal type was then tested for 120 hours at nominal operating conditions of 7 feet per second, 1,600° F, and a calcium-sulfur ratio of 1.5.

Next, CPC modified the CPU-400 system to provide the capability for coal and dolomite storage and feeding. This modified CPU-400 is known as the process development unit. Long-duration tests were planned in the process development unit using the data from the model experiments to determine and minimize exhaust emission levels of noxious gases and particulates. In addition, candidate turbine blade materials and coatings were installed in the turbine rotors and stators to evaluate erosion and corrosion effects.

The results of the tests indicated that both dolomites used were equally effective in suppressing sulfur dioxide, the relative effects of superficial velocities and bed temperatures were slight, and the optimum calcium-sulfur ratio was 1.5. Limestone was consistently 10 to 15 percent less effective than dolomite under all test conditions. The most serious problem encountered during the tests was that the separators installed in the process development unit were found to be inadequate to ensure acceptable turbine blade life or to meet current EPA particulate exhaust emission standards. To meet the stringent turbine exhaust emission requirements, CPC designed and installed a moving-bed granular filter.

Work during 1975 generally focused on studies of corrosion problems associated with the hot gas from the combustion chambers. Various metals and alloys that might be used for the gas turbine

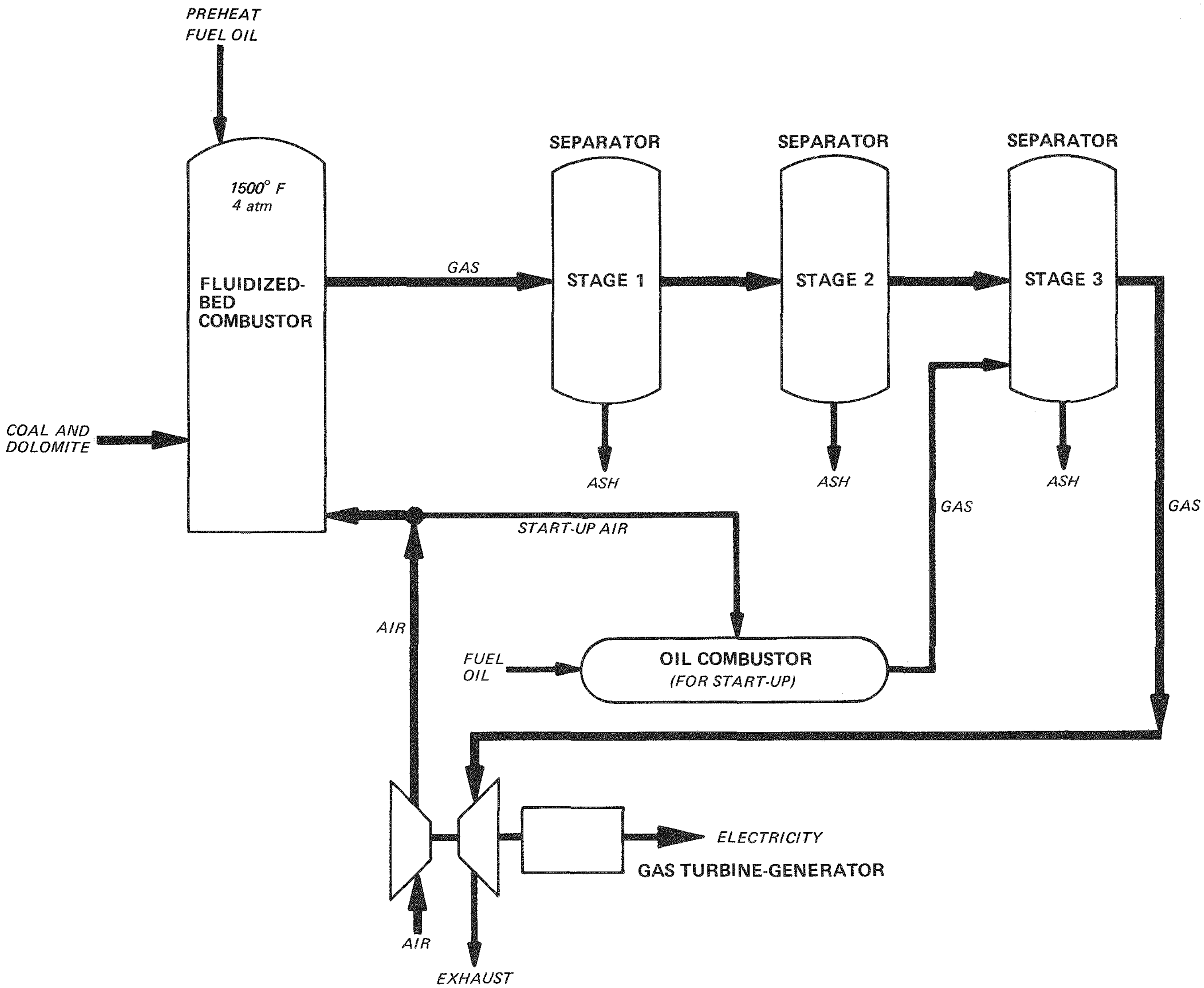


Figure III-2. COMBUSTOR-GAS TURBINE SCHEMATIC

were subjected to long-term tests to determine how well they would stand up under commercial operating conditions. The effect of various additives for inhibiting corrosion of these materials was also investigated.

Solutions to various other problems associated with the operation of the fluidized-bed combustion chamber were sought in the long test runs. Three major test series were conducted in the process development unit. One series (with no corrosion inhibitors) was to establish baseline parameters for the hot-corrosion effect of Illinois No. 6 coal combustion at high pressure; the other two were to evaluate the effect with corrosion inhibitors. Tests in the model combustor were run to screen possible additives and select those with the best potential for inhibiting corrosion. Burgess No. 10 clay pigment was selected for evaluation in the fluidized-bed combustor. A 1,000-hour test was started late in the year using the clay-pigment corrosion inhibitor and exposing three specimens of each of 22 alloys at two locations. One specimen of each alloy was removed after 464 hours. Comparisons with data from the baseline test conducted with no inhibitor show that the corrosion rate is significantly reduced by the clay-pigment additive.

PROGRESS DURING JANUARY-MARCH 1976

Process Development Unit

General modifications to the process development unit were in progress throughout the quarter. CPC does not expect the unit to be operable until July 1976.

The louver panels of the granular filter, which had failed causing the premature termination of Test P501 (made in December), were redesigned, along with their supporting structure. Instead of being integral to the load-carrying structure, the panels will only transmit solids and gas flow loads to the supporting structure, so that any deformation of the panels will not affect the structural integrity of the unit. The new louver panels are being constructed of thicker (12 or 10 gauge rather than 14 gauge) metal. The alloy, RA 330, appears to be the most suitable metal.

To control the flow of the filter medium in the granular filter, a new design was developed that includes a 33-cubic-foot reservoir for storing additional filter media and a method for controlling the amount of media in the reactor bed which requires no gate valves. The gate valves in the original design continually caused problems. In the new design, pulsed air jets can be used to clear filter material from (1) the entrance to the reservoir, thus allowing more of the filter media to enter the reservoir, reducing the amount present in the active bed, or (2) the line at the bottom of the reservoir, thus allowing more filter media to enter the active bed. In cold tests, the new system was found to be both simple and reliable.

The temperature of the air leaving the granular filter could not be correctly predicted from the model previously used. As this temperature effectively determines the inlet gas temperature to the turbine, and as the operation of the turbine depends upon the inlet gas temperature, it is vital to be able to control the exit air temperature from the granular filter. A new model was consequently developed, and indicated that the required inlet temperature of 1,200° F to the turbine would be reached after 13 hours of operation with a combustor temperature of 1,550° F, or after 18 hours with a combustor temperature of 1,500° F. Temperatures taken during operation were lower than those predicted by the model, because the hot-gas flow rate was lower than had been assumed. To correct this situation, steps are being taken whereby the inlet gas pressure to the turbine is reduced, which in turn will permit a lower pressure in the compressor outlet. With this lower pressure, a greater air flow can be maintained.

A full report on the failure of Test P501 and on the redesign of the process development unit is being prepared.

Laboratory Research

Test M405 in the model combustor unit, started in November 1975, was completed in January 1976 after 1,003 hours of operation. Although the test comprised eight individual segments for which test parameters were changed, the only significant difference lay between the first six and the last two segments. During the last two segments, the fine particles carried off from the combustor were recycled at a substantially better rate, which in turn halved the concentration of sulfur dioxide in the exit gas stream. The coal feed rate was also higher in these two segments due to the increased rate of partially cooled fine particles returned to the combustor, which required reheating.

This test was run to evaluate the ability of Burgess No. 10 pigment to inhibit hot corrosion in the combustion of high-sulfur coal. The Burgess pigment was added at a rate of 0.004 pound per pound of coal. To remove the sulfur, dolomite was added at a rate of 0.24 pound per pound of coal, or at a calcium-to-sulfur ratio of 1.2. The average sulfur removal was 87 percent, with a removal of 92 percent during the last two segments.

To study corrosion, CPC placed samples of 22 different structural and turbine blade alloys at three locations in the model test unit—one in the space above the combustor, and one in each of the special chambers between the first- and second-stage separators. Specimens removed after the first half of the test, at 464 hours, were examined by scanning electron microscope (SEM) and by energy-detection-analysis X-ray (EDAX). The analysis showed that isolated sulfur-rich spots in the sample of one alloy, FS414, were inherent in the alloy as casted. CPC also found that, although the higher freeboard temperature during the latter half of the test resulted in a higher rate of oxidation, the improved recycling of the fine particles of dolomite reduced the concentration of alkali and sulfur dioxide, so that no further sulfidation of the samples occurred during the latter half of the test. In general, Inco 713C was found most resistant to attack.

It was thought that extraneous factors, such as irregularities in the feed rate, changes in the temperature of certain spots, the use of high-phosphate coal, and ash forming in layers, might influence the results as much as the absorbents added to the feed. Test M406 was therefore started during the quarter to form a new standard, or baseline, from which the effects of 0.4 percent by weight of Burgess No. 10 pigment plus 0.1 percent by weight of magnesium oxide could be established. Magnesium oxide had been found effective in reducing stickiness of municipal solid waste combustion products, and should be effective against phosphates as well. The planned 1,000-hour test was divided into two segments: 400 hours (Test M406A) to constitute a new baseline test without corrosion-inhibiting additives, and 600 hours (Test M406B) using corrosion inhibitors.

In test M406A, samples of the 22 alloys previously tested were exposed, along with 20 additional samples. Preliminary examination of the samples indicated that a higher temperature is required to differentiate the amount of corrosion suffered by the various samples.

Test M406B was started late in the quarter. By the end of the period, 114 hours of the 600-hour test were completed.

Supporting Research

Westinghouse Research Laboratories did a theoretical analysis of the chemical reactions taking place in the process development unit. The study of the effect of sodium chloride on sulfur capture showed that (1) there is a correlation between increased sodium content of limestones and their increased capacity for reaction with sulfur dioxide, and (2) introducing sodium salts into a pressurized fluidized-bed combustor driving a hot exhaust gas turbine cannot be seriously considered because there results a 10-fold excess of sodium in the exhaust gas over that required to deposit sodium sulfate on the turbine blades.

The pressurized reactor was modified to permit salt injection into the gas stream. The system was tested satisfactorily at atmospheric pressure, but when tested under pressure, the temperature rose too high causing the injection system to fail. A smaller furnace is being installed.

Experimental tests showed that Burgess pigment (an aluminum oxide-silicon dioxide) was a very efficient absorber of sodium in the low concentration levels studied. More than 99 percent of the sodium was retained with a gas residence time of 0.01 second in the pigment filter. Potassium chloride, usually found condensed above the reactor bed when Tymochtee dolomite is heated to 1,650° F, was not present when the Burgess pigment was mixed with the dolomite. Kaolinite (a hydrated aluminum oxide-silicon dioxide) was found equally effective in sorbing sodium.

The effect of the size of the turbine blades on particle deposition was studied by calculating the boundary layer development on blades of different sizes and estimating the rate at which small particles are deposited on the blades. Westinghouse estimated this rate by using a model that describes deposition caused by eddy impaction and diffusion caused by boundary layer development. The effect of changing the size of the turbine blades is more pronounced for particles larger than 1 micron in diameter than for smaller particles. In all instances, greater rates of deposition resulted as the turbine blade size decreased. Further calculations are needed to determine the rate of growth of these deposits.

Solar (Division of International Harvester Company) is analyzing the environment in the process development unit, particularly the vapor and particulate phases. These phases, rather than the gas phase, are expected to be responsible for most of the hot corrosion that may be experienced during operation of the unit. As part of this work, Solar collected samples of ash from two points in the process development unit and characterized them according to size, shape, and composition. A significant percentage of large particles (roughly 11 microns) was found in samples taken after the second cyclone separator, indicating the need for more effective separation of particulates in the system. A device such as the moving-bed granular filter installed in the model combustor unit appears capable of efficiently removing particulate matter from the hot gases.

The shape and crystalline structure of the particles in the gas stream were studied. Of the four predominate types, two–quartz and calcium sulfate, or anhydrite—would be expected to do considerable damage to turbine components during high-speed impact because of their size and angularity.

Chemical analyses indicate that some carbon is leaving the combustor bed unoxidized and is consumed in the excess air. Particles collected in the exit stream from the granular filter in the model combustor unit have a relatively high sodium, potassium, and aluminum content.

Preliminary tests made with ash collected from Test P403B of the process development unit show an erosion rate of 0.02 inch per hour at a particle loading 16 times greater than encountered in the actual run. The deep pits found may indicate a melting phenomena caused by particle impact at high velocities, rather than of the chipping attack usually observed.

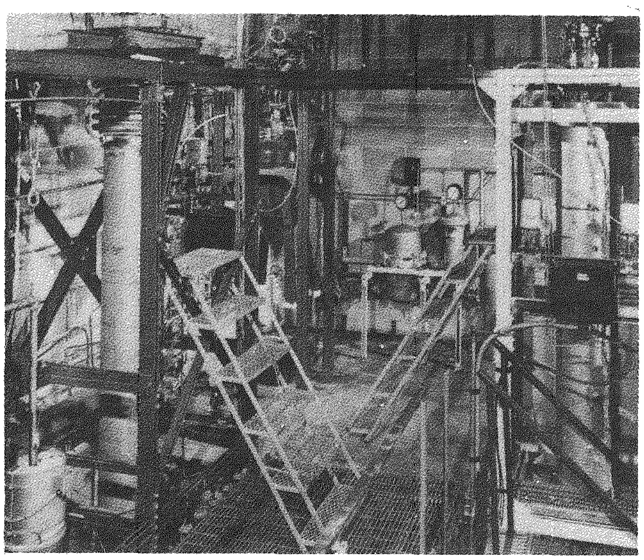
IV. SUPPORTIVE STUDIES OF PRESSURIZED FLUIDIZED-BED COMBUSTION

ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

INTRODUCTION

Pressurized fluidized-bed combustion is being studied by the Argonne National Laboratory (ANL) under the sponsorship of ERDA. This research and development program is being conducted to evaluate the feasibility and potential of fluidized-bed combustion at high pressures (up to 10 atm). The specific objectives are to:

- Optimize combustion procedures while maximizing retention of sulfur dioxide in the fluidized bed, minimizing the amount of nitrogen oxides in effluent gas, and increasing combustion efficiency.
- Evaluate the behavior and efficiency of the system when using different types of coal such as lignite and subbituminous.
- Study the levels of trace-element pollutants in the flue gas and the effects of process operating conditions on these levels.
- Determine the mechanisms of the various reactions in the process and how their thermodynamics and kinetics are affected when parameters are varied.



PROCESS DESCRIPTION

A schematic of the pressurized fluidized-bed combustor being used in the ANL test program is provided in Figure IV-1. The combustion unit has a diameter of 6 inches and is 11 feet long. The exterior is wrapped with electrical heaters to raise the bed temperature to coal ignition temperature and with cooling coils to regulate the bed temperature during coal combustion. Four additional hairpin coils for cooling are immersed in the fluidized bed. An internal overflow pipe is used for maintaining a constant bed level. The system is thoroughly instrumented and equipped with an automatic data-logging system.

Coal and dolomite are transported by an air stream into the base of the combustor. Compressed air for fluidizing the mixture is also fed into the base of the combustor. The coal is entirely burned in the fluidized bed of dolomite. The sulfur contained in the coal is released during combustion as sulfur dioxide, which is then absorbed by the dolomite. (The sulfated dolomite is regenerated for reuse in the combustor.) The gases produced must be mechanically cleaned, and can then be used to generate steam or to drive a gas turbine or in a combined-cycle process.

An advantage of the pressurized fluidized-bed combustor being developed by ANL is that nearly all of the atmospheric pollutants (mainly sulfur and nitrogen compounds) that are normally generated during the combustion of fossil fuels are removed from the effluent gas.

