COAL POWER & COMBUSTION

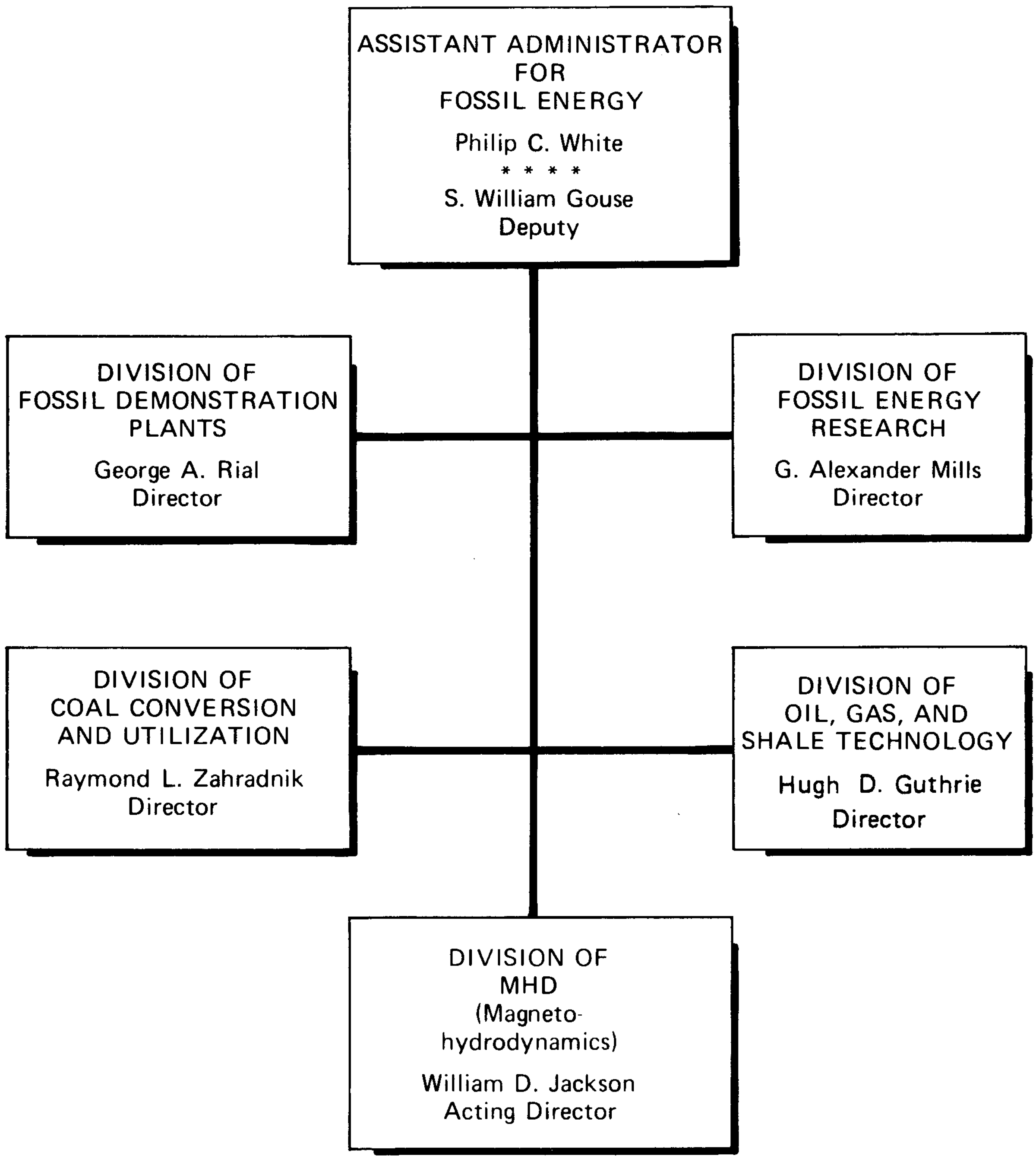
QUARTERLY REPORT
JULY – SEPTEMBER 1976

Philip C. White
Assistant Administrator
Office of Fossil Energy

Raymond L. Zahradnik
Director
Division of Coal Conversion and Utilization

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
Hugh D. Guthrie
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, and 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, are potentially feasible both technically and economically (in terms of the costs 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. Efforts in the area of direct combustion are concentrated on:

- Development of atmospheric and pressurized systems capable of burning high-sulfur coal of all rank and quality in fluidized-bed combustors
- Development of advanced technology power systems to generate power more economically than present technology permits while using medium- and high-sulfur coal in an environmentally-acceptable manner.
- Development of the technology enabling coal-oil slurries to be substituted as feedstock for gas or oil-fired combustors

- Improvement of 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 and operating costs may be realized. The benefits from high-pressure combustion are a reduction of furnace size due to decreased gas volume and better sulfur removal. High-pressure combustion, however, requires the development of equipment to clean the hot combustion products to make them suitable for use in power generation turbines.

The advanced power systems program is directed toward developing electric power systems capable of operating 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. It is anticipated that these systems will have lower electricity costs than new steam power plants constructed using today's technology and burning medium and high-sulfur coals.

To develop direct combustion and advanced power systems as quickly as possible, ERDA is sponsoring a variety of 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 improve plant operability and reliability. The Lewis Research Center, National Aeronautics and Space Administration, through contracts with several corporations, is conducting an energy conversion alternatives study (ECAS), whereby performance and economic comparisons are made of advanced power generation technologies. Combustion Power Company, Inc. and Argonne National Laboratory are studying pressurized fluidized-bed combustion. Combustion Power is developing a combustor-gas turbine electric power generation system using high-sulfur coals, and combining desulfurization with combustion. Argonne National Laboratory is conducting a research and development program to evaluate the feasibility and potential of fluidized-bed combustion and sulfur dioxide absorption at elevated pressures. Oak Ridge National Laboratory is developing an externally fired closed-cycle gas turbine for use in a modular integrated utility system, in which the resource requirements of one service are met by utilizing the effluent of another.

The National Research Development Corporation is researching the combustion characteristics of pressurized fluidized-bed furnaces. 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 investigating the combustion characteristics of anthracite refuse materials in fluidized-bed combustors. The Construction Engineering Research Laboratory of the U.S. Army Corps of Engineers is studying high-temperature dust control, Exxon Research and Engineering Company is analyzing applications of fluidized-bed combustion technology to industrial boilers, and the Leeds and Northrup Company is studying on-line particulate analysis instrumentation. Other projects include particle measurement in fluidized-bed combustion systems by Spectron Development Laboratories and boiler tube bundle and burner module tests by Oak Ridge National Laboratory.

Five firms are investigating the industrial application of fluidized-bed combustion processes. In response to a Program Opportunity Notice issued by ERDA, Battelle Memorial Institute and Georgetown University are studying industrial boilers and Combustion Engineering Company is investigating industrial superheated steam boilers. Indirect fired heaters are being investigated by Exxon Research and Engineering Company and Flui Dyne Engineering. Support studies for these projects are being conducted by Arthur G. McKee and Company.

Fluidized-bed combustion processes are being mathematically modeled by the Massachusetts Institute of Technology through a 21-month program which began in May 1976. Four separate contractors are investigating the potential use of fluidized-bed waste material for soil modification. Studies at the Virginia Polytechnic Institute and State University involve the use of the material as a nutrient source of calcium for crops and efforts by the Tennessee Valley Authority will demonstrate the use of the material as a liming agent. Additional agriculture-related studies will be conducted by the Agriculture Research Service. The Federal Highway Administration will assess the value of the material for use in soil stabilization programs.