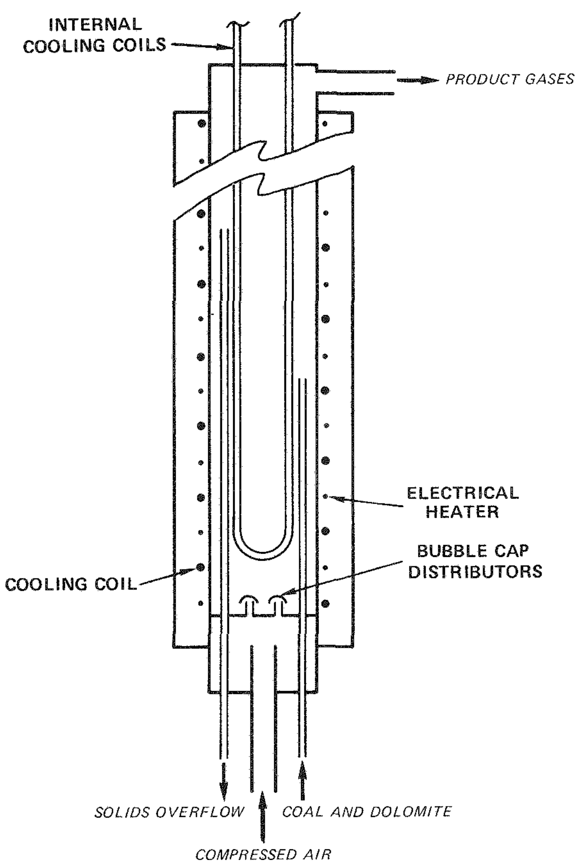


Figure IV-1. ANL PRESSURIZED FLUIDIZED-BED COMBUSTOR

HISTORY OF THE PROJECT

Initial research and development of pressurized fluidized-bed combustion done by ANL included 11 experiments to measure the effects on a variety of dependent variables of temperature, fluidizing gas velocity, and ratio of the calcium content of the dolomite to the sulfur content of the coal. In these experiments, Pittsburgh seam coal was burned, at 8 atm, in a 3-foot-high fluidized bed and with 3 percent oxygen in the flue gas. The results indicated that:

- For calcium-sulfur ratios above 2.0, more than 90 percent of the sulfur dioxide was retained in the dolomite bed; the amount retained decreased as the calcium-sulfur ratio decreased.
- Nitrogen oxide levels were extremely low, ranging between 0.40 and 0.15 pounds of nitrogen dioxide per million Btu, as compared to the EPA emissions standards of 0.70.
- Combustion efficiency varied directly with combustion temperature, ranging from about 89 percent at 1,450° F to about 97 percent at 1,650° F. Unburned carbon elutriated from the bed was the major source of inefficiency.
- Additive entrainment varied directly with the superficial gas velocity, varying from about 5 percent at 2 feet per second to as high as 80 percent at 5 feet per second. The use of larger dolomite particles would have reduced entrainment considerably at the higher gas velocity.
- Values of heat transfer coefficients varied directly with gas velocity, ranging from about 40 Btu per hour per square foot per degree Fahrenheit at a gas velocity of about 2 feet per second, to about 115 Btu per hour at 5 feet per second.

ANL also conducted experiments using a subbituminous coal with a high ash content and a lignite with a low heating value. The operating performance of the fluidized-bed combustor in processing these western coals was excellent, thus demonstrating the versatility of the fluidized-bed concept for processing coals of widely varying rank and quality.

Another series of experiments was conducted to study the effect of combustor operating pressure on concentrations of nitrogen oxides and other noxious gases in the flue gas. In the absence of dolomite, the concentration of nitrogen oxide increased rapidly as the combustor pressure was reduced, going from less than 200 parts per million at 8 atm to around 1,600 parts per million at 1 atm. In the presence of dolomite, the concentration of nitrogen oxide also increased as the pressure decreased, but only to about 400 parts per million at 1 atm. In both cases, the sulfur dioxide concentration was relatively unaffected. Temperature (1,450° F to 1,650° F) had little or no effect on gas impurity concentration.

The distribution and potential emission of trace elements from fluidized-bed combustors were studied for comparison with available data from conventional coal-fired combustors. The elements of primary interest were lead, beryllium, mercury, and fluorine. Generally, the results indicated that the concentration of trace elements emitted from the fluidized-bed combustor may be significantly lower than that emitted from conventional coal-fired combustors.

Under the current program, ANL is continuing its experiments. Specifically, ANL is studying combustion and regeneration, including the chemistry of the ash-limestone mixture, limestone decrepitation, reaction kinetics, and gas pollutant levels; characterizing high calcium and dolomite limestones; and testing and evaluating materials of construction for fluidized-bed combustor and regenerator systems.

During 1975, ANL studied combustion, sulfation and regeneration, sulfur recovery and emission control, trace elements in effluent gas, and fluidization. Combustion studies focused on:

- Comparing the sulfur retention properties of limestone and dolomite; Tymochtee dolomite, with a sulfur retention level of about 95 percent, was found to be superior to Greer limestone.
- Measuring the relative effects of the particle sizes of coal and sorbent on combustor response; according to the measurements, sulfur retention may be improved when the particle size of the coal is increased and that of the sorbent decreased.
- Evaluating the effects of recycling on sorbent performance and decrepitation.

The sulfation and regeneration rates of α-alumina pellets impregnated with calcium oxide were studied and compared with those of other sorbents. Calcium oxide sorbent compared well with other sorbents tested. Because calcium oxide is the least expensive of the materials tested, it is probably the most desirable for use in commercial fluidized-bed systems. The technical feasibility of one-step reductive regeneration of sulfated sorbent was also studied.

In studies of sulfur recovery and emission control, ANL emphasized analysis of solid-solid reactions for recovering sulfur from sulfated dolomite, Several experiments were run to determine whether the best (kinetically) reaction was technically feasible as a regeneration method.

Most of the work on trace elements involved preparing for experiments to determine which elements and how many of each are in the effluent gas, and to differentiate between the particulate and gaseous components. Some work was also done to obtain data on the vaporization characteristics of trace elements in coal and their volatilization rates. Experiments were also conducted to determine the quality of fluidization of a fresh unsulfated dolomite bed and correlate minimum fluidization velocities with particle-size distribution of the solids in the bed, bed temperature, and reactor pressure.

PROGRESS DURING JANUARY-MARCH 1976

Combustion Studies

The experimental program initiated last quarter to evaluate the effects of recycling on sorbent activity and regeneration continued. The first experiment, RC-1A (conducted during the fourth quarter of 1975), showed that, of the additive fed to the combustor, 62 percent was removed in the product overflow, 30 percent was recovered in the primary cyclone, 2 percent was recovered in the secondary cyclone, and 6 percent was unaccounted for. In anticipation of losses that may occur in a test involving 10 complete cycles, a large amount of dolomite sorbent is being prepared. The limited data available so far indicate very little decrepitation of the sorbent in the combustor during one combustion cycle. Based on the flue gas analysis, the sorbent fully retained its activity for sulfur removal into the second combustion cycle, as it absorbed 90 percent of the sulfur in the coal.

Sulfation and Regeneration Studies

The effect on subsequent limestone regeneration of the relative lengths of the oxidizing and reducing zones of a fluidized-bed combustor was studied. In the oxygen-rich, or lower, portion of the fluidized-bed, calcium sulfate is formed from limestone and sulfur oxides. Calcium sulfate can be regenerated to form calcium oxide (limestone) again. However, in the upper, fuel-rich portion of the bed, calcium sulfate may be reduced to calcium sulfide by carbon monoxide. Calcium sulfide does not regenerate directly to calcium oxide under the conditions used. ANL ran two tests with two different ratios of oxidizing-zone height to reducing-zone height. This was accomplished by changing the location of the coal injection line. Increasing the length of the oxidizing zone relative to that of the reducing zone allowed calcium sulfide to reoxidize as it circulated through the bed. Thus the buildup of calcium sulfide was reduced, and greater regeneration could be obtained.

Testing, begun last quarter, was continued to investigate the possibility that sulfated sorbents and coal ash combine during regeneration to form mixtures that have lower melting points than their constituents. The investigation showed the lowest fusion temperature at a composition of 70 percent ash and 30 percent sulfated sorbent. This suggests the possibility of a eutectic formed from the constituents of the ash and sulfated dolomite. The fusion temperature of this composition is about 2,100° F, which is near the regeneration temperature. This low fusion temperature suggests a mechanism for the agglomeration of ash and sorbent in the regenerator: at small temperature variations from the normal 2,000° F regenerator temperatures, molten ash and/or eutectic material serve as coalescing agents that accumulate sorbent particles in the regenerator. To further test this proposed mechanism, the composition of sorbent, sulfated sorbent, and ash were compared. Oxides of silicon, iron, and aluminum (compounds present in the ash) were found in the spent sorbent. Based on a comparison of the fraction of silicon in the spent sorbent and ash (no silicon is found in fresh sorbent), the ash content of the spent sorbent was calculated to be 10 percent.

A study was begun to determine the effects of regeneration on sulfur concentration profiles within the sorbent particles. An electron microprobe was calibrated and used to analyze for sulfur across the face of particles that had been split in half. The analysis showed that the sulfur concentrated near the outer surface of the sphere in the early stage of sulfation, then diffused slowly into the interior of the particle. Conversely, during regeneration sulfur is first removed rapidly from the outer shell of the sphere, comprising the bulk of the particle volume. Following this first stage of regeneration, the sulfur in the center of the particle must diffuse to the surface before being removed. This second stage is relatively slow and, in an industrial process, probably would not occur at all.

As alternatives to calcium oxide sorbent, a list of 16 metal oxides was prepared from literature references. The most promising compounds on the list from a thermodynamic standpoint are lithium aluminum oxide and lithium titanium oxide. Neither of these proved satisfactory, however. They both lost, rather than gained, weight during sulfation. This happened presumably because of the tendency of lithium sulfate to decompose to elemental lithium, oxygen, and sulfur dioxide at elevated temperatures. (Oxides of potassium, sodium, barium, and strontium, included on the list, have been investigated and reported previously.) Potassium and sodium oxide sorbents have unstable sulfates. Barium and strontium oxide sorbents have about the same sulfation rate as calcium oxide sorbent. Calcium oxide, being the least expensive, is still the most promising of all.

ANL continued its investigation into methods of producing supports for sorbent material with the required properties of surface area, porosity, and strength. To the data on porosity of boehmite heat treated at 2,000° F and 2,250° F, ANL added data on boehmite heat treated for 8 hours at 2,730° F. The trend toward higher temperatures producing a larger number of large pores continued. This is desirable in that it strengthens the support and provides the large pores needed for impregnation with calcium oxide.

Sulfation rates of the 2,730° F treated substrate impregnated with 8.8, 11.1, and 11.4 percent calcium oxide were compared to the rates of sorbents prepared previously from the 2,000° F and 2,250° F treated boehmite. The sulfation rate of the new sorbent was superior, showing the highest rate of conversion from calcium oxide to calcium sulfate. This supports the hypothesis that the sulfation rate is at least partly controlled by diffusion, the larger pores increasing the diffusion rate.

One-step regeneration experiments continued throughout the quarter. Experiments on aliquots of sulfated dolomite were made at 1,650° F, 1,560° F, and 1,470° F to add to the 1,740° F experiments of the last quarter. Reaction times and reducing gas (hydrogen in helium) concentrations and flow rates were also varied. ANL found that the calcium oxide concentration in the sorbent increased from the initial 12 percent to the final 37 percent at 1,470° F with 0.1 percent hydrogen in the reducing gas. This is a significant yield when compared to that at the much higher temperature of 1,740° F, when the final concentration was 49 percent calcium oxide at the same hydrogen concentration. The balance of the sulfated sorbent is predominantly calcium sulfate. After the one-step regeneration process, it is predominantly calcium sulfide. It should be noted that the reaction time was three times as long at the lower regeneration temperature (15.7 hours versus 4.7 hours).

Two-step regeneration experiments also continued. With reducing gas concentrations an order of magnitude higher (1 percent hydrogen in helium), the formation of calcium sulfide from calcium sulfate is favored over the formation of calcium oxide, especially at lower temperatures. This is confirmed by the one-step regeneration data. In the second (carbonation) step of the regeneration, carbon dioxide and water react with the calcium sulfide to form calcium carbonate and hydrogen sulfide. It appears that calcium oxide, even in small quantities, forms a barrier to the diffusion of the carbon dioxide and water, thus inhibiting the formation of calcium carbonate. Therefore, the two-step process has been necessary. This suggests though that one might be able to do the two reactions simultaneously, leaving small quantities of calcium oxide distributed throughout the calcium carbonate. Two such experiments have been run using 3.6 percent hydrogen and 40 percent carbon dioxide in helium as the reaction gas. The results are encouraging: 40 percent calcium carbonate, 10 percent calcium oxide, and 34 percent calcium sulfide were in the product at 1,470° F; 46 percent calcium carbonate and 22 percent calcium sulfate were produced at 1,380° F. Again, the lower temperature required a longer reaction time: 42 hours versus 17 hours.

Analyses of Trace Elements

Preparation for experiments to determine the presence of inorganic constituents in the effluent gas from coal combustion continued throughout the quarter. Since some chemical elements in certain forms are known to cause severe metal corrosion, the objective of this study is to make a quantitative determination of the elements present and to differentiate between particulate and gaseous forms. A laboratory-scale fixed-bed combustor is being built for use in this test program.

Work also continued on the project to determine the vaporization characteristics of trace elements in coal by analysis of the elements present in ashes prepared from Illinois Herrin No. 6 Montgomery County coal. Two series of experiments were run. In the first, coal ground with iron plates was burned in aluminum oxide boats and ashed in a muffle furnace with air at 640° F for 48 hours. These samples were further treated in the muffle furnace with air at six different temperatures from 1,000° F to 1,810° F, for 24 hours. In the second series, coal was prepared using a ceramic ball mill, ashed in platinum boats at 640° F, then returned to the muffle furnace for 24 hours at six different temperatures from 1,560° F to 2,280° F using air or oxygen-enriched air to promote combustion.

Ash samples were analyzed (using atomic absorption, neutron activation, and X-ray fluorescence) for several elements: lithium, sodium, magnesium, berylium, lead, vanadium, cobalt, copper, chromium, potassium, calcium, titanium, and chlorine. The only element that showed a significant decrease at high temperatures was chlorine. The samples treated at 1,190° F and above showed a chlorine content of about 20 parts per million compared to about 90 parts per million for samples treated at lower temperatures. The metallic elements were generally retained in the ash up to the highest temperature, and no sodium or potassium was lost at these temperatures.

Other Studies

Fabrication of New Equipment

To improve experimental capabilities, three major pieces of new equipment are being designed: regenerator, combustor, and a system for continuously recycling additive between the combustor and regenerator. The new regenerator is to be 6 inches in diameter (the old one is 4.25 inches) and will be capable of operating at 10 atm and 2,100° F. The heat loss is expected to be 1,300 to 1,500 Btu per hour-foot of bed (one-third the present design), which should result in an offgas more concentrated in sulfur dioxide.

Construction drawings for the new combustor are being reviewed. The equipment for continuous cycling of the additive (the present process is manual) is in various stages of development: fabrication of inertial separators is complete; solids product receivers are scheduled for completion April 1; solids feeders, feeder hoppers, system pressure control valves, and filters for particle removal from the offgas are being designed.

Mathematical Modeling

To understand the basic nature of noncatalytic solid-gas reactions such as the combustion of coal, a study was undertaken to develop a mathematical model. The purpose was to predict the temperature at the location inside the coal particle where the oxygen is combining with unburned coal. The rationale is that the temperature at this point may affect the composition of the products of reaction.

A spherical model for a coal particle was assumed in which the size of the unreacted core decreases slowly as it reacts with the gas phase. This slow process assumption allows solution of the resulting equations, assuming no accumulation of material or energy inside the particle—the quasi-steady-state assumption. A mass balance for the gaseous components of the reaction was written giving the concentration profile of the component inside the particle. This differential equation was solved subject to the gas concentration gradient at the outer surface of the particle and the concentration profile at the point of reaction inside the particle, which is affected by the rate at which the reaction occurs. The rate of reaction is taken to be linearly dependent on the solid concentration in the bulk phase and on gas concentration in the core (which may be controlled by diffusion), and is assumed to increase exponentially as temperature increases.

The temperature profile inside the particle was obtained by solving an energy balance in conjunction with the concentration profile. Boundary conditions for the energy balance include the transfer of heat from the particle by convection and radiation, and the addition of heat to the particle by the reaction. The concept of time is brought in to the analysis by relating the rate at which the unreacted core is shrinking to the rate of reaction.

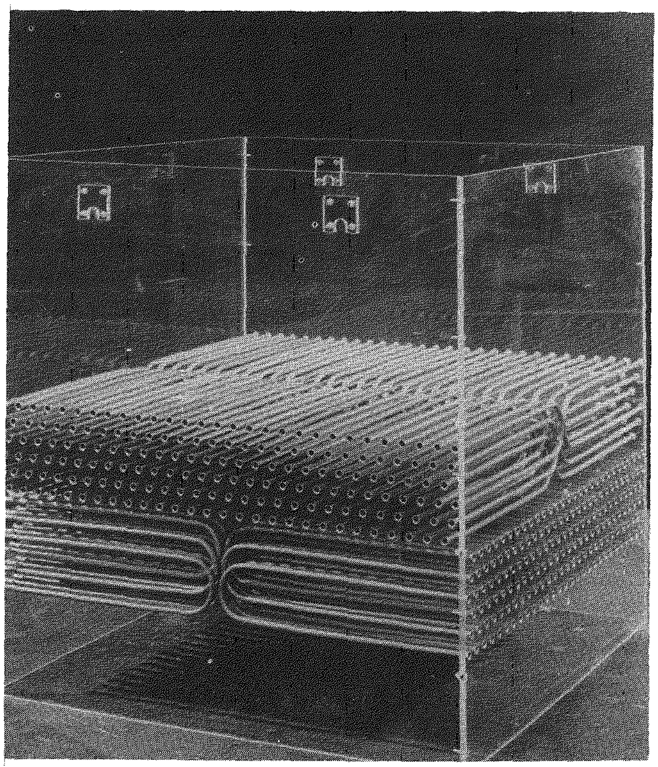
To solve the equations, a number of physical constants are required: the physical properties of the gas phase and ash; the heat of reaction, activation energy, and reaction rate constant; heat and mass transfer coefficients at the particle surface; the diffusivity of the gaseous reactant in the gas and ash; the temperature and gaseous reactant concentration in the gas phase; and the size of the particle.

V. EXTERNALLY FIRED GAS TURBINE FOR MODULAR INTEGRATED UTILITY SYSTEM (MIUS)

OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE

INTRODUCTION

An externally fired gas turbine is being designed by Oak Ridge National Laboratory (ORNL) as part of the Modular Integrated Utility System (MIUS). ERDA and the Department of Housing and Urban Development (HUD) (under HUD contract 1AA-H-40-72) are the joint sponsors of this project.



The objective of MIUS is to provide services consistent with reduced use of national resources, protection of the environment, and minimized cost. MIUS might be sized to accommodate several hundred or a few thousand multifamily dwelling units, single-family units, and associated commercial facilities. MIUS is modular in that it can be located near appropriate users in phase with the actual demands of community development, as opposed to forecast of requirements. It employs an integrated systems approach in a total energy concept whereby some resource requirements of one service are met by utilizing the effluent of another. For example, heat rejected from a prime mover for heating buildings, processing potable water, operating absorption-type refrigeration units, etc., can be used, as can heat from solid waste incineration. In addition to conserving energy, MIUS should realize a savings in capital costs because long transmission lines and municipal sewers are not required.

ORNL's contribution to this project is to conduct a multiphase research program to develop one or more coal-fired power plants for use in a MIUS demonstration project. These phases include preliminary evaluation of the con-

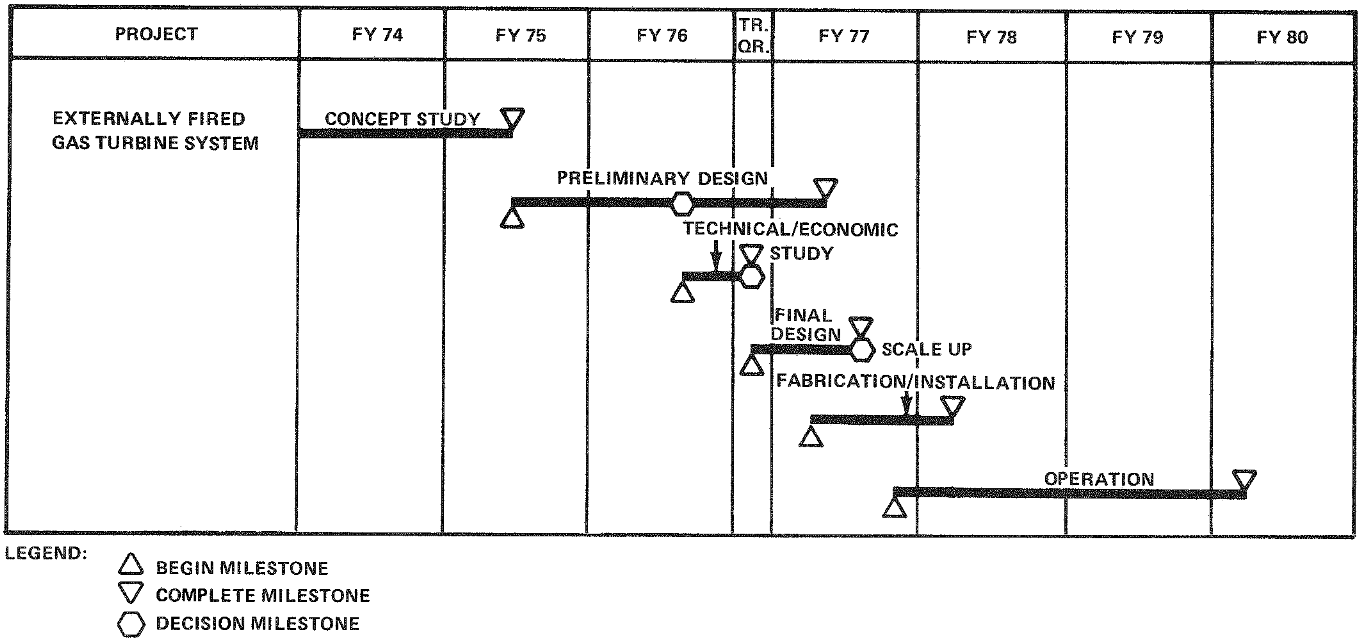


Figure V-1. COAL-FIRED TURBINE FOR MIUS PROGRAM SCHEDULE

cept; design of a coal-fired power plant that can be used in the small total energy system envisioned, each module of which will have a capacity of about 0.5 Mw; and construction, operation, and evaluation of the plant. In conjunction with this project, ORNL has a continuing research program. The development schedule for this program is shown in Figure V-1.

PROCESS DESCRIPTION

For MIUS operation with coal, ORNL is designing a fluidized-bed combustion system combined with a closed-cycle gas turbine. A vertical sectional drawing of the proposed combustor is shown in Figure V-2. The design must provide for efficient operation at less than peak load since this will be the normal operating condition. As currently designed, the fluidized bed in the combustion system is composed of coal and limestone. The function of the lime is to absorb sulfur from the burning coal. Calcium sulfate is formed in the fluidized bed, making it unnecessary to remove sulfur oxides from the stack gases. The bed is about 20 inches deep. Preheated air enters a plenum chamber under the bed, flows up through the bed, through a plenum chamber over the bed, and then through the economizer region. The plenum chamber over the bed allows particles thrown up from the bed an opportunity to decelerate and fall back into the bed. The superficial velocity of combustion gases can be varied from 2 to 4 feet per second. The air for the bed furnace is preheated by a heat generator consisting of a stationary heat transfer matrix, with the hot stack gas flowing through one portion where the heat is transferred from the gas to the solid matrix. The particle movement in the fluidized bed promotes good combustion of the coal particles and provides excellent heat transfer coefficients with combustion gases. The bed temperature is maintained at about 1,600° F by air tubes about one-half inch in diameter welded into manifolds at the top and bottom. This configuration provides sufficient heat transfer surface area to remove the appropriate fraction of the heat of combustion.

The temperature through the entire closed-cycle system is kept relatively constant, and its power output is changed by varying the basic pressure in the system. Current parametric studies agree with previous analyses; namely, the optimum pressure ratio for a closed cycle with recuperation is between three and four to one. A conventional, plate fin heat transfer matrix is used for the recuperator. A larger fraction of the

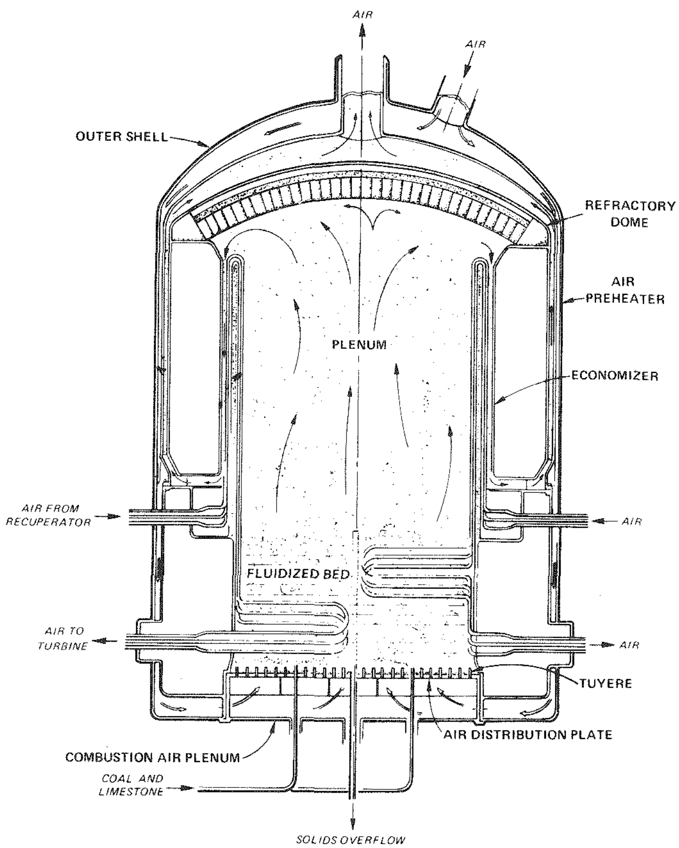


Figure V-2. FLUIDIZED-BED COMBUSTION SYSTEM FOR MIUS

heat of combustion goes into the air heated by the fluidized bed and a smaller fraction goes into the waste heat boiler, operating at 250° F. (The waste heat boiler simplifies both the fabrication and control problems.) For good cycle efficiency, the compressor inlet temperature should be 80° F if a standard outside air or cooling water temperature of 60° F is maintained. A fan is currently included to reduce the backpressure on the turbine and increase the thermal efficiency.

Particulates in the stack gases must be removed. Two stages of cyclone separator remove fines of 10 microns and larger. If the gases are cooled to below 600° F, the bulk of the remaining fines can be removed with porous bags made of glass cloth.

The MIUS coal-fired gas turbine process has several advantages. For example, it provides the required overall thermal efficiency at full load, with little degradation in thermal efficiency for part-load operation, the more common operating condition. Furthermore, the fluidized-bed combustion system operates well with liquid or gaseous fuel, including char, low-sulfur coal, or solid organic waste; hence, it could also be used as an incinerator. In addition, keeping combustion at about 1,600° F prevents the formation of appreciable amounts of nitrogen oxide and keeps the ash temperature below its fusion point, so there is no difficulty with the formation of clinkers or glassy cinders.

ORNL has given much attention to basic problems such as (1) the uneven distribution of coal and limestone across the fluidized bed, (2) bed pulsations and tube vibrations, (3) decrepitation rates and reactivities of various limestones and dolomites after recycling, (4) the upper limits of gas velocity and bed depth, (5) the possibility of excessive corrosion on the combustion gas side of the tubes, and (6) the effectiveness of fly ash removal equipment.

HISTORY OF THE PROJECT

HUD foresaw the impending energy shortage and enlisted the assistance of ORNL in an investigation of total energy systems for use with new building complexes as a part of the MIUS program. ORNL assisted HUD first by looking at the problems of supplying heat to housing complexes from district heating systems tied to central stations and subsequently by examining various aspects of small total energy systems. Hundreds of these systems, employing diesel or gas engines or gas turbines, are in use currently in the United States and have proved to be economically attractive. When shortages of gas and fuel oil began to develop in 1972, HUD asked ORNL to investigate the possibility of developing a small total energy system that would operate with coal as the fuel, particularly with high-sulfur coal which is readily available. This led to the formulation of a program in May 1974, funded by OCR (now part of ERDA), to be carried out at ORNL through HUD.

Phase I of this program, concept and preliminary evaluation, entailed the comprehensive review of a wide variety of ways of employing coal in small total energy systems for HUD applications. Completed in July 1974, Phase I concluded that one promising way to use coal as the energy source for MIUS application is to burn it in a fluidized bed of limestone to produce air for expansion in a closed-cycle gas turbine. The thermal efficiency of the closed-cycle turbine is sufficiently high under part-load conditions, at which MIUS normally operates, to produce power that is competitive with power generated by utility companies, insofar as cost is concerned. The closed-cycle system can convert about 30 percent of the energy in the fuel to electricity and about 60 percent to heat, either as steam at 250° F or as hot water at 150° F.

Critical evaluations of the results of Phase I work were generally favorable. To supplement that work, an additional study of gas turbine bucket erosion, deposits, and corrosion was carried out, with particular emphasis placed on experience with coal-fired gas turbines. In January 1975, ORNL was authorized to proceed with Phase II, the development of a firm conceptual design and cost estimate for the construction of a system for test and evaluation. ORNL also has a continuing research and development program supporting this contract.

During 1975, the conceptual design and cost estimate were completed. The major task involved designing the fluidized-bed furnace and heater assembly. The overall plant design work also included testing key components, examining the feasibility of modifying commercially available components, and conducting several special studies on problems, such as bed pulsation, tube stress and vibration, instrumentation and control, corrosion, and safety.

The turbine engine to be used in the fluidized-bed coal combustion system is one developed by AiResearch Division of Garrett Corporation. Late in the year, AiResearch was awarded a contract for engineering studies of design problems involved in adapting its engine to MIUS.

Laboratory research included the selection of three commercially available coal feed and metering systems to determine whether they can be modified for use with the MIUS. Some components of the coal feed and metering systems were tested to determine the precision with which the coal can be metered, divided, and conveyed by air into the bed, and to monitor the systems for reliability and potential operating problems.

Another major research project done in 1975 involved designing and building a 10-inch-square Plexiglas fluidized-bed model and a 4-foot-square model with full-scale tubes. These models are being used to study the fluidizing characteristics of the bed when it is operated with air and limestone particles. The preliminary results show that the minimum air velocity for good fluidization is 1.7 feet per second.

Among other studies done during 1975 was an economic comparison between the coal-fueled MIUS concept and two other coal-fueled systems, development of an analytical model for studying fluidized-bed pulsation problems, and an evaluation of the possible environmental effects of the MIUS coal distribution and ash collection systems.

PROGRESS DURING JANUARY-MARCH 1976

Plant Design

Several meetings were held with AiResearch to review the turbine evaluation study. The major subject covered in these meetings involved ways to adapt the AiResearch Model 831-200 engine to MIUS. ORNL and AiResearch decided that the Model 831-200 engine could be modified and that a speed of slightly less than 80 percent of the original design would be optimum for the closed-cycle system, since the power level can be reduced to 30 percent of full power with atmospheric pressure at the compressor inlet. Above 80 percent of the original design speed, the turbine-generator power level cannot be lowered below 36 percent of full power without the inlet pressure to the compressor dropping below 1 atm. Also, when the speed ranges from 70 to 80 percent of design, the generator efficiency is 95 percent. Aerodynamic performance and control studies were completed, indicating no aerodynamic or surge problems with closed-cycle operation. The shaft seals and bearings and the thrust bearing must be replaced due to the closed-cycle operating pressures imposed on the seals.

Another subject discussed involved recuperator design. Because of higher efficiency, a six-module recuperator, rather than the originally designed four-module recuperator, appears to be a more attractive choice. It was estimated that the modified turbines and recuperator can be delivered in 14 to 16 months after the order is placed, part of this time to be used in testing the units.

Drawings were completed for a bid package for the furnace assembly, and meetings were held with prospective vendors. The drawings for the bid package included a set of assembly and subassembly drawings and necessary specifications. The specifications were written to allow the vendor to propose alternate shapes, materials, dimensions, or other design details that would be better suited to fabrication on location. The contract will be awarded on the basis of the proposal that would yield a furnace that will meet the system requirements at the lowest cost and meet the MIUS development schedule.

An ORNL request for a directive to proceed with procurement and construction was approved by ERDA. Bids for the longest term procurement item, the Incoloy 800 tubing for the tube matrix in the fluidized bed, were received. A vendor was chosen and contractual arrangements were completed. A small quantity of Inconel 600 tubing for the tube matrix was also ordered. Negotiations were under way to choose a vendor to supply a small number of stainless steel tubes that will be included in one of the tube bundles.

Laboratory Research

Work on the coal metering and feed system consisted of investigating three alternatives for coal handling and transport. The flow splitter type of system was tested, the vibrator-eductor coal transport system was developed, and the Iron Fireman was installed.

Tests of the flow splitter type of system, which divides the coal feed stream into four equal parts, indicate that each of the four streams can be kept within 5 percent of the mean coal flow rate over the entire operating range. Endurance running at the full design power coal feed rate was also investigated; no problems occurred in 35 hours of operation. These tests have shown this system to be satisfactory for the full-scale MIUS system.

Development of the vibrator-eductor coal feed system included fabricating four eductors with adjustable stainless steel outlets. These eductors are being tested. The total weight of the feed trough and eductor assembly was optimized, such that the vibratory mass gives a reproducible amplitude capable of delivering about 520 pounds per hour at a maximum setting of the voltage controller. Connecting the outlet of each of the four eductors by a 0.75-inch line to a Lucite cylinder allowed ORNL to measure the coal feed rate of each eductor. However, after numerous tests at various air flow settings, showed a variation of flow among the four lines of about 15 percent at a maximum setting of the vibrator. The total flow rate was fairly predictable (within about 5 percent) but additional development is required before equal feed rates can be obtained from all four eductors for all settings of vibratory amplitude.

A new 7.5 hp motor was mounted on the Iron Fireman feeder and various switches and explosion-proof receptacles installed.

Three tests on the mixing rate of coal in a fluidized bed of limestone in the 4-foot-square cold-flow model were completed. In the first test, a 25-pound charge of coal was blown in at the lower center of the bed and the fluidizing air was run for several short time intervals. Samples were taken at four points at three levels. The fluidizing velocity for the test was slightly lower than the minimum operating velocity that had been selected from flow visualization tests. The results from the samples from the 20-second time interval showed good vertical mixing, but no horizontal mixing. After 40 seconds, the coal distribution was uniform in the vertical direction, but there was still very little horizontal mixing. The amount of horizontal mixing after 80 seconds was also small. ORNL concluded that, at a very low fluidizing velocity, good vertical mixing will occur, but essentially no horizontal mixing will be obtained in the bed. In the second test, the fluidizing velocity was slightly higher than the minimum operating velocity chosen. The results indicated that the mixing rate was good in both the vertical and horizontal directions.

The fluidizing velocity for the third test was about 2.2 feet per second, which is equivalent to about 50 percent of full power air flow rate for the hot furnace. Preliminary results indicate that the mixing rate was considerably higher at a fluidizing velocity well above the minimum operating velocity. Upon completion of the test, the cold-flow system was modified by removing the cyclone separator to reduce the pressure drop in the air outlet line, thus allowing tests at higher velocities.

Other Studies

Funds were received this quarter ($725,000) from ERDA for supplemental studies on the coal-fired MIUS program, and six tasks were started. A report was written describing the work to be done on a study of problems associated with solid materials handling. ORNL is arranging for a subcontractor to conduct corrosion tests and also heat transfer tests on air-cooled tubes in a fluidized-bed furnace. Reports on reliability, system performance with alternate cycles, and economic comparison of the closed-cycle gas turbine with two alternative energy systems are being prepared.

VI. COAL-OIL SLURRY COMBUSTION PROJECT

PITTSBURGH ENERGY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA

INTRODUCTION

The coal-oil slurry combustion project is being conducted by the Pittsburgh Energy Research Center (PERC) to provide ERDA with an in-house capability for investigating and validating the potential of this near-term retrofit technology for oil conservation and increased coal utilization. PERC is designing and constructing a liquid-fuel-fired Combustion Test Facility (CTF) analogous to the one currently operated by the energy conversion group for solid fuel research. The CTF should provide the data required to design combustion systems using various slurries under process development for both industrial and utility boilers.