Pressurized fluidized-bed combustion is also being studied by the Curtiss-Wright Corporation. The firm is conducting a program to design, construct, operate, and evaluate a coal-fired combined-cycle pilot plant for electric utility power applications.

Major construction of the ***Multicell Atmospheric Pressure Fluidized-Bed Boiler*** facility at Rivesville, West Virginia was completed during the quarter. The unit was reviewed and evaluated to identify and perform all required field modifications and additions. The carbon burnup cell was successfully fluidized in the cold mode and the startup oil burners were operated. At the Alexandria, Virginia site, construction was completed on systems required to operate the fluidized-bed module as a carbon burnup cell.

Several reports were prepared for the ***Energy Conversion Alternatives Study (ECAS)***. The preparation of ECAS contractor Phase II final reports and NASA-Lewis Phase II comparative evaluation studies continued. Meetings were also held during the quarter with General Electric, Westinghouse, and United Technologies Corporation to discuss the reports.

Studies dealing with the ***Pressurized Fluidized-Bed Combustor and Turbine Power Generation*** revealed that temperature is the single most important factor in determining whether or not sulfidation will occur in a coal-combustor system. Corrosion/erosion studies were also continued by the subcontractors, Westinghouse and Solar.

A ten-cycle acceptor test was completed as part of the ***Supportive Studies of Pressurized Fluidized-Bed Combustion.*** The test was conducted to determine the effect of repeated utilization cycles (sulfation-regeneration) on the performance of sulfur dioxide-accepting additives. The testing of synthetic sorbents continued with experiments being conducted on the sulfur dioxide sorption capacity of a calcined sample of natural bauxite. Studies were also made on the cost/environmental effect tradeoff of synthetic sorbents.

Bids for the construction of the furnace of the ***Externally Fired Gas Turbine for Modular Integrated Utility System (MIUS)*** will be requested from manufacturers for both design and fabrication. This new approach will lead to a more economical and more nearly commercial design. The results of fluidizing tests conducted in August indicated a considerably lower fluidizing velocity and heat transfer coefficient than expected.

Modifications to the combustor for ***Pressurized Fluidized-Bed Combustion Research*** were completed during the quarter. Equipment problems encountered in September will require two weeks for repair and testing will begin at the end of October.

A 1000-hour test was completed in the 100 HP firetube boiler used in the ***Coal-Oil Slurry Combustion Program.*** The calculated efficiency was 83 percent and following the test the tubes were given a metallographic analysis to determine the erosive and corrosive effects of slurry combustion. From the operating experience gained during the test, a number of modifications are planned which will improve the operation of the unit and establish the unit as a quantitative diagnostic tool.

In the ***Solvent-Refined Coal (SRC) Combustion Program,*** additional combustion tests were conducted on a combination of SRC product and Illinois No. 6 coal. Combustion appeared to be quite stable with only minor deposition occurring. The pulverizing system processed more than 22 tons of coal to 90 percent through 200-mesh during the period. A motion picture is being prepared on solvent-refined coal combustion, including pictures of flames obtained during combustion tests after each of several modifications of burner design.

The ***High Temperature Dust Control*** program fell slightly behind schedule during the quarter, however, the final report on the project is being prepared and should be completed by next quarter.

Efforts dealing with the ***Application of Fluidized-Bed Combustion Technology to Industrial Boilers*** were concentrated on the preparation of the final project report. The report was submitted to ERDA for review in September.

Work dealing with ***On-Line Particulate Analysis Instrumentation*** included equipment modification to increase the applicability of the instrument to larger duct sizes and provide greater sensitivity to small particles. The current instrument can accommodate duct sizes up to ten inches in diameter.

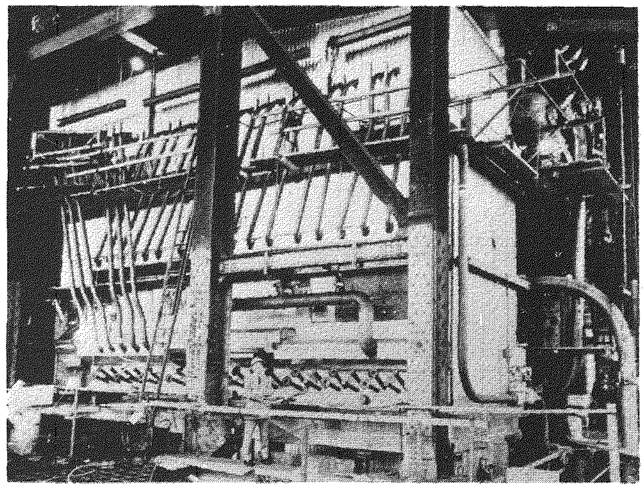
There was very little activity during the quarter on ***Particle Measurement in Fluidized-Bed Combustion Systems***, as windows were not installed in the fluidized-bed combustion facility until late in the period. Initial tests with the particle morphokinetometer began in late September. However, no results are yet available.

Studies dealing with ***Boiler Tube Bundle and Burner Module Tests with Potassium*** included the installation of the gas-fired potassium boiler module and initial testing with boiling water. The major part of the mechanical design of the potassium fill and drain system and the potassium condenser was completed.

Because the studies dealing with the ***Industrial Application of Fluidized-Bed Combustion Processes,*** the ***Modeling of Fluidized-bed Combustion Processes,*** and ***Fluidized-Bed Waste Material Utilization*** just began during the quarter, progress on these projects has, of course, been very limited. Activities in these areas will be reviewed beginning with the October-December quarter.

During the quarter the conceptual design of the commercial plant for the ***Combined-Cycle Electric Power Generation Using Pressurized Fluidized-Bed Combustion*** continued. The design of the gas turbine power train, combustor, and heat exchanger is nearing completion. Small gas turbine/combustor and heat exchanger test rig system performance and process analyses were initiated to establish combustor design and material handling requirements.

I. MULTICELL ATMOSPHERIC PRESSURE FLUIDIZED-BED BOILER



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

Plant Site: Rivesville, West Virginia
Contract No.: E(49-18)-1237
Total Funding: $19,244,313
(100% ERDA)

INTRODUCTION

A multicell atmospheric pressure 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 environmentally acceptable method of burning high-sulfur or corrosive coals without excessive maintenance problems. The system is to have a capacity of 30 megawatts (Mw) and is to be operated under practical electric utility conditions. PER is also conducting a laboratory research program to optimize boiler hardware and operational parameters. Experience gained from designing and operating the boiler and from laboratory research will be used as the basis for scaling up to a utility-sized system. The schedule for development of the fluidized-bed boiler is shown in Figure I-1.

PROCESS DESCRIPTION

The fluidized-bed boiler is 12 feet wide, 25 feet high, and 38 feet long. It has conventional water tube walls, a convection economizer, and a capacity of 300,000 pounds of steam per hour. The boiler is unique in that it has horizontal superheater tube bundles submerged in the combustor bed of fluidized coal, ash, and limestone. The unit is divided into four separate cells, three of which are about equal in size. The fourth cell, the carbon burnup cell, is smaller in width due to its own design parameters. 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 functions as follows:

Cell A, the primary superheater, has a horizontal superheater tube bundle submerged in the fluid-

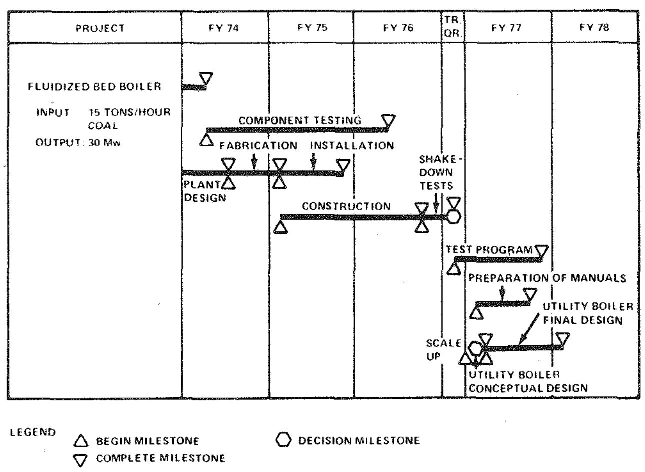


Figure I-1. MULTICELL FLUIDIZED-BED BOILER PROGRAM SCHEDULE

ized-bed, with two additional horizontal bundles, the evaporator and the economizer, located in the convection zone (free board).