The specific objective of the CTF is to demonstrate the potential for using coal-oil slurries in a commercial oil-fired boiler without requiring extensive modifications or large capital expenditures for retrofit. Burner designs and system requirements must be developed and refined to permit the use of coal-oil slurries. In addition, coal-oil slurries will, in many cases, result in products with combustion characteristics different from those experienced when burning petroleum fuels. These fuel characteristics affect the design of feed systems, atomization and mixing of fuel with combustion air, air-preheat requirements, flame character and stability, and heat-transfer properties. (Slurry characteristics will be studied using a 100 hp firetube boiler.)

The CTF test program includes CTF shakedown tests, slurry combustion tests, slurry suspension stability tests, slurry erosion tests, slurry handling modifications and tests, slurry characterization tests, flue gas emission control tests, and an economic analysis on the use of various coal-oil slurries in retrofitted steam generating plants. The data will be used to design combustion systems using various slurries under process development for both industrial and utility boilers. In-house funding for this project was granted in July 1975.

PROCESS DESCRIPTION

The CTF consists of a 700 hp combustion test watertube boiler, a closed-loop heat-removal system consisting of an air-cooled steam condenser and condensate unit, coal-oil slurry mixing and feed equipment, flue gas cleaning equipment, fuel storage facilities, and coal preparation equipment.

Initially, coal is unloaded into the coal storage bin, ground to 95 percent through 200 mesh (or an optimally defined mesh) in the coal pulverizer, stored in the coal supply hopper, and conveyed to a mixing tank by the coal feeder. Dust control equipment for the coal pulverizer includes a coal filter (cyclone separator and bag house) and a pulverizer blower. No. 6 oil is initially unloaded into a storage tank, then is heated to 100° F by a suction heater and conveyed to a mixing tank by the No. 6 fuel oil pump. The pulverized coal and No. 6 oil are blended into a slurry in a proportioning feeder tank. After mixing, the fuel is conveyed to a slurry hold tank mounted on a weigh scale. The slurry feed pump then injects the fuel through a 300° F slurry preheater into the combustor. Enough air to burn the coal-oil slurry is supplied to the combustor from the combustion-air blower.

The hot flue gas from the combustor passes through a cooler to lower the temperature below the design requirements of the bag house. To reduce the sulfur dioxide level, sodium bicarbonate is injected into the stack gas before it enters the bag house. After particulate cleanup in the bag house, the flue gas is discharged to a 60-foot stack by the stack ID fan.

All the steam produced by the test boiler is condensed in an air-cooled heat exchanger. A condensate unit then pumps the liquid into a deaerator where the appropriate feedwater conditioning chemicals are added. The boiler feed pumps return the conditioned water to the boiler.

HISTORY OF THE PROJECT

When considering coal as an alternate fuel to oil, the difficulties of its direct use and the costs of converting oil-fired facilities are well documented. However, preliminary work has shown a potential for supplementing fuel oil with pulverized coal-oil slurries at a cost less than that of oil and requiring only minimum changes in existing boiler house equipment. Development of slurry as a fuel and of techniques for its use poses a short-term solution to restrictions on fuel oil supplies by reducing oil consumption by as much as 40 percent in applicable units presently firing oil. The specific markets identified are both large and small industrial units and the utilities.

The philosophy used in designing the CTF was to build around a commercial packaged boiler and auxiliaries to permit eventual industrial application of test results. However, the CTF will be supplied with extensive and sophisticated monitoring sensors and instruments, as well as an existing computer-controlled data-acquisition system, to allow on-line real-time analysis and computation capabilities. The system will allow definition of the operating characteristics in the combustion of slurries with a minimum of experimental tests.

During 1975, PERC focused on completing a preliminary shakedown test in a 100 hp firetube boiler using No. 6 fuel oil. Boiler efficiency was tentatively determined to be about 85 percent. Preparations for a 1,000-hour slurry test were nearly completed, and the first batch of slurry was mixed. In addition, about 90 percent of the facility bid package specification for the 700 hp watertube boiler was completed by the end of the year. Plant layout drawings were prepared for the coal-oil slurry preparation equipment, the CTF, and the flue gas cleanup system, and detailed drawings were prepared for seven major vessels.

PROGRESS DURING JANUARY-MARCH 1976

100 hp Firetube Boiler

Preliminary slurry tests in the 100 hp firetube boiler, firing No. 6 fuel oil, resulted in formation of carbon deposits in the combustion chamber. These deposits were eliminated in subsequent tests by increasing the atomization pressure. Two long-duration combustion tests were then completed firing slurry containing 20 percent bituminous coal (90 percent −200 mesh). Approximately 800 gallons of slurry were consumed in the tests with no deposit formation and no apparent operational difficulties. Combustion efficiency will be determined when fuel analyses are received.

Fuel for the 1,000-hour coal-oil slurry test is being pulverized in the coal handling unit of the 500-pound-per-hour combustion system being used in the solvent-refined coal combustion test program (Section VII). Pulverization will continue as the test progresses.

The 1,000-hour combustion test was started in March. Its purpose is to record data for determining combustion and boiler efficiency. After about 250 hours of operation, control difficulties were experienced with the burner. These are electrical problems, and are not directly related to the combustion of coal-oil slurry. New parts were obtained. The test program will resume after the parts are installed.

During the 250 hours of operation, PERC detected no increase in tube metal temperature. Visual inspection of the interior of the boiler tubes in the second gas pass showed only a light ash deposit on the surface, with no appreciable buildup.

700 hp Watertube Boiler

The facility bid package specification was completed by PERC and reviewed by ERDA's Chicago Engineering Construction and Facilities Management (ECFM) Division. The ECFM Division decided that the facility bid package specification needed several modifications prior to acceptance and strongly urged that the specification be divided into separate process and construction packages.

As a result of a meeting held in March, it was decided to hire a contractor to do the detailed design of the CTF and to act as construction manager. The contractor will complete the detailed design packages on a staged construction schedule basis, submit the packages to PERC and the ECFM Division for review, then let contracts for each package on a fixed price, competitively procured basis. A board of five members was formed to decide on operating procedures and methods of advertising for potential contractors.

The ECFM Division agreed to permit PERC to procure equipment with long lead times. Purchase requisitions and accompanying equipment specifications were processed for both the 700 hp watertube combustion test boiler and the coal pulverizing and drying system. The purchase requisitions must be reviewed and accepted by the ECFM Division prior to actual advertisement.

VII. SOLVENT-REFINED COAL (SRC) COMBUSTION TEST PROGRAM

PITTSBURGH ENERGY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA

INTRODUCTION

Combustion tests on Solvent-Refined Coal (SRC) are being done by the Pittsburgh Energy Research Center (PERC) as part of an ERDA program to increase coal utilization. SRC is a reconstituted material that has been dissolved from coal, filtered, and separated from its solvent. The product is low in sulfur and ash, which allows compliance with environmental regulations. Although the process of solvent refining is apparently well defined, there has been no effective evaluation of SRC as a utility boiler fuel. The specific purpose of this PERC project, therefore, is to study the handling, pulverizing, burning, and fouling characteristics of SRC.

PROCESS DESCRIPTION

The SRC combustion test program is being conducted using a multiburner, water-wall furnace designed to burn pulverized coal at a nominal rate of 500 pounds per hour. The SRC being used in this project was obtained from a 6-ton-per-day SRC pilot plant in Wilsonville, Alabama. The SRC was produced from a high-sulfur Illinois coal, contains 0.8 percent sulfur and 0.3 percent ash, has a heating value of 15,400 Btu per pound, and has a melting point temperature of less than 300° F.

The SRC is air dried, transported to a feed hopper, then delivered to a pulverizer by a screw feeder. The fuel is pulverized in an impact mill with integral classification. (Earlier studies were made using hammer mills and ball-and-race type mills, with little success. The problems were generally related to generation of heat in the pulverizing process which caused the SRC to soften and agglomerate in the mills. The difficulties could possibly be overcome by rather strict temperature control of the material in the mills.)

After being pulverized, the SRC is pneumatically transported to a recycle loop. The recycle loop, inserted in the primary air-fuel transport line, minimizes fluctuations in the primary air-fuel ratio. The fuel is then burned in the direct-fired system through four burners in the front wall of the rectangular furnace (7 feet wide, 12 feet high, and 5 feet deep). The burners are designed to impart swirl in both the primary and secondary air streams.

HISTORY OF THE PROJECT

Early SRC combustion tests resulted in sticking and eventual clogging of burner passages because the SRC was too hot. To minimize the contact of SRC with hot metal surfaces, new burners were designed and fabricated, with water cooling provided to all surfaces that contact the primary air-SRC stream. A water-cooled conical shield was added to protect the stream against radiation from the burner flame.

In combustion tests with the modified burners during 1975, satisfactory combustion results were achieved without appreciable deposit formation or burner fouling. To optimize recirculation and flame shape and to overcome burner fouling, swirl in the secondary air stream was reduced and a longer flame established. Although flame temperatures obtained with SRC were several hundred degrees higher than those obtained with bituminous coal, the emission of nitrogen oxides was considerably lower than that obtained with coal fired through the more conventional burners originally used in the combustion system. Carbon conversions exceeded 99 percent, which is similar to the conversion obtained when bituminous coal is burned.

PROGRESS DURING JANUARY-MARCH 1976

Several combustion tests were completed firing SRC from the Wilsonville, Alabama, pilot plant in the 500-pound-per-hour furnace. In all tests, combustion appeared to be quite satisfactory. The fuel and ash are being analyzed to determine combustion efficiency. The emission of nitrogen oxides and carbon conversion values are also being determined.

A supply of SRC from the Tacoma, Washington, pilot plant will be obtained so that handling and combustion characteristics of that fuel can be also studied in the 500-pound-per-hour combustion system.

In addition to SRC combustion tests, tests were conducted using a Pittsburgh seam coal or an Illinois No. 6 coal (the parent coal for the SRC used in previous tests). The purpose of these tests was to characterize the combustion of these coals and to provide some explanation of the low emission of nitrogen oxides noted in the combustion of SRC.

During the combustion tests with Pittsburgh seam coal, the emission of nitrogen oxides was low (325 parts per million) when the burners were adjusted to produce flames similar to those produced during SRC combustion tests. These flames were rather long; however, they did not impinge on the furnace rear wall. Long flames were desirable in the SRC combustion tests, because they were just slightly detached from the burner and thus did not overheat metal surfaces causing the SRC to stick. When burner adjustments were made to produce a short, intense flame with Pittsburgh seam coal, the emission of nitrogen oxides exceeded 500 parts per million. Apparently the emission is related to the intensity of combustion.

A paper was prepared for presentation at a Combustion Institute meeting in Columbus, Ohio, in April 1976. The paper describes the modified burners for the 500-pound-per-hour furnace and their performance firing SRC from the Wilsonville, Alabama, pilot plant.

At the end of the quarter, the pulverizing system of the 500-pound-per-hour combustion system was being used to produce fuel for coal-oil slurry tests (Section VI).

VIII. ANTHRACITE REFUSE UTILIZATION

MORGANTOWN ENERGY RESEARCH CENTER
MORGANTOWN, WEST VIRGINIA

INTRODUCTION

Anthracite refuse and silt bank materials are potential low-carbon, high-ash fuels resulting from mining and cleaning anthracite coal (principally in northeastern Pennsylvania). In the mining region, this refuse material is piled in a densely populated, geographically small area of about 480 square miles. The U.S. Bureau of Mines estimated that 800 banks containing 910 million cubic yards of refuse can be found within the anthracite mining fields. This material has been deposited from mining operations or from the reject streams of preparation and cleaning plants. Many of the banks contain refuse spanning the history of mining in the region. The deepest layers may have been deposited 100 years ago when preparation methods were crude, while surface layers have resulted from much better heavy media washing procedures and are essentially depleted in coal. Some of the older banks have been reworked using the better cleaning methods to recover coal; consequently the characteristics of the refuse varies widely from bank to bank or even within a given bank.

The Morgantown Energy Research Center (MERC) is examining the combustibility characteristics of these refuse materials in a fluidized-bed combustor. The value of this refuse as a fuel is important in the anthracite region because of the decline in mining in the area, which has led to a growing dependence on oil. Currently, the refuse banks are aesthetic eyesores that have supplanted valuable land from other uses, along with posing potential health and safety hazards from spontaneous combustion. The burning of this material in fluidized-bed combustors would provide fuel in a region that needs fuel, along with reducing some of the problems presented by the refuse banks.

PROCESS DESCRIPTION

The MERC atmospheric pressure fluidized-bed combustor is basically a refractory-lined cylindrical combustor of 18-inch internal diameter in the bed region, with an expanded freeboard cross section of 24-inch diameter. The combustor is equipped with a horizontal, water-cooled heat exchanger submerged in the bed and a separate water-cooled tube bundle in the freeboard to reduce exit gas temperatures. To control temperatures with the low-heating-value refuse fuels, six hairpin loops of 1/4-inch 310 stainless steel pipe with individual water flow controls were installed.

Fuel is pneumatically injected into the base of the combustor with room temperature air. Fluidizing air is provided through a plenum that feeds a number of orifices in the conical distributor. The reject solids that are separated from the exit flue gas by the primary cyclone can be reinjected into the bed with an air injector for carbon burnup. Flue gases are further cleaned by the secondary cyclone and parallel bag filters before exiting through the stack. Gases are sampled for on-line analysis at the exit of the combustor. Excess spent bed material is withdrawn through the apex of the inverted conical air distributor with a screw feeder.

An operating period with the combustor typically lasts 5 days, 24 hours per day. Start-up begins by preheating the empty combustor vessel with a premixed natural gas-air flame through the air distributor. When operating temperature is reached, the fluidized bed is built by feeding either 50-50 mixture (by weight) of anthracite coal and inert material (as limestone) or with the refuse directly. When the planned bed depth has been achieved, the natural gas flow is curtailed and the temperature of the bed stabilized by adjusting water flow in the submerged heat exchanger followed by reinjection of the primary cyclone ash. The complete start-up procedure requires 2 to 4 hours from cold lightoff to stabilization of temperatures with normal feeding of refuse and reinjected ash.

HISTORY OF THE PROJECT

Two anthracite refuse materials with widely different characteristics have been burned. These include a fine silt refuse from the Powderly Bank, south of Scranton, Pennsylvania, and a much lower quality material from a reworked bank north of Scranton, the Mid-Valley Bank. These refuse materials represent two extremes of fuel quality. The silt approaches anthracite coal in analysis and heating value, while the reworked refuse bank is much poorer in quality, containing mostly slate and "bone" (a laminated coal/slate agglomerate of medium carbon value). Similar low-grade coal-related waste materials have been burned in fluidized-beds in England in the form of slurries, usually with a supplementary fuel required. The fluidized-bed combustor is well suited to burning such materials because of the inherent low carbon in the bed coupled with the good mixing and long residence times to burn the relatively unreactive carbon found in such waste materials.

The Powderly Bank silt combustion test demonstrated that this fine material can be handled at low velocities in the fluidized-bed combustor. The variability of these refuse piles also became evident with the procurement of this feed material. A preliminary sample indicated that the Powderly silt would contain 52 percent carbon and 39 percent ash (8,400 Btu per pound), but the bulk sample (5-ton load), obtained in the same vicinity as the preliminary sample, proved to be of much better quality.

The burning of the Mid-Valley Bank refuse was a much more severe test of the combustibility limits for these low-grade fuels. In the first test burning this material, limestone addition was avoided to demonstrate that this high ash material would build and maintain its own bed. Based on the results from this first run, however, it was evident that some limestone would be required to meet sulfur emission standards.

Generally, the combustion tests with these two refuse materials have demonstrated satisfactory carbon burnout and smooth sustained operations. (Each presented its own unique operating requirements to achieve these results, however.) The results indicate that the fuel value in the refuse carbon can be easily recovered in a fluidized-bed combustor. Fluidized-bed combustors with waste heat boilers located near the supply of anthracite waste could recover the heating value contained in this reject material and reduce the demand for expensive and scarce fuels. The burning of the waste would also somewhat reduce the environmental impact of the refuse piles, although the ash would remain a disposal problem of somewhat reduced magnitude.

The study of emissions from the burning of the wastes was started late in 1975. Initial indications are that some sulfur capture with limestone or other sulfur acceptor may be necessary to meet emission standards even though the sulfur content in the waste is low.

PROGRESS DURING JANUARY-MARCH 1976

The MERC fluidized-bed combustor was prepared for a run with two main objectives: (1) measure the sulfur dioxide emission from combustion of Mid-Valley Bank anthracite refuse and determine the amount of limestone (absorbent) needed to meet the sulfur dioxide emission standards, and (2) test the new sulfur dioxide, nitrous oxide, and carbon monoxide stack gas analyzers. The anthracite culm was used for building the bed, and limestone was used as an absorbent. The run conditions were basically the same as those used previously: the culm feed rate was 120 pounds per hour, the bed temperature 1,610° F, and the superficial air velocity 2.9 feet per second. Ash was recycled from the first cyclone, and the bed was drained periodically to maintain the bed at a predetermined level. A complete analysis of the run will be reported later, but several points were noted.

Through an 8-hour period of steady-state operation, the emission of nitrogen oxides (expressed as pounds of NO_2 per million Btu) was approximately 0.27. As expected, this is well below the EPA emission standard of 0.7. An analysis of the ash content of the spent bed material and of the material collected in the cyclones and bag filters showed that the constituents of the ash are basically the same for both materials.

A sulfur balance for the run showed that the calculated value of the emission of sulfur dioxide (440 parts per million) was very close to the value obtained from the sulfur dioxide analyzer (480 parts per million). Although this run was made with no limestone addition, the sulfur dioxide emissions were only slightly above the EPA emission standards.