Cell B, the finishing superheater, has a horizontal bank of superheater tube bundles in the fluidized-bed zone with horizontal boiler and economizer bundles in the convection zone.

Cell C, has a horizontal boiler tube bundle in the fluidized-bed zone with horizontal boiler and economizer bundles in the convection zone.

Cell D, the carbon burnup cell, contains only horizontal economizer tubes in the convection zone.

The bottom of the fluidized-bed is located approximately where the grate would be in a conventional coal-fired boiler. The expanded bed is four feet thick, has a six-foot free zone above it, and there is an additional six-foot convection heat transfer volume above the free zone. The partition walls between the cells are of the membrane type, i.e., a waterwall of finned tubes without refractory protection.

Coal and limestone are fed to cells A, B, and C, which are then fired with 18% excess air. Elutriate from these cells contains approximately 0.1 pound of carbon per pound of coal feed and is collected in a mechanical dust collector. This material is then sent to Cell D and burned with 25 percent excess air. The carbon is burned in an inert ash and sulfur-absorbing fluidized-bed of limestone at nominal bed temperatures of 2000° F in the carbon burnup cell whereas coal is burned at 1550° F in cells A, B, and C. The mixing tendencies of the fluidized-bed are controlled by using boiler tubes as baffles and walls. The particles are moved from one portion of a cell to another by the inherent fluid-like behavior of the bed.

One of the advantages of the multicell fluidized-bed boiler is that sulfur dioxide and nitrogen oxide emissions are controlled and well within current EPA standards. Other than electrostatic precipitators, expensive cleanup and energy-consuming flue gas equipment is not required. The sulfur dioxide emissions are captured by limestone in the fluidized-bed combustor which operates at a controlled temperature low enough to avoid objectionable NO_x emissions. The limestone may be kept reactive by regeneration to recover concentrated sulfur dioxide or by the addition of fresh limestone. Emission of ash particles is low because the coal is not pulverized, resulting in a mean dust-particle size of 100 microns, compared to 20 microns for similar processes.

Other advantages of the fluidized-bed boiler include:

- Low-quality, high-sulfur coal can be burned without danger of slagging due to low combustion temperatures.
- The heat release and heat transfer coefficients are high, thus reducing boiler size, weight, and cost.
- The multicell design lends itself to mass production assembly of the major components, thus facilitating shipping and saving plant construction time.
- It is anticipated that use of the fluidized-bed boiler, rather than a conventional coal-fired unit requiring a flue gas scrubber system, can result in an overall cost savings for the boiler of up to 25 percent.
- The overall operating efficiency of the multicell fluidized-bed boiler power plant is projected to be 39 percent, compared to approximately 32 percent for a conventional coal fired plant using a stack-gas cleanup unit when operating with the same coal and at the same steam pressure and temperature.

HISTORY OF THE PROJECT

In February 1965, the Office of Coal Research (OCR, now part of ERDA) awarded Pope, Evans and Robbins, Inc., (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 eliminated. Furthermore, the boiler promised improved power plant efficiency and cleanliness when burning chars, anthracite, or conventional coal and eliminated the need for pulverizing the coal feed.

Under another OCR contract, initiated in May 1972, PER (in its Alexandria, Virginia, laboratory) performed additional experimental work using a 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 of 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 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 practical utility conditions. Boiler steam pressure and temperature conditions were designed to meet the requirements of the Monongahela Power Company plant at Rivesville. Foster Wheeler Energy Corporation, as sub-contractor to PER, is responsible for the fabrication and installation of the 30 Mw boiler. Foster Wheeler is also responsible for:

- 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 boilers
- Preparation of an auxiliary system test program
- Design, construction, and testing of a cold model.

Champion Construction and Engineering Company, Inc., was awarded the contract 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.

Field erection work in the Monongahela Power Company power plant is nearing completion, as are auxiliary systems, plant general construction, and laboratory construction work. Boiler installation is complete and cold test operations of individual systems and equipment have begun.

Concurrent with work on the 30 Mw boiler, PER has continued its laboratory research program, including cold-model and fluidized-bed module tests.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

Equipment checkout, acceptance, and preliminary cold mode operation of major mechanical systems continued throughout the quarter at the Rivesville plant. The unit was reviewed and evaluated to identify and perform all required field modifications and additions. During September, the limestone bed in Cell D (carbon burnup cell) of the Rivesville facility was successfully fluidized. Startup oil burner operation in the cell was also achieved.

At the Alexandria, Virginia site, construction was completed on systems required to operate the fluidized bed as a carbon burnup cell. The unit began operation in September in the hot mode and spent bed material was generated for subsequent tests to determine its value for industrial and/or agricultural purposes. Studies also continued on bed cleansing techniques.

Boiler Design and Construction

Activities during the quarter concentrated on the testing of equipment for acceptance and cold mode operation. The phases of cold mode operation which were completed or were in the process of being completed at the end of September included:

- Operation of limestone supply and storage system to obtain the necessary stock of limestone for cold mode operation.
- Reduction and analysis of data obtained during the multicell fluidized-bed boiler air supply and flue gas system operation to determine pressure drops and flow characteristics in the ductwork.
- Operation of furnace feed system.
- Successful fluidization of cold limestone from five and 14-inch static beds in the carbon burnup cell.
- Operation of the startup oil burners in Cell D.

During this reporting period, Champion Construction and Engineering Company completed the installation of nearly all major mechanical, structural, and electrical equipment. In addition to completing the base contract work, material expediting efforts were made to hasten delivery of outstanding orders. The logic portion of the boiler control system was reviewed and thus additional relays, switches, and wiring will be required. Installation of the power distribution system and control wiring were progressing satisfactorily at the end of the quarter.

Laboratory Research

During this quarter, the following deserve reporting:

a. Primary emphasis during the quarter was placed on the conversion of appendage and systems of the fluidized-bed unit to accommodate the carbon burnup cell (CBS) mode of operation. Mechanical subcontract work was completed in August and startup and component testing of systems began. During initial operations in September, difficulties were encountered in the coal and limestone conveyors, vibrating feeder table, bed material handling system, and weighing hoppers.

Steps were subsequently taken to alleviate these problems in future tests.

b. Cold testing of the flyash feed system, designed and built by Petrocarb, Inc., was completed during the quarter. The tests were designed to determine the extent of change in flyash feed rate with changes in the Petrocarb system operating parameters. The test results will be used to develop calibration curves which can be used to estimate the flyash feed rate during CBC hot tests.

c. Hot mode shakedown runs were also conducted with the newly installed/converted systems to verify equipment operation and determine the adequacy of the exposed vertical wall heat transfer surfaces. The test runs indicated that too much of the vertical walls were exposed and hence an excessive amount of heat was removed via steam generation. Additional vertical heat transfer surfaces were covered with refractory to eliminate the problem. Other objectives of the hot mode testing included initial flyash feeding tests and initial operation of the CBC in the automatic control mode.

d. Tests also continued throughout the quarter on the maintenance of bed purity by means of the operation of a classifier which selectively removes large coal-derived ash particles from the sulfur-sorbing limestone bed. Data from the test program were combined with theoretical concepts to obtain a mathematical model of the bed cleansing system. The areas studied in the test program were limestone surface area, reactivity of the limestone surface, and calcium utilization by bed cleansing.

The conclusions which were drawn regarding limestone surface area included:

- Increasing the bed height at constant expansion can theoretically reduce the limestone requirements significantly.
- In some cases this reduction in limestone requirements could be accomplished by decreasing the particle radius accompanied by corresponding increases in air distributor area.
- The third effective means of significantly reducing the limestone feed requirements consists of increasing the inherent reactivity of the limestone. One way to do this is to add an additive such as sodium chloride.
- The operation of the bed classifier has a relatively minor effect on overall limestone economy at high calcium to sulfur feed ratios, and its use, therefore, may be eliminated in some cases.

The studies also showed that limestone reactivity is closely related to the particle size, internal microstructure, and internal microchemistry. The inherent reactivity of the particle surface may be enhanced in the following three ways:

- Reduction of particle size, thus increasing the surface to volume ratio.
- Addition of an additive, such as sodium chloride.
- Calcination of limestone in a carbon dioxide atmosphere.

e. In preparation for full-scale testing of the CBC, commercial laboratories were sought to perform check analyses on the flyash product from the tests. During this quarter, sufficient spent bed material was generated to satisfy the immediate needs of ERDA in the analysis of the material for industrial and agricultural use. Approximately 5,000 pounds of material was shipped to West Virginia University Agricultural Research Services at Morgantown for their studies.

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
ERDA: $1,600,000
National Science Foundation: $1,000,000

INTRODUCTION

The Energy Conversion Alternatives Study (ECAS) is being managed by the National Aeronautics and Space Administration's Lewis Research Center under the sponsorship of ERDA and the National Science Foundation. Each sponsor contributed 50 percent of the total funding for the first task with ERDA providing additional funds for the later tasks. 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 personnel.

The overall objective of this project, started in August 1974, is to study advanced power generation techniques which can use coal or coal-derived fuels and to evaluate their relative merits and potential benefits. ECAS is to be conducted using a common basis of technology and materials performance in the light of new national goals and current conditions. In addition, ECAS is to define development plans for 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

The objectives of the ECAS program involve a review of the technical claims, designs, performance, materials selection, development needs, costs, etc. of each power generating system currently being studied. To determine the relative performance, economics, natural resource requirements, environmental impacts, development requirements, and risks of the various advanced energy conversion 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. The project is divided into four tasks:

- Task I—Parametric Analyses
  - 25 to 300 Mw of generating capacity
  - Variety of coal or coal-derived fuels
  - Variety of heat rejection methods
  - Variety of combustors/furnaces
  - 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
    - Assess uncertainties and risks
    - Identify 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

Task I, Parametric Analyses, was completed during the second quarter of 1975. A variety of overall systems were studied, based on combinations of the following types of units:

Combustors: fluidized-bed, pulverized coal with scrubbers, and coal-derived liquid fuel; both atmospheric and pressurized.

Power cycles: coal-fired steam cycles, coal-derived liquid-fueled simple and recuperative cycle gas turbine, combined gas turbine-steam turbine cycles, with air-cooled, water-cooled, and ceramic turbines using coal-derived low-Btu gas as fuel; supercritical carbon dioxide (Fehr) cycle; alkali metal vapor Rankine topping cycle; closed cycle gas turbines with organic liquid Rankine bottoming cycle; open and closed cycl including liquid-metal magnetohydrodynamics.

Fuel cells: low-temperature phosphoric acid; low-temperature alkaline; high-temperature molten carbonate; high-temperature solid electrolyte. For these, clean liquid and gaseous fuels from coal together with integrated gasifiers were used.

Preliminary results of the parametric analyses, including a benefit and break-even cost analysis, indicated that potentially large dollar benefits may be possible for some of these advanced systems.

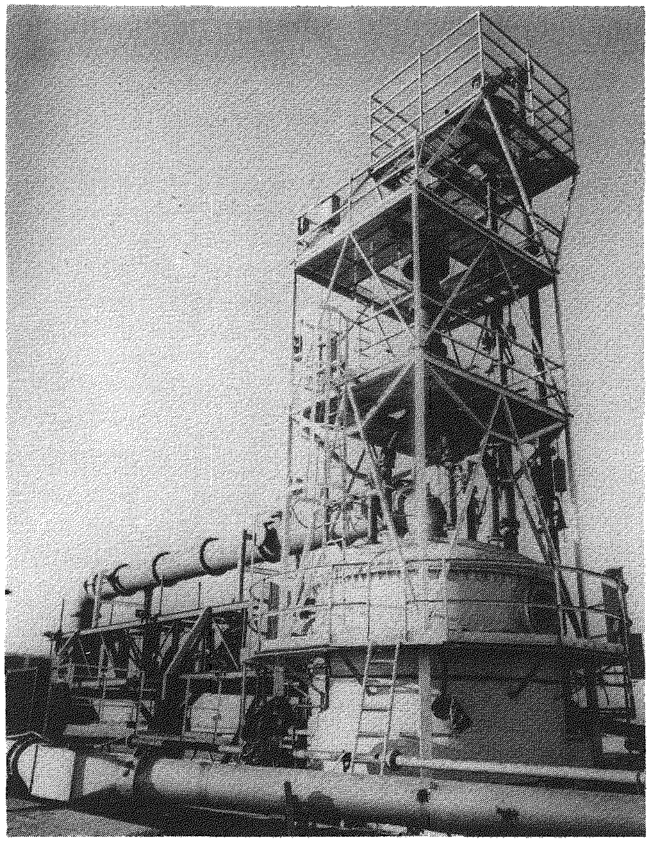
PROGRESS DURING JULY-SEPTEMBER 1976

Efforts during the quarter dealt primarily with the preparation of reports by both NASA-Lewis and the subcontractors. The preparation of ECAS contractor Phase II final reports and NASA-Lewis Phase II comparative evaluation studies continued. General Electric submitted drafts of Volume III (implementation assessment) and Volume I (executive summary) during August. Representatives of General Electric also met with NASA-Lewis personnel for a "dry run" review of Task III results.

Also during the quarter, Westinghouse submitted Section 6, "Advanced Steam PFB" to NASA-Lewis for review. Sections 4 and 5 were also submitted in the latter part of the quarter. Sections 4, 5, and 6 contain the three conceptual designs and the respective R&D plans and implementation assessment.

United Technologies Corporation prepared a draft report entitled "Integrated Coal Gasifier/Molten Carbonate Fuel Cell Powerplant Conceptual Design and Implementation Assessment." The report was submitted to NASA-Lewis for comments. Representatives of United Technologies Corporation visited NASA-Lewis to "dry run" the Task III briefing and for discussion of the draft report.

III. PRESSURIZED FLUIDIZED-BED COMBUSTOR AND TURBINE POWER GENERATION



COMBUSTION POWER COMPANY, INC.
MENLO PARK, CALIFORNIA

Plant Site: Menlo Park, California
Contract No.: E(49-18)-1536
Total Funding: $3,465,780
(100% ERDA)

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 the Environmental Protection Agency (EPA) in which municipal solid waste was burned with minimal pollution in CPC's CPU-400 pressurized fluidized-bed combustion and gas turbine system. The program objective is to develop a process to generate electrical energy through the combustion of high-sulfur coals mixed with dolomite, using an on-line gas turbine for direct power generation. The program schedule is shown in Figure III-1.