Equipment changes were made during the quarter to improve combustor operation:

- All the instruments, analyzers, and gauges were moved to the control room, and sulfur dioxide, oxygen, carbon dioxide and nitrous oxide analyzers were installed and calibrated.
- Additional equipment has been adapted to the coal screw feeding system, including two cylindrical coal storage hoppers, a rotary feeder, and an auxiliary coal hopper.
- A hydrocarbon analyzer was ordered.

A sight glass installed on the top of the combustor gives a good view of the bed as it is being built, as well as of characteristics of fluidization with the bed fully built.

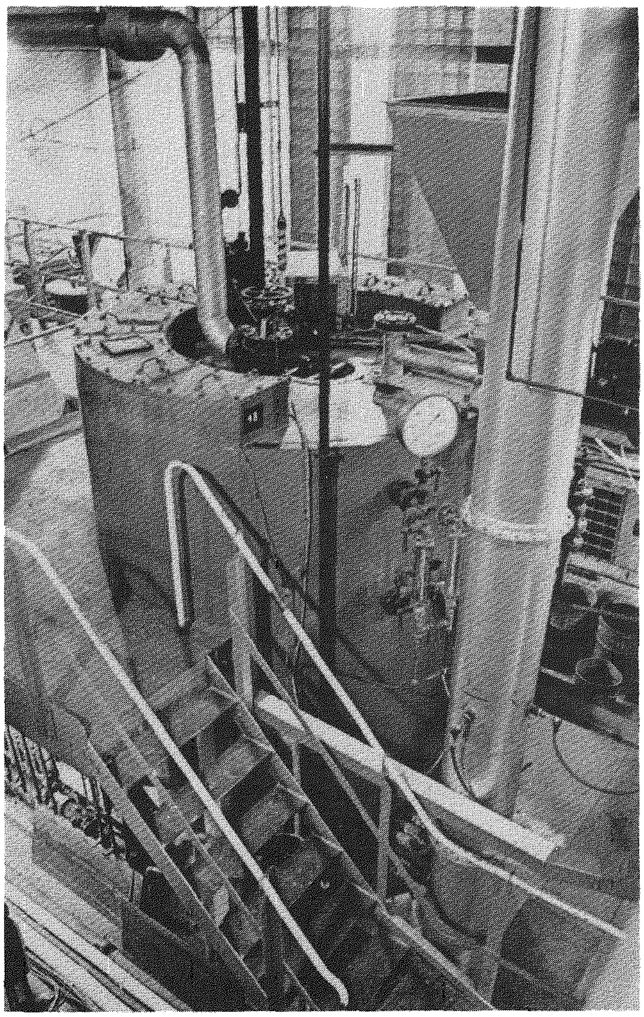
A 20-ton load of anthracite refuse from the Taylor Bank near Scranton, Pennsylvania, was obtained and is being dryed and crushed. This material is "breaker" refuse.

IX. PRESSURIZED FLUIDIZED-BED COMBUSTION RESEARCH

NATIONAL RESEARCH DEVELOPMENT CORPORATION

LONDON, ENGLAND

Contract No. E(49-18)-1511 Total Funding: $850,831



INTRODUCTION

The National Research Development Corporation (NRDC), in conjunction with the British Coal Utilization Research Association, Ltd. (BCURA), is studying pressurized fluidized-bed combustion under the sponsorship of ERDA. This research and development program is being conducted to assess the capabilities of pressurized fluidized-bed combustion from the point of view of minimizing pollution, especially from high-sulfur coals; avoiding excessive maintenance because of corrosion in conventional plants; and reducing capital and operating costs of electric power generating systems. The program enables ERDA to obtain combustor performance data on systems of substantial size (applicable to pilot plant design), while obtaining added research information. The specific purpose of this contract is to establish the effect on performance of (1) fouling of turbine blades, (2) emission of alkalis and sulfur and nitrogen oxides, and (3) bed behavior (clinker formation) at higher temperatures (1,650° F to 1,750° F) than previously used for this type of combustor (1,470° F). The data acquired will be combined with other data on fluidized-bed combustors and will be used as the design basis for a pressurized fluidized-bed combined-cycle plant.

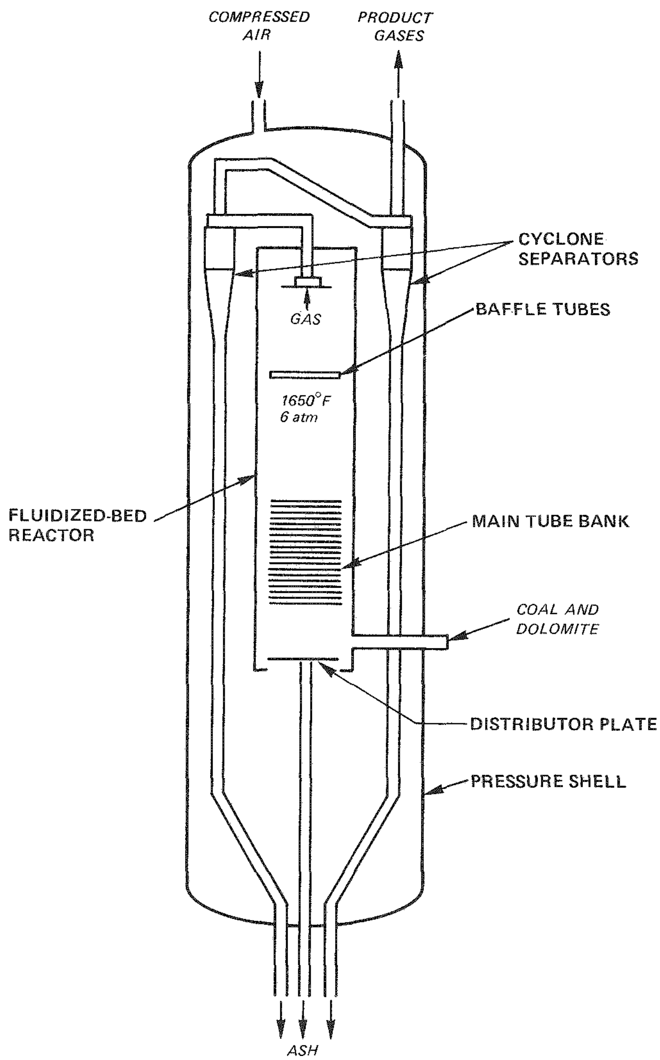


Figure IX-1. NRDC PRESSURIZED FLUIDIZED-BED COMBUSTOR

PROCESS DESCRIPTION

A schematic of the pressurized fluidized-bed combustor being used in the NRDC test program is provided in Figure IX-1. The reactor, the principal component of the unit, has a distributor plate, but also has an immersed bank of water-cooled tubes for regulating the bed temperature. Baffle tubes (without cooling) are placed above the bed surface for fluid dynamic stability. Another important component of the combustor is a two-stage system of cyclone separators. The reactor and separators are enclosed in a pressurized shell (which has an internal diameter of 6 feet) to eliminate stresses that large pressure differentials would generate on the reactor refractory. Pulverized coal, with dolomite added for removal of sulfur compounds, is carried to the base of the fluidized-bed reactor by an air stream. Pressurized air enters the top of the shell, flows around the internal components, and enters the base of the reactor through the distributor plate, where it is used as the fluidizing medium. The product gases are passed through the cyclone separators to remove entrained fines. The gas can then be used in a combined-cycle process.

HISTORY OF THE PROJECT

Early work done by NRDC/BCURA on pressurized fluidized-bed combustion involved 1,000 hours of test runs (1968 to 1971) at a bed temperature of 1,470° F, using Pittsburgh seam and some United Kingdom coals. The results of these tests indicated that turbine erosion and deposition were negligible and that sulfur emissions could be controlled by adding dolomite.

Under the current contract, beginning in August 1972, the combustor was modified to permit it to operate at higher temperatures. Four tests were conducted, with changes in combustor pressure, coal origin (Pittsburgh seam and Illinois), bed temperature (1,650° F and 1,750° F), and sulfur dioxide acceptor (dolomite and limestone). In these experiments, NRDC/BCURA found that:

- Combustion efficiencies exceeded 99 percent at 1,750° F and were only slightly lower at 1,650° F.
- Sulfur emissions for 3 percent sulfur coal could be limited to 0.1 pound per million Btu by adding dolomite at a calcium-sulfur ratio of slightly greater than 2.
- Nitrogen oxide emissions averaged about 0.2 pound per million Btu.
- Deposits on the cascade blades did not occur to a significant extent at bed temperatures of 1,650° F, but were sufficiently extensive at bed temperatures of 1,750° F to be a potential source of operating problems.
- The ash in the bed did not sinter or adhere to the walls under any of the operating conditions investigated.

The main conclusion from these results, with respect to the emission of sulfur and nitrogen oxides, the fouling or corrosion of turbine blades and heat transfer surfaces, sintered accumulations in the bed, and combustion efficiency, is that performance of the combustor when burning Illinois and Pittsburgh seam coals at bed temperatures of around 1,650° F should be as good as the performance achieved in earlier tests at 1,470° F. The ability to operate at higher temperatures in a combined-cycle plant will result in a further saving in fuel (about 2 percent) and an extension in the operating load range that can be achieved by varying the bed temperature.

This test program (Tests 1-4) was completed in September 1973, and NRDC prepared a final report. In late 1974, the program was extended to include a fifth test to investigate fluidized-bed combustion at a bed temperature of 1,650° F and 100 percent excess air, with attention also directed to primary or secondary cyclone depositions and to cascade erosion, corrosion, and deposition. Test 5, completed in 1975, was a 57-hour test using Illinois No. 6 coal at a bed temperature of 1,595° F and an excess air rate of about 90 percent. The combustion and sulfur retention efficiencies of the acceptor achieved in Test 5 were similar to those achieved in earlier tests. Emission of nitrogen oxides was lower than expected, given the high excess air rate, and sulfur emission was somewhat higher than expected, possibly because of experimental scatter, the high excess air rate, or feeding dolomite separately from the coal. The equipment showed no hard deposits in the primary cyclone, but some erosion of the refractory in the cyclone. Whether the lack of deposits resulted from operating conditions different from those in previous tests (mainly more excess air) or the modifications of the design could not be determined.

Late in 1975, the contract was expanded to include three additional fluidized-bed combustion tests. These tests will investigate the effect of different bed depths (4 and 8 feet), excess air rates (20 and 100 percent), and fluidizing velocities (2.5 and 7 feet per second) on (1) fouling, erosion, and corrosion of a static cascade of turbine blades and of target rods; (2) emissions of sulfur dioxide, alkali, and nitrogen oxides; (3) bed behavior as regards clinker formation; and (4) combustion efficiency. Work to modify the combustor was started.

PROGRESS DURING JANUARY-MARCH 1976

Modification of test equipment continued throughout the quarter, and included:

- Fabrication of the combustor casings and installation of refractory in the casings that make up the end walls of the combustor (i.e., those that do not support the tube bank). The simulated tube wall for measuring heat transfer rates was also installed.
- Dismantling of the existing combustor in preparation for incorporating the new tube bank. The new tube circuits for the main tube bank were delivered and are being installed on the new combustor casings.
- Initiation of a detailed design of the bypass system. Some items for this system are being manufactured.
- Fabrication of a modified start-up burner and testing of the burner at atmospheric pressure in an existing fluidized bed; no problems have arisen and testing with deeper beds will continue.
- Modification of the design of the base of the pressure shell; bids for doing the work were solicited.
- Design and fabrication of a venturi section to be installed downstream of the turbine cascade to measure the quantity of gas passing through the cascade during tests when most of the exhaust gases are bypassing the cascade.
- Completion of a detailed design of the corrosion probes to be inserted in the tube bank, and selection of the alloys to be tested. Two of the probes will be cooled to give metal temperatures of 1,250° F to 1,450° F, while the third probe will operate at bed temperature.
- Replacement of some of the baffle tubes (which reduce "splashing" from the bed) and the freeboard cooling circuits.

X. HIGH-TEMPERATURE DUST CONTROL

CONSTRUCTION ENGINEERING RESEARCH LABORATORY
U.S. DEPARTMENT OF THE ARMY
CHAMPAIGN, ILLINOIS

Contract No. E(49-18)-1782 Total Funding: $80,979

INTRODUCTION

Under the sponsorship of ERDA, Construction Engineering Research Laboratory (CERL), U.S. Department of the Army, is to evaluate the efficiency of a Particle Precipitating Heat-Transfer Surface (PPHTS) device for removing dust particles from the high-temperature exhaust gas stream of a fluidized-bed combustor. The fluidized-bed combustor to be used in this project is a modified coal-fired boiler plant owned by ERDA. This plant is currently being operated for ERDA by Pope, Evans and Robbins, Inc. (PER), at a government-owned test facility in Alexandria, Virginia.

PROGRAM DESCRIPTION

The PPHTS evaluation project, initiated in July 1975, is to be completed in mid-1976. This project comprises several tasks:

- Design of the test apparatus and PPHTS test sections.
- Procurement of the necessary components and fabrication and installation of the apparatus.
- Calibration of the automatic particulate analyzer, flow monitoring apparatus, and pressure and temperature transducers.
- Development of procedures for data acquisition and reduction.
- Provision of assistance to PER during operation of the combustor in acquisition of the necessary data and performance of subsequent data analyses and summaries.

Design of the test apparatus was completed in August 1975. The apparatus will be placed on the roof of the Alexandria test facility and will connect to the exhaust gas stream of the fluidized-bed combustor. The configurations of the test sections include four collector rod angles (at constant rod shape) and two additional rod shapes (at constant rod angle to the gas stream). The six different sections will be tested in sequence. Each of the six tests will be conducted for 2 weeks.

The general experimental design was established. The experiments will involve measuring the dust load entering the test section and the amount of dust captured by the PPHTS collector rods in the test section. The dust load and velocity of the flue gas stream will be measured using a venturi meter and a manual stack sampler. (Automatic continuous monitors were in the original design of the test apparatus, but were eliminated to prevent interference with PER's operation of the Alexandria test facility.) The dust will be collected in a dust hopper located below the test section. After each test, collector efficiency, defined as the ratio of the captured-to-incoming dust load, will be calculated. The shape and angle of inclination to the gas stream of the dust collecting rods in the PPHTS device will be varied to determine the effects of angle and shape on collection efficiency.

Procurement of equipment was started late in 1975, and a contract to fabricate dust collecting rods of aluminum was awarded. In addition, scope-of-work statements were prepared for fabrication of the ductwork and the test sections, but the responses to requests for quotations were received late. Because of this delay, the fabrication and installation task was about 2 months behind schedule at the end of the year.

PROGRESS DURING JANUARY-MARCH 1976

Contracts for the fabrication of the ductwork and test sections were awarded at the beginning of the quarter. A contract was also awarded for the erection of the test apparatus on the roof of the ERDA test facility in Alexandria.

The test sections, completed by the end of the quarter, were fabricated of SAE 1020 steel and 6063-T5 aluminum dust collecting rods. The overall dimensions of each section are the same, but the shape of the rods varies, as does the angle that the rods make with the vertical line of the bottom panel.

Ducts were added to the roof of the Alexandria test facility during the quarter. One length of duct connects the discharge end of an induced draft fan to the upstream end of the test section. Another length extends from the downstream end of a test section far enough for uniform flow to exist at the velocity sampling point of the duct. The discharge of the induced draft fan is at the top of the discharge side, the bottom of the duct being about 8 feet off the roof of the lab building adjoining the boiler facility. CERL personnel visited the ERDA fluidized-bed boiler test site at the end of the quarter to test the duct. The boiler plant fluidized-bed module was activated and a high-temperature gas stream with dense smoke was put into the duct by operating a fan on the roof. Five leaks were found and corrected. The control panel for monitors, the pressure top leads, and two duct supports were found to be improperly located; these items have also been corrected.

All equipment, instruments, supplies, test sections, and dust hopper were delivered to the ERDA test facility. The dust hopper, the visible emission monitor, and other equipment were placed into position on the roof.

Several pieces of equipment, including the Lear-Siegler visible emission monitor RM-41 and the Leeds and Northrup dual-pen Mark III chart recorder, were operationally checked at CERL. The Lear-Siegler velocity monitor FM-10, received late, was checked in the field and found satisfactory. The mass emission rate computer from Lear-Siegler was back-ordered until May. CERL cancelled the order and will determine mass emission rate by computation. The dust determination assembly was also checked operationally at CERL.

A meeting was held in March between CERL and PER personnel. CERL was informed that PER, under contract to ERDA, plans to replace old equipment in the ERDA boiler facility. Fly ash tests will be performed thereafter, through August.

XI. APPLICATIONS OF FLUIDIZED-BED COMBUSTION TECHNOLOGY TO INDUSTRIAL BOILERS

EXXON RESEARCH AND ENGINEERING COMPANY
LINDEN, NEW JERSEY

Contract No. E(49-18)-1798 Total Funding: $100,000

INTRODUCTION

Several coal conversion technologies, including direct combustion of coal in a fluidized-bed boiler, coal liquefaction, and coal gasification, are currently being developed. When implemented on a commercial scale, these technologies will greatly increase the utility of coal as a highly acceptable source of industrial energy. Of these technologies, fluidized-bed combustion offers the possibility of near-term implementation. Therefore, Exxon Research and Engineering Company is conducting a research project to study the diverse industrial applications of fluidized-bed combustion technology. This project is being sponsored jointly by ERDA, EPA (EPA Contract No. D5-E-767), and the Federal Energy Administration (FEA) (FEA Contract No. CO-04-50168-00).

The objective of this study is to conduct economic, energy, and environmental analyses of the industrial applications of atmospheric and pressurized fluidized-bed technology as a method of using coal to generate electrical power and process steam for in-plant use. Some advantages anticipated with fluidized-bed combustion technology are improved pollution control, high thermal efficiencies, reduced capital and operating costs, and the ability to use a wide variety of coal types. Fluidized-bed combustion systems are expected to surpass air quality standards for stationary source emissions.