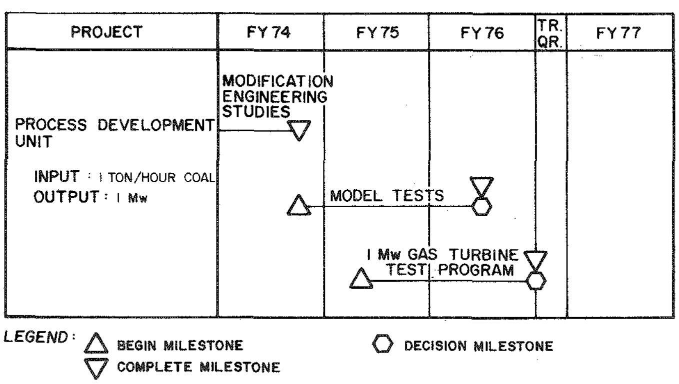


Figure III-1. COMBUSTOR-GAS TURBINE DEVELOPMENT SCHEDULE

PROCESS DESCRIPTION

A schematic of the CPC combustor-gas turbine system is shown in Figure III-2. In this process, the coal is crushed to a size smaller than ¼-inch, mixed with dolomite, and fed into the fluidized-bed combustor in a stream of compressed air. Fluidization is maintained by injecting air from the turbine compressor.

In the fluidized-bed combustor, the coal is burned to produce gas and 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 which remove par-

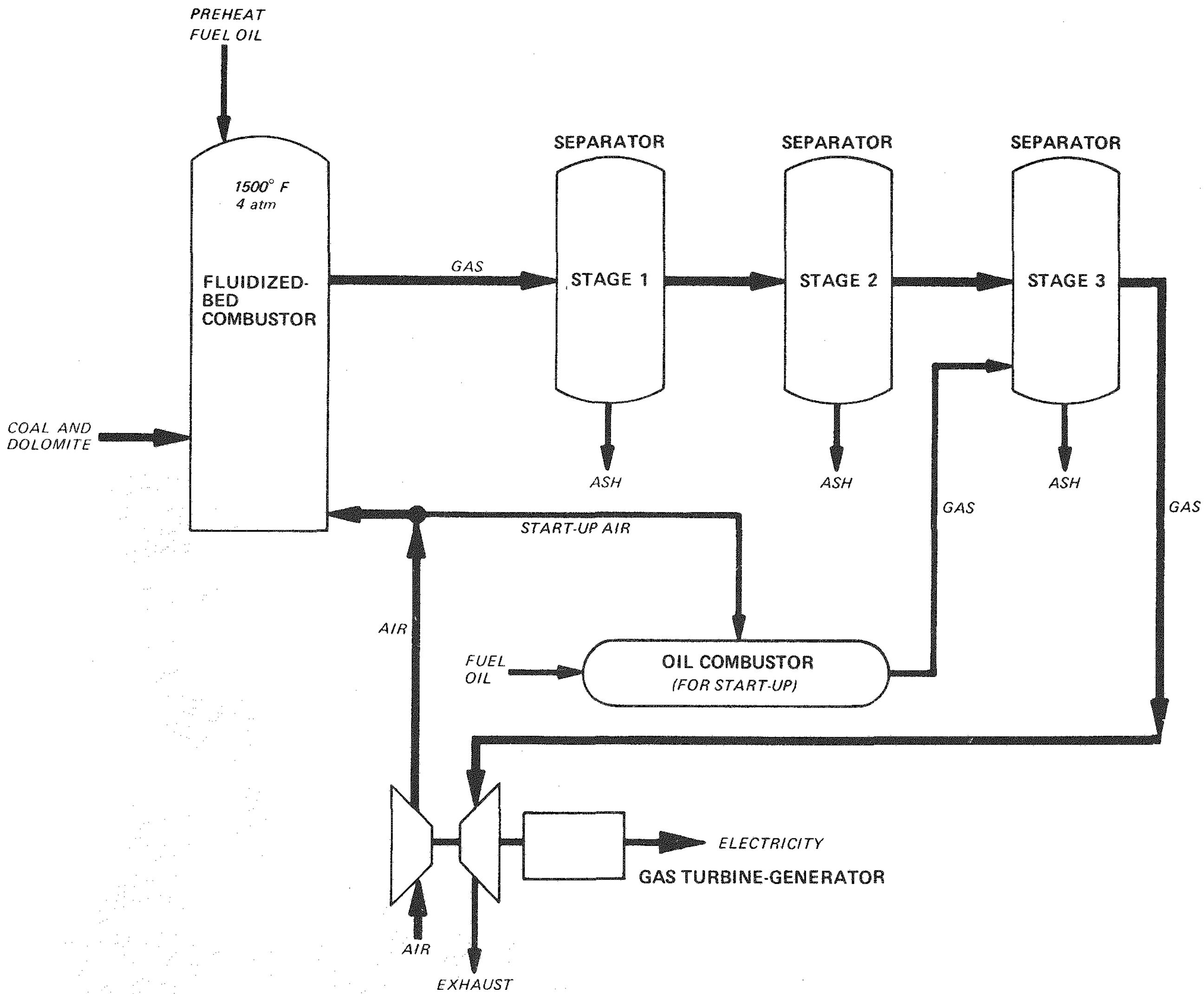


Figure III-2. COMBUSTOR-GAS TURBINE SCHEMATIC

ticles greater than five microns in size. The third stage uses inertial separators to remove particles as small as two microns. A moving-bed granular filter is being installed to replace this third stage separator to improve the hot gas cleanup process. The cleaned gas is then expanded in a gas turbine driving a one Mw generator.

To facilitate start-up, fuel oil is used to preheat 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.

Some of the advantages of the CPU-400 system are:

- 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, Combustion Power Company, Inc. has been conducting a 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 cooperatio of EPA, the Office of Coal Research (OCR, now a part of ERDA) contracted with CPC in June 1973 to conduct a research and development program designed to demonstrate the combustion of high-sulfur coal using CPU-400 technology.

Under the current contract, CPC 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 and the noncaking coal used was Illinois No. 6. The coals were burned using superficial velocities of four, seven, and ten feet per second, bed temperatures of 1400° F, 1600° F, and 1800° F, calcium-sulfur ratios of 1.5, three, and five, and three additives for absorbing sulfur compounds (two types of dolomite and one type of limestone). Each coal type was tested for 120 hours at nominal operating conditions of seven feet per second, 1600° F, and a calcium-sulfur ratio of 1.5.

The CPU-400 system was modified 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 using the data from the model experiments were designed 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 test program indicate 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 in controlling particulates to a degree which would ensure acceptable turbine blade life or to meet current EPA particulate exhaust emission standards.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

Combustion Power Company continued to conduct corrosion tests during the quarter and published a special report summarizing the testing of 22 alloys with hot combustion gases. It was determined that temperature is the single most important factor in determining whether or not sulfidation will occur in a coal-combustor system. Studies conducted by Solar on the ash collected by the granular filter indicate that sintering and densification may occur, tending to protect the metal surface from subsequent fouling. Following completion of their materials and additive evaluations, Westinghouse began a long-duration test in a pressurized passage wherein six alloy and coating combinations were exposed to a turbine expansion gas containing controlled amounts of HCl, NaCl, and SO_2/SO_3.

Discussion of Activities

Manufacturers of oil-burning turbines specify that the fuel contain less than one part per million—and the air less than about ten parts per billion—of sodium or potassium. This is to guard against hot corrosion and assure operating periods of one to two years between overhauls. Oil fuels can be washed with water to eliminate alkali compounds. Coals, on the other hand, contain two or three thousand parts per million of sodium as well as several thousand parts per million of sulfur, which cannot be easily washed from the coal.

In spite of such orders-of-magnitude differences between the two fuels, the only severe sulfidation attacks that have been encountered in the testing conducted to date have been traceable to random temperature excursions. Even excursions which occur prior to the introduction of coal produce this result. Apparently, traces of alkali in the dolomite and sulfur in the oil are sufficient to cause sulfidation. Because of these results, it has been concluded that temperature is the single most important factor in determining whether or not sulfidation will occur in a coal-combustor system. Below 1670° F, oxidation rather than sulfidation controls the corrosion rates.

Corrosion data collected thus far on IN 738 alloy indicates that if one assumes that the allowable loss for a blade initially 0.125-inch thick is 20 percent per side, then the rate of attack at 1600° F projects to a turbine life limitation of approximately 14,000 hours. At 1670° F, this limit is reduced to about 9,000 hours. If the temperature is reduced to 1550°F, a life of as much as 50,000 hours might be realized if corrosion is the limiting factor.

A special report entitled "Hot Corrosion in the Direct-Coal-Fired Gas Turbine" was compiled and issued during September. This report describes over a year of testing in which specimens of 22 alloys were exposed to hot combustion gases.

Studies conducted under the subcontract with Solar indicated that in laboratory-generated ash deposits, sintering and densification may occur, thus tending to protect the metal surface from subsequent erosion. It was also found that the melting of ash particles in the combustion flame of the test-rig burners poses a serious problem in process simulation for erosion studies. The work at Solar indicates that such local overheating results in the formation of dense deposits, rather than erosion. Proposed equipment modification to alleviate such problems will probably require more time than is included in the present program.

Following completion of the materials and additive evaluations by Westinghouse, under their subcontract, a long-duration test was initiated. The test will be conducted in a pressurized passage wherein six alloy and coating combinations are exposed to a turbine expansion gas containing controlled amounts of HCl, NaCl, and SO_2/SO_3. The preliminary results indicate that addition of sodium:chlorine:sulfur dioxide at 0.5:25:100 ppm to the fuel oil does not prevent the condensation of sodium sulfate.

IV. SUPPORTIVE STUDIES OF PRESSURIZED FLUIDIZED-BED COMBUSTION

ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

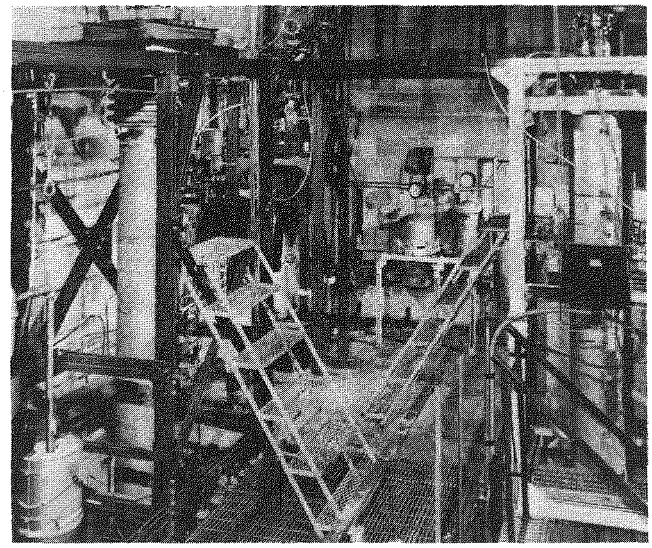
INTRODUCTION

Argonne National Laboratory (ANL), under ERDA sponsorship since November 1974, is conducting a research and development program to evaluate the feasibility and potential of fluidized-bed combustion at pressures up to ten atmospheres. The objectives are:

- 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 for 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.

FACILITY DESCRIPTION

A schematic of the pressurized fluidized-bed combustor is provided in Figure IV-1. The combustion unit is six inches in diameter and 11 feet long. The exterior is wrapped with electrical heaters to raise the bed temperature to the 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 injected. The coal is entirely burned in a fluidized bed of dolomite. During combustion, the sulfur contained in the coal is released as sulfur dioxide, which is then absorbed by the dolomite. The sulfated dolomite is subsequently regenerated and reused in the combustor.

HISTORY OF THE PROJECT

Initial research and development efforts on pressurized fluidized-bed combustion included experiments to measure the effects of temperature, fluidizing gas velocity, and the ratio of the calcium content of the dolomite to the sulfur content of the coal. In these experiments, Pittsburgh seam coal was burned at eight atmospheres in a three-foot-high fluidized bed with

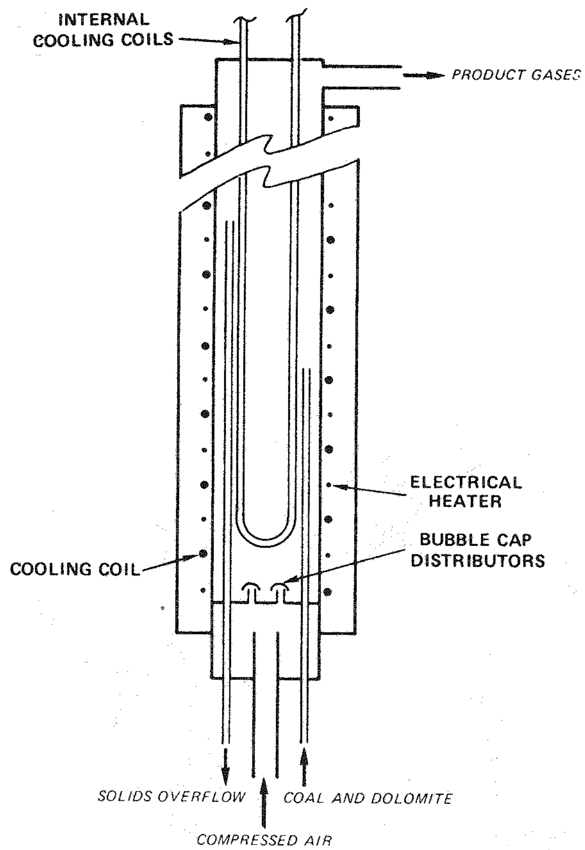


Figure IV-1. ANL PRESSURIZED FLUIDIZED-BED COMBUSTOR

three 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 and 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 1450° F to about 97 percent at 1650° 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 five percent at two feet per second to as high as 80 percent at five 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 two feet per second, to about 115 at five feet per second.

Experiments were also conducted using a subbituminous coal with a high ash content and a lignite. 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 eight atmospheres to approximately 1,600 parts per million at one atmosphere. 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 in the range of 1450° F to 1650° 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 indicate that the concentration of trace elements emitted from the fluidized-bed combustor may be significantly lower than that emitted from conventional coal-fired combustors.

Current support studies include regeneration process studies, synthetic sorbent development, limestone characterization, and trace element and combustion emission studies.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

The effect of repeated utilization cycles on the performance of Tymochtee dolomite as a sulfur dioxide acceptor was evaluated in a ten-cycle test. Cycles five through ten were conducted during the quarter. It was found that the reactivity of the dolomite decreased in each succeeding combustion cycle. The extent of coal ash buildup in the dolomite during the sulfation and regeneration steps of the ten cycles was also monitored.

The testing of synthetic sorbents continued with experiments being conducted on the sulfur dioxide sorption capacity of a calcined sample of natural bauxite. The bauxite sample exhibited a high attrition resistance but did not have a high enough sulfur dioxide sorption capacity for practical use. In other activities, a study was conducted to estimate the cost/environmental effect tradeoff if synthetic sorbents are successfully developed.

Shakedown tests on the combustor were conducted in July following construction completion. The test run was conducted to gain familiarity with the control and operational characteristics of the system. Tests were conducted in August and September to test the cold trap and hot filter operation and to test the controllability of the system.