PROGRAM DESCRIPTION

Accomplishment of the objective of this project, started in January 1975 and to be completed in June 1976, requires consideration of both new and retrofitted atmospheric fluidized-bed boilers with steam output capacities ranging from 10,000 to 500,000 pounds per hour. The effects of fluidized-bed combustion technology on each industrial sector as well as the composite for all industries and on each geographic region as well as the entire nation are being studied for 1978, 1980, 1982, 1985, 1990, 1995, and 2000. The project comprises several tasks:

- Determination of the applicability of fluidized-bed combustion technology for meeting industrial boiler requirements based on life-cycle cost, energy conversion efficiency, reliability, maintainability, stack gas emissions, waste disposal and utilization, required plant characteristics, fuel flexibility, and installation and operational problems.
- Development of estimates and confidence limits for the maximum degree of industrial application based, as a minimum, on

fluidized-bed combustion technology characteristics, industrial sector specifications for boilers, boiler age distribution, and boiler replacement data.

- Assessment of the demand for fluidized-bed combustion technology, including consideration of the cost of fluidized-bed combustion systems, prices of various fuels and their availability by region and by industry, capital availability, equipment production capabilities, environmental acceptability, industrial propensity to switch to new boiler design, competing technologies, and solid waste characteristics with respect to disposal and utilization. The assessment is to provide the sizes, numbers, and types of fluidized-bed boilers that will be required by industry type and region to satisfy the maximum, minimum, and most realistic projected demand.
- Determination of the impact that demand for and application of industrial fluidized-bed combustion technology will have on total national energy consumption and on reduction of fuel oil and natural gas consumption.
- Analysis of economic data, capital requirements, and operating costs of each component of the fluidized-bed combustion systems; calculation of the economic implications of fluidized-bed combustion applications; and comparison with the costs of other alternatives, such as the use of clean fuels in a conventional boiler.
- Determination of the effect of industrial fluidized-bed technology applications on air emissions, solid waste production, and effluents to water, and comparison with the environmental effects of other technologies and other fuels and industrial power and steam sources.
- Determination of specific technical requirements for representative industrial fluidized-bed boilers, based on the demand, economic, environmental, and technical analyses.

The analyses completed during 1975 indicate that the potential for fluidized-bed combustion of coal was concentrated in the chemicals, paper, petroleum refining/petrochemicals, and food industries. Estimates of the demand for boiler fuels showed that, in current manufacturing uses, the maximum potential will be nominal in 1980 but could reach 5×10^{15} Btu per year in 2000. This quantity is equivalent to 2.3 million barrels per day of oil or about 40 percent of the total industrial demand for boiler fuels. Current uses and additional potential uses associated with new applications of fluidized-bed combustion and with a higher level of in-plant generation of electricity could reach a combined maximum potential of about 8×10^{15} Btu per year.

Engineering and cost analyses for industrial boiler systems having a steam output of 100,000 pounds per hour indicate that:

- Much of the higher cost of burning coal instead of oil is due to the extensive fuel-handling and waste-handling facilities required for coal.
- Meeting environmental standards with high-sulfur fuels is much more costly than burning low-sulfur fuels; the cost of a flue gas scrubber and waste disposal system exceeds the cost of a boiler.
- Fluidized-bed combustion of high-sulfur coal is economically competitive with conventional combustion of the same coal in conjunction with stack gas scrubbing; future technological improvements could reduce the cost of the fluidized-bed boiler system significantly.
- Fluidized-bed combustion does not appear to be economically competitive with conventional coal combustion in areas where low-sulfur coal is readily available without excessive transportation costs.
- Larger boiler capacities favor fluidized-bed combustion since it may be possible to ship factory-assembled units with steam output of up to 250,000 pounds per hour; conventional coal-fired boilers of this capacity must be assembled in the field at a significant increase in cost.

Engineering and cost analyses for industrial boiler systems having steam outputs of 50,000, 200,000, and 400,000 pounds per hour were also completed. Based on high investment costs for coal versus oil and the distribution of boiler sizes in the industrial boiler population, a boiler with a steam output of 100,000 pounds per hour is about the smallest boiler size for which a general program to substitute coal for gas and oil will be viable from overall considerations. In general, the potential for coal-fired fluidized-bed combustion technology will be enhanced as the average size of boiler increases, i.e., the technology will be more applicable to industries that require large boilers.

Several areas of fluidized-bed combustion technology were identified in which real or apparent problems exist, principally, the availability of suitable limestone, disposal of waste solids, maintenance of desired particle size distribution in the fluidized bed, and retrofitting of fluidized-bed combustion systems to existing industrial boilers. Economically, the outlook for limestone availability and solid waste disposal is favorable, but a low-cost solution is needed to control buildup of oversized particles in the fluidized bed. Retrofitting is economically unattractive in most cases. Definite advantages of coal-fired fluidized-bed technology include reliability of the fuel supply, versatility of the technology, flexibility with respect to coal type, and ability to control nitrogen oxide emissions.

PROGRESS DURING JANUARY-FEBRUARY 1976

Economic, Energy, and Environmental Analyses

The requirements for classifying or screening hot bed materials are being studied. Exxon has confirmed that solids handling is one of the most important areas in the development of coal-fired fluidized-bed combustion technology.

The commercial potential for retrofitting coal-fired fluidized-bed combustion technology is being reevaluated. Initially, the working concept of boiler retrofitting was in terms of equipment that could be fitted onto or into an existing boiler. A broader definition, embracing conversion, rebuilding, substitution, etc., may be used instead, however. This broader definition would shift the basis for assessment of commercial potential from a question of feasibility to one of economic practicability.

The incremental cost of adding a single new oil- or coal-fired boiler to an existing boiler system was calculated. The results are summarized in Table XI-1. Generally, the results show that, if a new boiler is added to an existing coal-fired boiler plant, the use of existing facilities for coal receiving and storing makes a significant reduction in steam cost. Fuel for a fluidized-bed combustor, however, would be segregated from coal for the existing boilers, which puts fluidized-bed combustion at a slight disadvantage from conventional firing at sizes below about 400,000 pounds of steam per hour.

Proposed legislation covering the use of petroleum and coal in large industrial boilers was reviewed. The purpose was to develop a reasonable basis and timetable for coal substitution. This is also the framework on which estimates of the "most likely" and "minimum" potentials for coal-fired fluidized-bed combustion may be constructed. The bill reviewed (S. 1777) provides for a phased conversion to coal of all existing gas- and oil-fired boilers of 100 million Btu per hour firing rate or larger. In the first phase, all new or existing gas-fired boilers unable to burn coal would be required to convert to oil by January 1, 1979. In the second phase, all new or existing

New Boiler	Added to System Consisting of Several Package Boilers Firing Low-Sulfur Fuel Oil												Added to System Consisting of Several Coal-Fired Boilers								
Fuel	Low-Sulfur Coal			High-Sulfur Coal						Low-Sulfur Fuel Oil			Low-Sulfur Coal			High-Sulfur Coal					
Boiler Type	Stoker or Pulverized Coal Fired			Stoker or Pulverized Coal Fired			Fluidized-Bed Combustor			Package			Stoker or Pulverized Coal Fired			Stoker or Pulverized Coal Fired			Fluidized-Bed Combustor		
Environmental Control Facilities	Electrostatic Precipitator			Once-Through Limestone and Particulate Scrubber			Electrostatic Precipitator			None Required			Electrostatic Precipitator			Once-Through Limestone and Particulate Scrubber			Electrostatic Precipitator		
Capacity (1,000 pounds of steam per hour)	100	200	400	100	200	400	100	200	400	100	200	400	100	200	400	100	200	400	100	200	400
Investment (millions of dollars)																					
Boiler and stack	2.2	3.8	6.4	2.2	3.8	6.4	3.7	5.8	9.1	1.4	2.2	3.4	2.1	3.7	6.2	2.2	3.8	6.4	3.7	5.7	9.0
Fuel handling and waste disposal	5.7	7.5	10.1	6.8	9.3	12.9	5.6	7.3	9.6	0.1	0.2	0.3	0.8	1.2	1.8	2.7	4.3	6.7	2.3	3.3	4.7
Total	7.9	11.3	16.5	9.0	13.1	19.3	9.3	13.1	18.7	1.5	2.4	3.7	2.9	4.9	8.0	4.9	8.1	13.1	6.0	9.0	13.7
Unit cost (cents per 1,000 pounds of steam)																					
Direct operating cost, except fuel and feedwater	96	70	53	155	120	100	145	115	95	46	36	[illegible]	60	46	39	124	102	89	123	100	87
Capital charges	201	144	105	228	166	122	236	166	119	38	30	23	74	62	50	124	102	83	152	114	87
Assumed boiler feedwater	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60
Assumed fuel	124	124	124	129	129	129	129	129	129	[illegible]	221	[illegible]	124	124	124	129	129	129	129	129	129
Total	481	398	342	572	475	411	570	470	403	365	347	335	318	292	273	437	393	361	464	403	363

Table XI-1. COSTS OF ADDING SINGLE BOILERS TO EXISTING BOILER SYSTEMS

oil-fired boilers would be required to acquire the capability to use coal, and be using it by 1985. The bill provides FEA with authority to extend deadlines for oil and coal use under certain specified conditions.

A large quantity of statistical information was received from FEA. The data is based on a Natural Gas Task Force survey and a survey of all major fuel burning installations in the United States. The surveys, taken in 1975, give a clear picture of the number (4,000) of large (100 million Btu per hour) industrial boilers, how many have been converted from coal to gas firing, the fuel consumption of these boilers in 1974, the disposition of the steam output, and an indication of how many boilers may be converted (or reconverted) to coal firing in the near future. Exxon is using the data to determine the maximum potential for industrial coal-fired fluidized-bed combustion and to estimate the "most likely" and minimum potentials. In brief, large boilers as a group consumed 3.13 quads (3.13×10^{12} Btu) of petroleum and 1.12 quads of coal in 1974. While this indicates a maximum potential conversion of 3.13 quads, 0.65 quads is the collective opinion of the operators of large boilers. This quantity coincides with the 0.65 quads of reported previous conversion to oil or gas of boilers originally designed to burn coal. The implication is that additional oil and gas can be saved only by installing new coal-fired boilers. Complete tabulations and analyses of the data will be presented in the final report.

The environmental aspects of applying coal-fired fluidized-bed combustion to industrial boilers are being analyzed. Initial results show that, in most cases, the change from gas or oil in industrial heat generation adversely affects the environment. The data is being quantified on a regional and overall basis.

Market Survey

The market survey of companies that have a potential interest in fluidized-bed combustion was started. Forty-seven corporations were contacted to learn their attitudes toward the application of coal-fired fluidized-bed combustion to industrial boilers. All of the companies carry out large-scale, continuous manufacturing operations at several locations, and most are already burning coal. Detailed interviews are being held, and include topics such as:

- Short- and long-range expectations for supplying company's future boiler fuel needs.
- Specific problems that restrict or slow down company's use of coal.
- Company's perception of advantages, disadvantages, and overall outlook for its use of fluidized-bed combustion in boilers.
- Point of fluidized-bed combustion development at which company will be ready to consider installation of a fluidized-bed combustion boiler.

Early feedback from the market survey indicates many companies recognize that boilers will be coal fired in the long range, but have not yet considered how it will be done. Concerns include space to store coal, serious downgrading of steam generating capacity, high cost, and long outage during conversion. Final results of this survey will be published after interviews with all 47 companies have been completed.

XII. R&D PLANNING ASSISTANCE SERVICES

THE MITRE CORPORATION
McLEAN, VIRGINIA

Contract No. E(49-18)-1779 Total Funding: $1,840,000

INTRODUCTION

R&D planning assistance services are being provided by The MITRE Corporation under the sponsorship of ERDA. Under this contract, initiated in December 1974, MITRE is to provide technical and other assistance in the preparation and implementation of national program plans and analyses for R&D in coal-based advanced power and direct combustion systems. Advanced power systems research is directed toward development of power conversion systems that will permit, in an environmentally acceptable manner, efficient and economically competitive generation of electric power using coal and coal-derived fuels. The advanced power systems being considered in this program include open-cycle gas turbines (especially in combined-cycle configuration), closed-cycle gas turbines, and alkali metal vapor turbines. Direct combustion research, including atmospheric (utility, industrial, retrofit) and pressurized (utility, industrial) systems, seeks to develop commercial systems for efficient burning of coal in an environmentally acceptable manner.

PROGRAM DESCRIPTION

Provision of R&D planning assistance services for advanced power and direct combustion systems requires complete systems engineering and technical direction support. This support comprises five tasks:

Task I—Program Planning
- Definition and ranking of system selection criteria
- Trade-off analyses to determine relative merits of the alternative candidates and to place the program plans on a technically and economically defensible base
- Identification and ranking of the substantive technical issues that are key to successful development and implementation
- Support of the program plan by a substantive technical effort, including safety analyses, market penetration studies, cost-benefit analyses, technical risk assessment, scaling studies, test results assessment, etc.
- Updating the program plan to reflect technology advancements, funding level changes, and program decisions, and supporting the plan by development of budget justifications and relevant congressional hearing documents

Task II—Project Planning
- Development of basic R&D action documents
- Support of the project plans by appropriate technical and economic analyses

Task III—Project Implementation Support
- Assistance in management plan formulation

Assistance in development of technical specifications
Assistance in the coordination and integration of projects

Task IV—Program Review Support

Task V—Systems Engineering and Evaluation

Technology assessment, review, and documentation efforts are underway. The subcontractors assisting MITRE in this effort are Battelle Columbus Laboratories, Wittreich Associates, and Strasser Associates.

PROGRESS DURING JANUARY-MARCH 1976

Advanced Power Systems

A draft of the advanced power systems program plan was reviewed and revised so that it would be concise and representative of ERDA's current program. The program plan was drafted in storyboard and milestone chart formats for incorporation into a background document for the workshop on advanced power systems for utility implementation to be held in April. To support effective discussion of issues relating to implementation of advanced power systems, this document describes the substance, rationale, potential benefits, and financial and implementation issues of the program. Activity in preparation for the workshop included structuring the workshop and defining the issues to be addressed by each of four panels, and listing discussion topics to be supplied to panel chairmen. MITRE also completed an up-to-date bibliography of significant documents related to the development of advanced power systems.

Environmental aspects of advanced power systems were analyzed, and a report is being prepared. Technical requirements for particulate emission monitoring were specified informally to ERDA, and an analysis of the water use implications of advanced power systems, particularly in relatively arid regions of the country is being reviewed. Also studies of reliability/maintainability, safety, and technical risk aspects of advanced power systems were completed, and a report is being prepared.

Work on the cost-benefit analysis for advanced power and direct combustion systems continued, using updated fuel price data and revised input data which included the baseline and advanced technology descriptions, fuel price scenarios, nuclear market penetration scenarios, demand scenarios, and capacity factor assumptions. The input data is thus consistent with ECAS Task II results and the most recent ERDA estimates. The four computer programs used in the analysis were improved to reduce running time and cost. The interim results have been transmitted to ERDA.

MITRE responded to a request from ERDA by defining the requirements and beginning the development of a plan for the experimental evaluation of various methods for cooling turbine blades when operating the coal-derived fuels. MITRE contacted General Electric, Westinghouse, United Technologies, and Curtiss-Wright to enlist their support.

A survey of the research and development activity related to gas turbines was completed and the final document transmitted to ERDA. A working paper summarizing the status of the large utility gas turbine industry is being compiled. MITRE also evaluated gas turbine combustors operating on coal and coal-derived fuels, and analyzed the application of combustor technology to the advanced power systems program.

An analysis was done illustrating the sensitivity of the cost of electric power to efficiency, load factor, capital cost, construction time, and useful plant life. A document on this is being prepared.

MITRE assisted ERDA by reviewing and revising a program plan for evaluating, developing, and applying coal cleaning technology to advanced power systems. Other work during this quarter involved assisting in the coordination and monitoring of a joint ERDA/DOD study on ceramics technology. This work included attending various meetings relating to ceramics technology. MITRE also reviewed a draft of the work statements for a proposed RFP for the development of a primary heat exchanger for a closed-cycled gas turbine. Reports and related data on closed-cycle gas turbine systems components, cycle analyses, and working fluid characteristics were reviewed.

With the help of Battelle Columbus Laboratories, MITRE completed an analytical review of the performance and cost aspects of the ECAS Task I results. The review indicated some inconsistencies in ECAS component cost estimates, potentially important cycle configurations that were not considered for the closed-cycle systems, and several modified closed-cycle configurations that appear to offer significant improvements over ECAS cases and should be examined.

Direct Combustion Systems

During this quarter, MITRE worked on the program plan of the national fluidized-bed combustion program, incorporating comments from Foster-Wheeler and the Electric Power Research Institute. Milestone charts were also reviewed and updated to reflect the project status.

MITRE continued to assist the Morgantown Energy Research Center with engineering for the Component Test and Integration Facility (CTIF). During the quarter, MITRE generated:

- Detailed designs of both direct digital control and electric analog combustion control and diagnostic instrumentation systems.
- Specifications for the combustion control and diagnostic instrumentation system components.
- Cost estimates for the boiler and the combustion control and diagnostic instrumentation systems.
- Cost estimate for the project through the 36-month design and construction phases.
- Environmental assessment for the CTIF site at West Virginia University, which incorporated comments forwarded by ERDA.

MITRE worked to integrate all aspects of the CTIF design, including control systems, diagnostic instrumentation, physical design, design philosophy, and range of operating parameters, to ensure that the CTIF will make the maximum contribution to the national fluidized-bed combustion program. Arrangements were made for the construction of a model of the CTIF, which was delivered to MERC in February.

MITRE reviewed the program for staffing and training for the multicell fluidized-bed boiler at Rivesville, West Virginia, being developed by Pope, Evans and Robbins (PER). Emphasis was on the duties of PER personnel, development of operating and maintenance manuals and of training programs, and implementation of the staffing and training. MITRE also inspected the facility and reviewed contractor estimates of funding requirements as they related to requirements for personnel, supplies, and equipment. During MITRE's visit to the PER facility, it was decided, based on construction status, that light-off of the carbon-burnup cell might be possible in early July 1976. Two potential problems might force a delay, however: piping for several boiler subsystems and delivery of the forced-draft auxiliary fan.