Discussion of Activities

The experimental effort to evaluate the effects of repeated utilization cycles on the performance of sulfur dioxide-accepting sorbents continued throughout the quarter. Cycles five through ten of the ten-cycle program were conducted in July and August, thus completing that portion of the effort.

Results from the first five cycles showed that the regenerability of the Tymochtee dolomite remained good and that the sorbent retained its regenerable properties. The extent of calcium oxide regeneration for cycle five was 75 percent and the sulfur dioxide concentration in the dry off-gas was 8.8 percent during the regeneration step. The extent of calcium oxide regeneration for cycles six and seven were 75 percent and 77 percent, respectively. The sulfur oxide concentration during regeneration was 8.7 percent and 8.2 percent, respectively. During the eighth, ninth, and tenth cycles, the extent of calcium oxide regeneration remained at approximately 70 percent.

In the ten cyclic regeneration experiments, solids residence times of 6.8 to 8.1 minutes were used. The extent of calcium oxide regeneration varied from 67 to 80 percent, and the regenerability of the dolomite remained good throughout the test.

Combustion cycles five through ten were also completed during the quarter. Nominal conditions for cycles five and six were a 900° C bed temperature, 819 KPa pressure, 1.5 calcium/sulfur mole ratio, ~17 percent excess combustion air, 0.91 meter per second fluidizing-gas velocity, and a 1.07 meter bed height.

The level of sulfur dioxide in the flue gas for experiments five and six was ~600 ppm, which corresponds to a sulfur retention of ~71 percent. This level corresponds to 1.16 lb. sulfur dioxide/10^6 Btu. Although the sulfur retention decreased 15 percent in the first six cycles the sulfur dioxide emission recorded for the sixth cycle still met the EPA standard of 1.2 lb. sulfur dioxide/10^6 Btu.

Combustion cycles seven through ten were conducted at the same operating conditions as five and six except that the bed height was lowered to 0.9 meters. Similar results were obtained for these runs. Selected solids samples from the ten-cycle series of combustion-regeneration experiments are being subjected to further chemical and physical analyses in an attempt to determine the principal factors affecting the sorbent reactivity for sulfur retention.

Preparation of synthetic sulfur dioxide sorbents for use in the process development unit was continued in July. The current program calls for the preparation of 500 pounds of synthetic sulfur dioxide sorbent consisting of α-alumina impregnated with calcium oxide. The material will be used in PDU tests to study its performance with respect to attrition, slag interaction, and ability to meet EPA sulfur dioxide standards. Approximately 160 pounds of alumina has undergone the initial preparation step.

In other areas of synthetic sorbent development, calcined bauxite was tested as a support material for calcium oxide. The calcium oxide was impregnated into the calcined bauxite material, producing a 5.5 percent calcium oxide sorbent. The sulfaction rate was low, with only 18 percent of the calcium oxide being converted to calcium sulfate in five hours. Only 14 grams of sulfur oxide can be captured in five hours per kilogram of sorbent, compared with 126 grams per kilogram for calcium oxide in α-alumina and 230 grams per kilogram for Tymochtee dolomite in the same period of time.

In earlier efforts, a cost analysis for synthetic sorbents was made. It was determined that the cost per ton for the sorbents would range from $200 to $2,000 per ton. Since dolomite presently costs $10 to $20 per ton, a study was conducted to determine the incremental increase in power production cost for the use of synthetic sorbents versus dolomite in pressurized fluidized-bed boilers (PFBB).

Using a base-case cost estimate by Westinghouse for a PFBB with a "once-through" sulfur oxide sorbent system, Argonne calculated that the electrical energy cost of using synthetic sulfur dioxide sorbents on a once-through basis would be 25.2 mills/kWh, increasing the total cost of PFBB from 20 to 45.2 mills/kWh. Argonne concluded that the use of synthetic sorbents could be considered only when regeneration is part of the PFBB system. The minimum cost of the entire PFBB process is approximately 23 mills/kWh (including regeneration of dolomite). Since dolomite is relatively inexpensive, the "makeup" of fresh sorbent was not included in the original Westinghouse evaluation. Due to the higher cost of synthetic sorbents, however, the "makeup" rate of fresh synthetic sorbents was determined to be important.

The investigation of the attrition resistance of naturally occurring and synthetic sulfur dioxide sorbents was continued in July. In this series of experiments, Tymochtee dolomite was tested under various fluidization conditions. The cold laboratory-scale fluidized-bed apparatus used in previous tests was replaced by a column of a new design. Several experiments were repeated in the modified apparatus and the attrition rates compared with previous results from the original apparatus. In experiments performed in the modified apparatus, the attrition rate was lower than in experiments with the original apparatus.

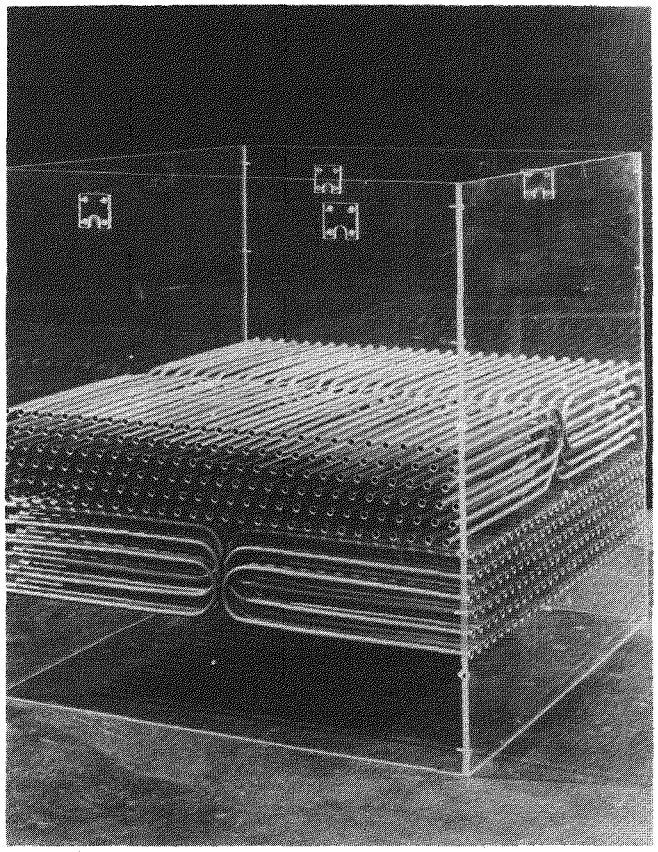
Tests were also conducted to determine attrition rate as a function of bed height. It was found that an increase in the length to diameter ratio produced higher attrition rates. The rate increased by a factor of 1.8 as the result of increasing the ratio from 1.30 to 2.13. Argonne reported that the results obtained do not agree with results previously reported for sulfated dolomite containing 6.8 percent sulfur. The differences could not be readily explained and therefore more tests are planned.

Assembly of the combustor for the trace element and combustion emission studies was completed in July. Shakedown experiments were initiated to gain familiarity with the control and operational characteristics of the combustor system. A test run was conducted with a mixture of coconut charcoal and three grams each of potassium chloride and sodium sulfate. The results demonstrated satisfactory performance of the combustor, with respect to operational control and the capability of the cold trap to condense inorganic constitutents present in the hot combustion gas.

Combustion tests were conducted in August using Illinois No. 6 coal. The rate of combustion was calculated to be about 10 to 15 grams per hour. During the run, a thick layer of tar and soot condensed on the hemispheric surface of the cold trap. Further testing was undertaken in September in an attempt to alleviate the condensation problem. The test run demonstrated the capability of controlling the burning of coal under the same experimental conditions in the combustor system. During operation, the cold trap was controlled at 150° F. It remained dry and completely free of tar and/or soot. Argonne stated that the formation of iron sulfate on the cold trap, caused by corrosion reactions, would result in ambiguous qualitative and quantitative analyses of the condensates. In an effort to eliminate the problem, the surface of the cold trap will be electroplated with a thin layer of rhodium metal.