MITRE assisted ERDA in reviewing the granular-bed filter program of the Combustion Power Company. It was decided to convene a panel to review the developmental program history, review existing and proposed design plans, and assess the likelihood of success of the granular-bed filter in removing particulates from hot gas streams.

XIII. TECHNICAL AND ENGINEERING SERVICES

GILBERT ASSOCIATES, INC.
READING, PENNSYLVANIA

Contract No. E(49-18)-1236 — Total Funding: $2,095,000

INTRODUCTION

Under contract with ERDA, Gilbert Associates, Inc., is providing technical and engineering services in support of a program to find clean and efficient methods for utilizing coal to produce electric power. Some of these services are in direct support of programs involving fluidized-bed combustion of coal with in situ sulfur removal using limestone. (Gilbert Associates also provides services in support of programs involving combined-cycle systems using low-Btu fuel gas and magnetohydrodynamics.) ERDA's electric power program will culminate in the operation of demonstration plants that utilize advanced power systems for the clean generation of electricity from coal.

PROGRAM DESCRIPTION

Initiated in November 1972, this program is oriented to surveying the progress of novel and advanced power systems technology and providing ERDA with additional technical expertise to evaluate the feasibility and economics of the various electric power systems. Much of the effort involves:

- Identifying proven methods and components that could be used in pilot plants wherever practical.
- Identifying major equipment under development that should be designed for flexibility of operation to permit the investigation of variations in process conditions.
- Recommending to ERDA independent subcontracts that should be initiated to develop components and subsystems that may significantly improve the performance and economics of electric power plants.

Gilbert Associates representatives provide technical assistance in monitoring work performed on power systems contracts by reviewing progress reports and evaluating proposals for expansion or modification of development work as required to expedite progress and optimize results. Gilbert Associates also helps coordinate appropriate technical information among contractors involved in similar technical disciplines and helps perform technical and economic studies as directed by ERDA. Recommendations are presented to ERDA for action.

PROGRESS DURING JANUARY-MARCH 1976

Technical and engineering services to support ERDA continued throughout the quarter. Late in the quarter, a new contract—Contract E(49-18)-2220—was signed, extending and expanding the work being done under Contract E(49-18)-1236. The specific objectives of the new contract are to provide ERDA with:

- In-depth design, economic, and environmental engineering and technical consulting support to assure the effectiveness of ERDA programs to develop clean, commercially attractive processes for converting coal to electric power and other forms of energy required by industry.
- Operational support, including systems and project engineering services for ERDA's program management activities of organizing, planning, directing, and evaluating individual projects, as well as the total program.

Fluidized-Bed Combustion

Gilbert assisted ERDA with the Pope, Evans and Robbins (PER) multicell fluidized-bed boiler, focusing specifically on providing technical surveillance, project management consultation, and construction surveillance. In the area of technical surveillance, Gilbert assisted in the preparation of a project briefing presented to ERDA, attended weekly construction meetings and monthly progress meetings, and developed the critical path method network for all mechanical, electrical, and instrumentation systems. The management consulting aspect of Gilbert's work included developing the preliminary schedule to establish a date for completing construction, reviewing the operator training program, and submitting biweekly reports to ERDA on the status of the project.

Technical surveillance of the Combustion Power Company's pressurized fluidized-bed combustion process development unit was resumed after the granular-bed filter failed. Gilbert's work in this area consisted primarily of participating in a failure analysis and proposal of design modifications to permit restart of the unit with minimum delay. A report was prepared reviewing the findings of other consultants and evaluating the structural design of the filter. Gilbert assisted the Morgantown Energy Research Center (MERC) with the preparation of a conceptual design and cost estimate for the Component Test and Integration Facility (CTIF) for studying atmospheric fluidized-bed combustion. Work during the quarter focused on the steam and water system facility. The documentation of the piping schematic, equipment list, and cost estimates for this system was completed, and effort continued on the design of the air distributor plate. Also, discussions were held with ERDA technical consultants concerning the correlation and prediction of the pressure drop across the punched-plate, perforated grid; recommended technique of pressure drop data analysis; and calculations using PER test data.

Cleanup Systems

In a study of new sorbents for fluidized-bed combustion and regeneration of these sorbents, a literature search was done to determine the feasibility of using new metallic oxide sorbents for sulfur dioxide absorption.

A survey of high-temperature and high-pressure particulate-removal systems for combustion gases focused on the unique cleanup requirements of combustion gases versus those of gaseous fuels for application to gas turbines, and on high-temperature filter materials. The development of new materials was discussed with filter manufacturers.

The criteria for cleaning coal, the effect of various cleanup methods on combustion characteristics, and the concentration of impurities in the combustion gases were reviewed. As part of this work, Gilbert conducted a literature search on coal additives for minimizing the concentration of trace metals, nitrogen oxides, and other impurities in the combustion gases. Particulate measurement technology in combustion gases was reviewed, including a comparative evaluation of various light-scattering instruments.

XIV. BOILER TUBE BUNDLE AND BURNER MODULE TESTS WITH POTASSIUM

OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE

INTRODUCTION

An important step that can be taken to reduce fuel consumption is to increase the efficiency of thermodynamic cycles. (There has been no increase in efficiency since about 1950 because, at that time, the upper practicable temperature limit for the steam cycle (about 1,000° F) was reached.) Thermodynamic efficiency is directly related to the absolute temperatures at which heat enters and leaves the process. Thus, to increase thermal efficiency further, temperatures must be higher, which implies the use of other working fluids. A leading candidate for an advanced thermodynamic cycle is a potassium or cesium vapor cycle. Oak Ridge National Laboratory (ORNL) is conducting tests of a boiler tube bundle module and burner assembly with potassium, under proposal U50048PA.

The approach proposed by ORNL entails raising the peak temperature of the thermodynamic cycle by employing a potassium vapor Rankine topping cycle that operates with a turbine inlet temperature of 1,500° F to 1,600° F and a condenser temperature of about 1,100° F. This topping cycle is superimposed on a conventional steam cycle with a turbine inlet temperature of about 1,000° F by transferring the "waste" heat rejected from the condensing potassium vapor to the boiling water of the steam cycle. The combined cycle is similar to the mercury-steam binary vapor cycle employed in seven plants built in the United States between 1925 and 1948. However, the operating temperature of these plants was limited to 900° F because, at higher temperatures, severe corrosion of all types of steel by mercury made operation impractical. The 900° F mercury turbine inlet temperature was higher than the steam turbine inlet temperature in plants of the 1920s, but by the late 1930s it was surpassed by new steam plants whose higher temperatures and higher thermal efficiencies made the mercury vapor system obsolete.

PROCESS DESCRIPTION

The basic layout of the power plant envisioned is shown in Figure XIV-1. Three basic systems are coupled to form the power plant: a gas turbine that uses exhaust gases from the combustion chamber, the potassium vapor topping cycle, and an essentially standard steam cycle. Energy from hot gases produced by the combustion process is extracted by all three systems, for conversion to electricity in the generator. The most important components involving new technology are the

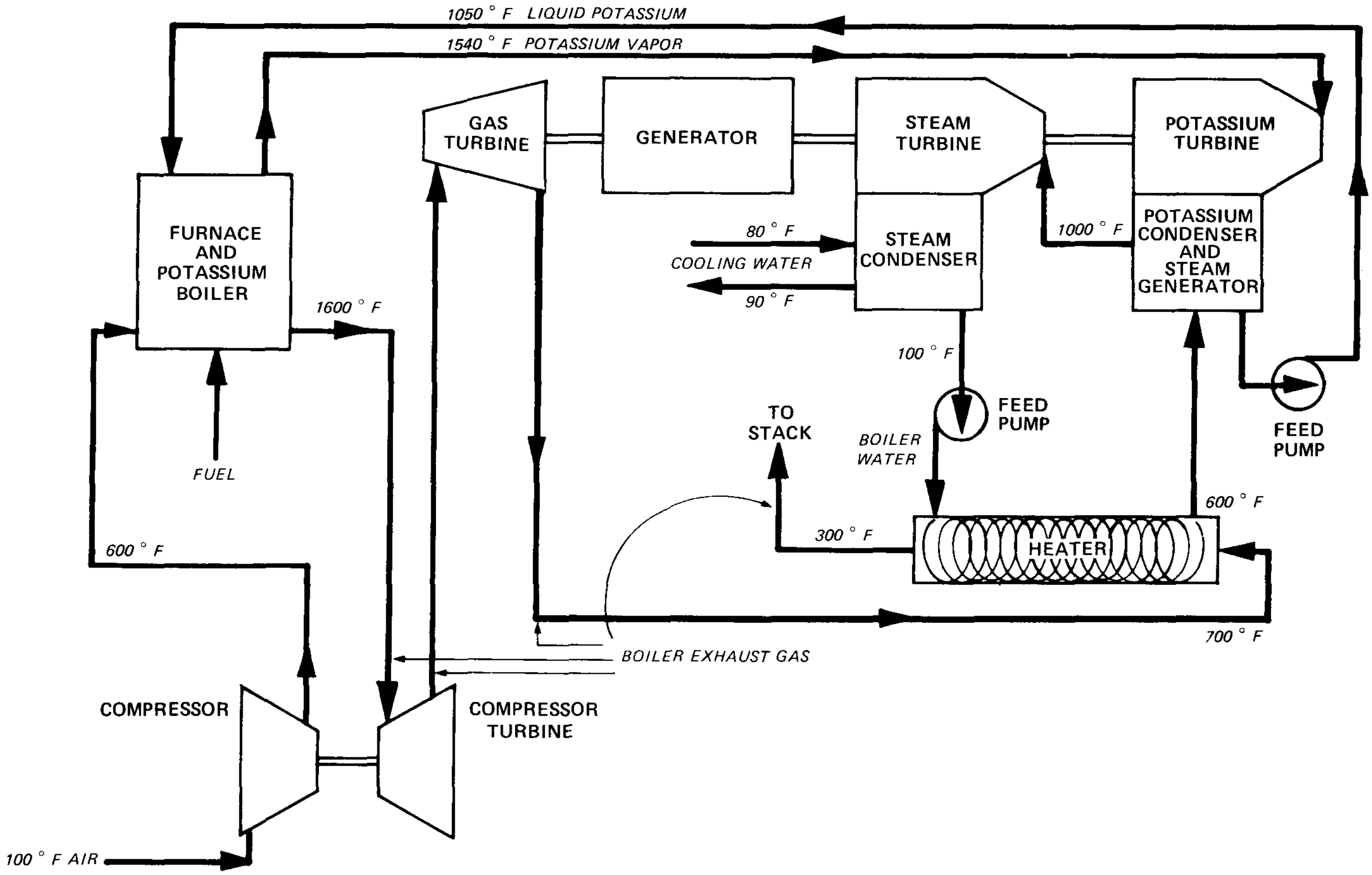


Figure XIV-1. SCHEMATIC OF POTASSIUM VAPOR COMBINED-CYCLE SYSTEM

furnace-potassium boiler and the potassium condenser-steam generator, both of which employ tube bundle modules as their basic unit of construction.

The ORNL gas- or oil-fired potassium boiler concept employs a basic tube bundle module that consists of two annular rows of 1-inch-diameter stainless steel tubes arranged around a 22-inch-diameter, long, vertical, cylindrical combustion chamber. The flame from the burner directs hot gas upward through this combustion chamber. The tubes are bent at the top to provide flow passages between them so that the hot gas from the top of the combustion chamber can flow radially outward and then downward through an outer annulus over the outer row of tubes. To reduce the amount of heat transfer surface area required, the furnace and combustion chambers would be operated at a pressure of 6 to 10 atm, substantially above the 2 atm which would be the design operating pressure of the potassium vapor system. Potassium would circulate by natural convection from a header tank at the top of the tube bundle through two downcomers, one on either side, to two ring-shaped manifolds at the bottom, and then vertically upward through the tubes back to a header drum and vapor separator at the top of the header tank. About 200 tube bundles of this type, grouped 19 to a furnace shell, would be required in a 600 MW(e) power plant.

The boiler tube bundles would be mounted in 4 to 8 furnace shells. In this layout, the burner assemblies are independently mounted in the bottom head of the furnace shell with individual flanges so that any burner can be removed without disturbing the others. The boiler tube bundles are also independently mounted to a grid at the top, which in effect serves as the top head. The design is such that any tube bundle can be replaced independently of the others by disconnecting it and withdrawing it through either the top or the bottom of the furnace.

The potassium condenser-steam generator unit would be mounted directly beneath the potassium vapor turbine in much the same fashion as steam condensers are mounted under steam turbines. The steam generator tubes would be of the reentry type with feedwater admitted to the bottom of a central tube (about 1/4 inch in diameter) in which it would boil as it rose to the top of the tube. The steam emerging from the top of the inner tube would then flow vertically downward in the annulus between the inner and outer tubes and would emerge at the bottom, superheated to 1,000° F. Potassium vapor would condense on the outside of the outer tube, and a film of liquid potassium would flow down over the outside of the outer tube to the sump at the base of the condenser. The reentrant tube design was devised to avoid large thermal stresses that might be induced if the temperature difference between the boiling water and the condensing potassium became too large under start-up or transient conditions. These stresses would be accentuated by the high heat transfer coefficients inherent in the boiling of water and condensing of potassium if these processes took place on opposite sides of a single tube wall.

HISTORY OF THE PROJECT

Work on alkali metal vapor cycles at ORNL began with some design studies under the Aircraft Nuclear Propulsion program in 1954 and was resumed in 1958 with studies of nuclear electric space power plants. This led to an extensive series of component and system tests. Boiling potassium systems were operated for about 200,000 hours in the 1960s. When the need for reductions in both fuel consumption and heat rejection to the environment became evident in 1970, a design study of a potassium vapor cycle plant was carried out under sponsorship of the National Science Foundation (NSF). This plant was designed to operate on clean gaseous fuel derived from coal, the preferred fuel of the future for central stations at that time. The study showed that the greatest uncertainties from both design and cost standpoints lay in the potassium boiler, and that these could be resolved best by designing, building, and testing a full-scale tube bundle and burner module. Funds to begin this work were made available by NSF in July 1972, and NSF funding was continued in 1973. When ERDA was proposed in June 1973, however, the responsibility for the potassium vapor cycle work became uncertain. Consequently, the program remained unfunded through 1974 until ERDA was formed, at which time interim funds were made available from NSF. Funds from ERDA became available at ORNL for the program in December 1975.

PROGRESS DURING JANUARY-MARCH 1976

Instrumentation was installed in the potassium boiler tube bundle assembly. The results of initial tests of the burner indicated that the burner pressure drop was much higher than had been estimated by the vendor and, hence, the pressure differential across the inner shroud between the furnace wall and the tube bundle would be so high that the shroud might buckle. This should not be a problem in the tests with water because the shroud temperature should be low enough so that creep buckling will not be a serious problem, but tests with potassium might yield shroud operating temperatures high enough so that creep buckling could occur. To ease this problem, it was decided to remove the aspirator arrangement for recirculating exhaust gas (to reduce nitrogen oxide concentrations).

Some difficulty was encountered in the fitup of the shroud in attempting to slip it over the tube bundle. This apparently occurred as a consequence of warpage during the welding operations on the shroud. This required some difficult straightening operations which were completed successfully. The boiler, shroud, and furnace assembly are now ready for installation and testing. The burner was installed on the test stand, and shakedown and performance tests on the open burner was started. Tests are intended to establish the general performance of the burner, particularly during start-up conditions. Special attention is being given to instrumentation designed to assure safe operation of the burner and also measurements of flame temperature and the flame temperature distribution.

The possibility of chloride corrosion of the boiler during tests with water led to the decision to install a sampling mechanism to assure a high level of water purity during the tests with water. The drawings for this installation have been completed, and fabrication has been scheduled.

GLOSSARY

The intent of this glossary is to give a general definition of terminology as used in this report. A glossary is considered desirable because of the diverse origin of the technology and broad spectrum of potential readers. For more precise and detailed definitions, the reader is referred to *The Annual Book of ASTM Standards* published by the American Society for Testing Materials (ASTM), *Chemical Engineers' Handbook* by R. H. Perry and C. H. Chilton, and *A Dictionary of Mining, Mineral, and Related Terms* published in 1968 by the U.S. Department of the Interior.

Å – Angstrom unit, a unit of length equal to 10^{-10} meters or 10^{-4} microns, generally used as the unit for describing interatomic distances; as an example, the carbon atoms in diamond are 1.5 Å apart.

absorption – the dissolution of a gas in a liquid.

acceptors – calcined carbonates that absorb carbon dioxide evolved during gasification, exothermically.

acid-gas removal – a section of a gas plant where hydrogen sulfide and carbon dioxide are removed from the gas stream.

activated carbon – carbon obtained by carbonization in the absence of air, preferably in a vacuum; has the property of absorbing large quantities of gases, solvent vapors; used also for clarifying liquids.

adiabatic – any process where heat is neither given off nor absorbed.

adsorption – the physical and chemical adherence of a gas to the surface of a solid.

agglomerate – assemblage of ash particles rigidly joined together, as by partial fusion (sintering).

anode carbon – carbon of high purity, usually crystallized to graphite form, widely used in Leclanche cells, in rods for alumina refining, in electric arcs and nuclear reactors.

anthracite coal – any coal containing 86 to 98 percent fixed carbon, on a dry, mineral-matter-free basis.

aromatic hydrocarbon – an unsaturated cyclic hydrocarbon containing one or more six-carbon rings.

ash – theoretically, the inorganic salts contained in coal; practically, the residue from the combustion of dried coal that has been burned at 1,380° F.

autoclave – a vessel, constructed of thick-walled steel (alloy steel or nickel alloys), for carrying out chemical reactions under pressure and at high temperatures.

bench-scale unit – a small-scale laboratory unit for testing process concepts and operating criteria as a first step in the evaluation of a process.

binder – carbon products, tars, etc., used to impart cohesion to the body to be formed; a coal-extract binder may be used to prepare formed-coke pellets from noncoking coals.

bituminous coal – a broad class of coals containing 46 to 86 percent fixed carbon and 20 to 40 percent volatile matter.

blow down – the removal of liquids from a process vessel by the application of pressure.

bottoming cycle – the lower temperature thermodynamic power cycle of a combined-cycle system.

Btu – British thermal unit, the quantity of energy required to raise the temperature of one pound of water one degree Fahrenheit.

BTX – benzene, toluene, xylene; aromatic hydrocarbons; toluene is methyl-benzene, xylene is dimethyl benzene.

caking – the softening and agglomeration of coal as a result of the application of heat.

calcine – to heat a solid to a high temperature to cause the decomposition of hydrates and carbonates.

carbon fiber – very fine filaments about 8 microns in diameter which are used in composite materials, being bound with resins.

carbonization – the destructive distillation of coal in the absence of air accompanied by the formation of char (coke), liquid (tar), and gaseous products.

catalyst – a substance that accelerates the rate of a chemical reaction without itself undergoing a permanent chemical change.

centrifuge – an apparatus rotating at high speed to separate solids from liquids, e.g., undissolved residue from coal solution in the SRC process.

char – the solid residue from coal after the removal of moisture and volatile matter, i.e., essentially ash plus fixed carbon.

Claus process – a process for recovering elemental sulfur from hydrogen sulfide gas, utilizing a brick-work kiln, at high temperatures with oxygen reacting with the hydrogen sulfide to yield dry sulfur and steam.

closed cycle – a thermodynamic power cycle in which the working fluid is recycled.

coal – a natural solid material consisting of amorphous elemental carbon with various amounts of organic and inorganic compounds.

coke – a solid consisting primarily of amorphous carbon having certain properties of strength, cell structure, and minimum impurities, and manufactured by the thermal decomposition of petroleum residues and certain types of coal.

coke breeze – coke particles smaller than 1/2 inch in size.

combined cycle – two sequential thermodynamic power conversion systems operating at different temperatures.

combustion gas – gas formed by the rapid oxidation of coal, e.g., burning.

combustor – a vessel in which combustion of gaseous products from a fuel takes place by the chemical union of oxygen with the gas.

coupon – a polished metal strip used to measure the rate of corrosion of the metal in a specific gaseous or liquid environment.

cracking – the partial decomposition of high-molecular-weight organic compounds into lower-molecular-weight compounds, generally as a result of high temperatures.

crude gas – gas produced in a gasifier containing a wide range of impurities, also known as offgas.

cyclone separator – essentially a settling chamber to separate solid particles from a gas, in which gravitational acceleration is replaced by centrifugal acceleration.

degasification – a process for draining naturally occurring methane from coal seams.

delayed coking – a process whereby coal is subjected to a long period of carbonization at moderate temperatures to form metallurgical coke.

demineralization – removal of mineral matter (ash) from coal by solvent extraction, usually under hydrogen atmosphere.

demonstration plant – a plant whose design is based on data derived from pilot-scale testing, of sufficient capacity to demonstrate the large-scale feasibility of a process.

depolymerization – the change of a large molecule (e.g., coal polymers) into simpler molecules (e.g., aromatics, BTX), usually accompanied by the substitution of hydrogen for oxygen.

destructive distillation – the distillation of coal or other solids accompanied by their decomposition; destructive distillation of coal yields coke, tar, ammonia, gas, etc.

desulfurization – the removal of sulfur from hydrocarbonaceous substances by chemical reactions. Various processes are Claus, Appleby-Frodingham, C.S.I.R.O., ferric chloride leaching, Kennecott.

devolatilization – the removal of a proportion of the volatile matter from medium- and high-volatile coals to prevent subsequent caking.

dissolution – the taking up of a substance by a liquid with the formation of a homogeneous solution.

distillation – a process of evaporation and recondensation used for separating liquids into various fractions according to their boiling points or boiling ranges.

dolomite – a mineral having the chemical formula $CaMg(CO_3)_2$, i.e., a carbonate of calcium and magnesium.

Dowtherm – trademark for a series of eutectic mixtures of diphenyl oxide and diphenyl used as high-temperature heat-transfer fluids.

ebullated bed – a boiling bed; gas, containing a relatively small proportion of suspended solids, bubbles through a higher density fluidized phase with the result that the system resembles a boiling liquid.

economizer – a heat exchanger for recovering heat from flue gases and using it to heat feedwater or combustion air.

effluent gas – gas issuing from a gasifier or combustor.

electrode carbon – see anode carbon.

elutriation – the preferential removal of the small constituents of a mixture of solid particles by a stream of high-velocity gas.

endothermic – a process in which heat is absorbed.

enthalpy – a form of thermal energy defined as the sum of the internal energy of a system plus the product of the system's volume and pressure.

entrained bed – a bed in which solid particles are suspended in a moving fluid and are progressively carried over in the effluent stream.

entrained flow – see entrained bed.

eutectic – that combination of two or more components which produces the lowest melting temperature.

exothermic – a process in which heat is liberated.

extraction – a process for dissolving certain constituents of a mixture by means of a liquid with solvent properties for selected components only.

extraction-hydrogenation – extraction carried out in the presence of hydrogen either as a gas or derived by transfer from hydrogen donor solvents.

extractive coking – similar to delayed coking process, with the emphasis on high tar yields to produce liquids.

filter cake – the moist residue remaining from the filtration of a slurry to produce a clean filtrate.

filtrate – a liquid free of solid matter after having passed through a filter.

filtration – the separation of solids from liquids by passing the mixture through a suitable medium, e.g., cloth, paper, diatomite.

Fischer assay – an assay for the determination of oil (tar) yields from coal or oil shale; conducted in a retort under an inert atmosphere with a gradual increase in temperature.

Fischer-Tropsch catalyst – iron and cobalt catalysts developed by Fischer and Tropsch for the catalytic synthesis of liquid fuels from coal-derived synthesis gas.

fixed bed – solid particles in intimate contact with fluid passing through them, but too slowly to cause fluidization.

fixed carbon – theoretically, the carbon content of coal which exists in the elemental state; practically, the difference between 100 percent and the sum of ash, moisture, and volatile matter percentages.

flash carbonization – a carbonization process characterized by very short residence times of coal in the reactor to optimize tar yields; also called flash pyrolysis.

flue gas – gas issuing from a combustor; either exhausted to atmosphere or expanded through a gas turbine.

fluidization (dense phase) – the turbulent motion of solid particles in a fluid stream; the particles are close enough as to interact and give the appearance of a boiling liquid.

fluidization (entrained) – solid particles transported by a high-velocity fluid stream with little or no solid interaction.

fluidized bed – a bed through which a fluid is passed with a velocity high enough for the solid particles to separate and become freely supported in the fluid.

fly ash – a fine ash from the pulverized coal burned in power station boilers, or entrained ash carried over from a gasifier.

fractionation – distillation process for the separation of the various components of liquid mixtures; an effective separation can only be achieved by the use of fractionating columns attached to the still; also called fractional distillation.

freeboard – the space in a fluidized-bed reaction between the top of the bed and the top of the reactor.

free swelling index – a standard test that indicates the caking characteristics of coal when burned as a fuel.

Freidel Crafts catalyst – the catalyst employed in the synthesis of benzene hydrocarbons by the action of alkyl halides on aromatics in the presence of anhydrous aluminum chloride.

fuel cell – a galvanic cell in which the oxidation of a fuel (e.g., coal) is utilized to produce electricity.

fuel gas – low heating value product generally utilized on-site for power generation or industrial use.

gasification of coal – the conversion of solid coal into a gaseous form by any of a variety of chemical processes.

gasifier – a vessel in which gasification occurs usually utilizing fixed-bed, fluidized-bed, or entrained-bed units.

high-Btu gas – a gas, largely methane, having a heating value of 900 to 1,000 Btu per cubic foot, which approaches the value for natural gas.

high heating value (HHV) – the heat liberated during a combustion process in which the product water vapor is condensed to a liquid.

hydrocoking – coking of tars, SRC, etc., under hydrogenating conditions to form liquid products.

hydrocracking – the combination of cracking and hydrogenation of organic compounds.

hydrocyclone – a small cyclone extractor for removal of suspended solids from a flowing liquid by means of the centrifugal forces set up when the liquid is made to flow through a tight conical vortex.

hydrogasification – gasification that involves the addition of hydrogen to the products of primary gasification to optimize formation of methane.

hydrogenation – chemical reactions involving the addition of hydrogen, present as a gas, to a substance in the presence of a catalyst under high temperatures and pressures.

hydrogen donor solvent – solvent, such as anthracene oil, tetralin (tetrahydronaphthalene), decalin, etc., which transfers hydrogen to coal constituents causing depolymerization and consequent evolution of liquid products of lower boiling range which are then taken up by the solvent.

hydrotreating – a process involving the reaction of hydrogen with hydrocarbon mixtures for the removal of such impurities as oxygen, nitrogen, and sulfur.

ideal gas – any gas whose equation of state is expressed by the ideal gas law, namely PV=RT where P is the pressure, V is the volume of one mole, R is the gas constant, and T is the absolute temperature.

ignition temperature – the minimum temperature necessary to initiate self-sustained combustion of a substance.

industrial gas – see fuel gas.

inerts – macerals in coal not readily changed by the action of solvents in the solvent extraction of coal, e.g., fusinite.

in situ – in its original place, e.g., underground gasification of a coal seam.

intermediate-Btu gas – synthesis gas product with an HHV between 250 and 500 Btu per standard cubic foot, consisting mainly of carbon monoxide and hydrogen.

lignite – a low rank of coal between peat and subbituminous.

limestone – a sedimentary rock composed mostly of calcium carbonate ($CaCO_3$) and possibly some magnesium carbonate ($MgCO_3$).

liquefaction – conversion of a solid to a liquid; with coal this invariably involves hydrogenation to depolymerize the coal molecules to simpler molecules.

liquefied petroleum gas (LPG) – those hydrocarbons that have a vapor pressure (at 70° F) slightly above atmospheric (such as propane and butane); kept in liquid form under a pressure higher than 1 atm.

lock hopper – a mechanical device that permits the introduction of a solid into an environment of different pressure.

low-Btu gas – a gas having a heating value of 150 to 350 Btu per cubic foot; when made from coal, water, and air, it contains varying quantities of carbon monoxide, carbon dioxide, nitrogen, hydrogen, and methane.

MAF – moisture- and ash-free; a term that relates to the organic fraction in coal; "moisture- and mineral-matter free" is equivalent.

methanation – the production of methane (CH_4) from a mixture of carbon monoxide and hydrogen.

micron – a unit of length equal to one millionth of a meter.

natural gas – naturally occurring gas extracted from sedimentary structures consisting mainly of methane and having an HHV to 1,050 Btu per standard cubic foot.

noncoking – a coal that does not form coke under normal coking conditions.

olefinic hydrocarbon – a class of unsaturated hydrocarbons containing one or more double bonds and having the general chemical formula C_nH_{2n}.

open cycle – a thermodynamic power cycle in which the working fluid passes through the system only once and is then exhausted to the atmosphere.

perfect gas – see ideal gas.

petrochemicals – those derived from crude oil or natural gas, or their coal-derived substitutes; they include light hydrocarbons such as butylene, ethylene and propylene, the raw materials for the production of plastics by polymerization.

phenols – a group of aromatic compounds having the hydroxyl group directly attached to the benzene ring. They give the reactions of alcohols, forming esters, ethers, and thiocompounds; phenols are more reactive than the benzene hydrocarbons; derived from coal tar.

pilot plant – a chemical process plant containing all the processes of a commercial unit, but on a smaller scale, for the purpose of studying the process.

pipeline gas – a methane-rich gas that conforms to certain standards and having an HHV between 950 and 1,050 Btu per standard cubic foot. Standards include minimum water content, minimum inert gases, minimum hydrogen and carbon monoxide content and compressed to 1,000 psig.

precoat – layer of suitable filtering medium, e.g., diatomaceous earth, laid down on a rotary filter cloth prior to operation.

prilling tower – a tower that produces small solid agglomerates by spraying a liquid solution in the top and blowing air up from the bottom.

process development unit – a laboratory-sized system used to study the effects of process variables on performance.

proximate analysis – analysis of coal based on the percentages of moisture, volatile matter, fixed carbon, and ash.

purification – removal of the wide range of impurities present in gases from coal gasification to yield purity gas. See Rectisol process.

pyrolysis – thermal decomposition of organic compounds in the absence of oxygen.

quenching – cooling by immersion in oil or water bath or spray.

Raney nickel catalyst – nickel sponge used as a catalyst in the hydrogenation of organic materials and the methanation of synthesis gas to methane.

raw gas – see crude gas.

reactivity – susceptibility to chemical change; in coal conversion, the reactivity of the coal for conversion to liquid products is a function of the MAF volatile matter content and the petrographic composition of the coal.

reactor – vessel in which coal-conversion reactions take place.

Rectisol process – a process for the purification of coal-gasification gas based on the capability of cold methanol to absorb all gas impurities in a single step; gas naphtha, unsaturated hydrocarbons, sulfur, hydrogen sulfide, and carbon dioxide are removed from the gas stream by the methanol at temperatures below 0°C.

reducing gas – used as a reducing agent in redox reactions, e.g., hydrogen, superheated steam.

reforming processes – a group of proprietary processes in which low-grade or low molecular weight hydrocarbons are catalytically reformed to higher grade or higher molecular weight materials; also applies to the endothermic reforming of methane, for the production of hydrogen by the reaction of methane and steam in the presence of nickel catalysts.

refractory – a material capable of withstanding extremely high temperatures and having relatively low thermal conductivities.

residence time – time spent by a typical particle in a reaction zone.

saturated hydrocarbon – a hydrocarbon in which all bonds are single covalent bonds and none are double or triple bonds.

scrubber – apparatus in which a gas stream is freed of tar, ammonia, and hydrogen sulfide.

semi-water gas – a mixture of carbon monoxide, carbon dioxide, hydrogen, and nitrogen obtained by passing an air-stream mixture through an incandescent bed of coke; HHV about 120 Btu per standard cubic foot.

sensible heat – that heat which results in only the elevation of the temperature of a substance with no phase changes.

shift conversion – process for the production of gas with a desired carbon monoxide content from crude gases derived from coal gasification; carbon monoxide rich gas is saturated with steam and passed through a catalytic reactor where the carbon monoxide reacts with steam to produce hydrogen and carbon dioxide, the latter being subsequently removed in a wash plant. The ratio of hydrogen to carbon monoxide in the product gas can be changed at will.

sintering – the agglomeration of solids at temperatures below their melting point, usually as a consequence of heat and pressure.

slag – a molten mixture of various metallic oxides and salts.

slurry – a suspension of pulverized solid in a liquid.

solvation – the association or combination of molecules of solvent with solute ions or molecules.

solvent – that component of a solution which is present in excess, or whose physical state is the same as that of the solution.

solvent extraction – selective transfer of desired coal constituents from finely divided coal particles into a suitable solvent after intimate mixing, usually at high temperatures and pressures in the presence of hydrogen, with or without a catalyst, followed by phase separation.

Solvent Refined Coal (SRC) – a coal extract derived by solvent extraction; a brittle, vitreous solid (M.P. 300° F to 400° F) containing about 0.1 percent ash and about 10 percent of the sulfur in the original coal feedstock; calorific value is about 16,000 Btu per pound. May be used as a clean fuel for power generation by combustion; utilized for the production of high-grade metallurgical coke, anode carbon, and activated carbon by coking; or hydrogenated to produce synthetic crude oil.

space velocity – the volume of a fluid (usually measured at standard conditions) passing through a unit volume in a unit time; units are in reciprocal time.

standard cubic foot (SCF) – the volume of a gas at standard conditions of temperature and pressure. The American Gas Association uses moisture-free gas at 60° F and 30 inches of mercury (1.0037 atm) as its standard conditions. The pressure standard is not universal in the gas industry; 14.7 psia (1.000 atm) and 14.4 psia (0.980 atm) are also used. The scientific community uses 32° F and 1 atm as standard conditions.

stoichiometry – the definite proportions in which molecules react chemically to form new molecules.

stripping – the removal of the more volatile components from a liquid mixture of compounds.

subbituminous coal – the rank of coal between bituminous and lignite, classified by ASTM as having a range of heating values between 8,300 and 11,000 Btu per pound on a moist mineral-matter-free basis.

substitute natural gas (SNG) – a synthetic gas conforming to natural gas standards.

superficial velocity – the linear velocity of a fluid flowing through a bed of solid particles calculated as though the particles were not present.

superheater – a heat exchanger which adds heat to the saturated steam leaving a boiler.

syncrude – synthetic crude oil; oil, produced by the hydrogenation of coal or coal extracts, which is similar to petroleum crude.

synthesis gas – a mixture of hydrogen and carbon monoxide which can be reacted to synthesize a hydrocarbon.

tail gas – a gas issuing from a gas-treatment unit which may be recycled to the process or exhausted.

tar (coal) – a dark brown or black, viscous, combustible liquid formed by the destructive distillation of coal.

therm – a unit of heat used as a basis for the sale of natural gas; equal to 100,000 Btu.

topping cycle – the higher temperature thermodynamic power cycle of a combined-cycle system.

turned down – the reduction of reactor flow rates to a fluidized-bed reaction vessel.

ultimate analysis – the analysis of coal based on the percentages of chemical elements.

volatile matter – those constituents of coal, exclusive of moisture, that are liberated from a sample when heated to 1,750° F (for 7 minutes) in the absence of oxygen.

water gas – gas produced by the reaction of carbon and steam to provide mixtures of carbon monoxide and hydrogen; similar to synthesis gas.

water gas shift – the reaction between water vapor and carbon monoxide to produce hydrogen and carbon dioxide or the reverse: $CO + H_2O \rightleftarrows H_2 + CO_2$.

working fluid – a gas stream which directly does work, e.g., powering a gas turbine.