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

OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE



INTRODUCTION

A fluidized-bed coal combustor for an externally fired closed-cycle 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 electricity and other utility services consistent with reduced use of scarce national resources, protection of the environment, and minimized cost. MIUS is modular, in that it can be located near appropriate users based on the actual demands of community development, rather than a forecast of requirements. MIUS might be sized to accommodate from several hundred to several thousand multi-family dwelling units, single-family units, and associated commercial facilities. 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, waste heat for a prime mover may be used for heating buildings, processing potable water, operating absorption-type refrigeration units, etc., 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 would not be 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 concept, design of a 0.5 Mw coal-fired power plant that can be used in the small total energy system envisioned, and construction, operation, and evaluation of the plant. In conjunction with this project, ORNL is conducting 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 to be coupled with a closed-cycle gas turbine. A vertical sectional drawing

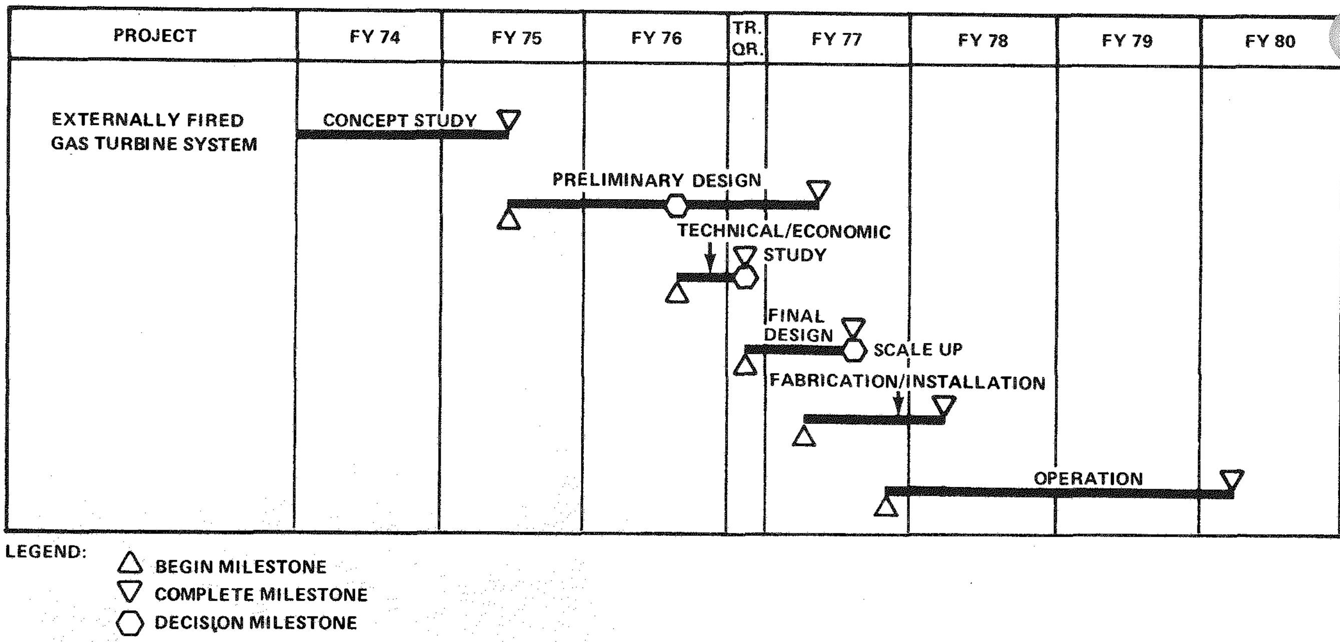


Figure V-1. COAL-FIRED TURBINE FOR MIUS PROGRAM SCHEDULE

of the proposed combustor is shown in Figure V-2. The design provides for efficient operation at less than peak load since this will be the normal operating condition. As currently designed, the fluidized beds in the combustion system are composed of coal and limestone, the function of the time being to capture sulfur dioxide from the burning coal. This reaction produces calcium sulfate, thus making it unnecessary to remove sulfur dioxides from the stack gases.

Preheated air enters a plenum chamber under the bed, flows up through air-distribution tuyeres in the bed plate, through the 20-inch deep 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 to decelerate and fall back into the bed. The superficial velocity of combustion gases can be varied from two to four feet per second. The air for the bed furnace is preheated by a heat regenerator consisting of a stationary heat transfer matrix. Hot stack gases flowing through one portion of the solid matrix transfer heat through the matrix to the air flowing through the other portion.

The particle movement in the fluidized bed promotes good combustion of the coal particles and provides excellent heat transfer coefficients with exposed heat transfer tube surfaces. The bed temperature is maintained at about 1600° F by air tubes about one-half inch in diameter welded into manifolds at the

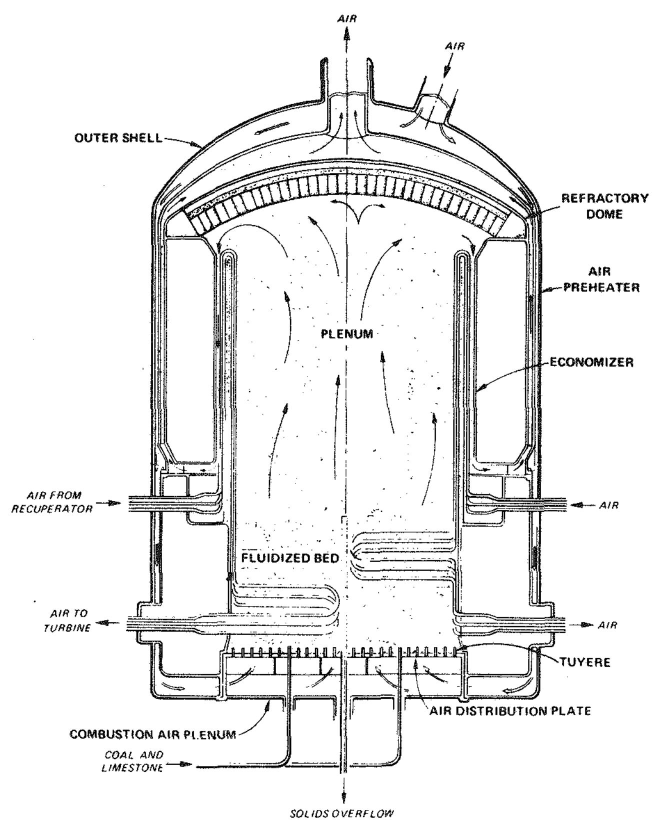


Figure V-2. FLUIDIZED-BED COMBUSTION SYSTEM FOR MIUS

top and bottom. This configuration provides sufficient heat transfer surface area to remove the appropriate fraction of the heat of combustion.

The temperature gradient through the entire closed-cycle system is kept relatively constant, the power output being changed by varying the pressure in the system. Current parametric studies agree with previous analyses which indicate that the optimum pressure ratio for such 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 heat of combustion goes into the air heated by the fluidized-bed and a smaller fraction goes into the waste heat boiler which produces 250° F water/steam. This waste heat boiler simplifies both fabrication and control. For good cycle efficiency, the compressor inlet temperature should be 80° F if outside air or cooling water temperature is maintained at 60° F. A fan is currently included to reduce back pressure on the turbine and thereby increase the thermal efficiency.

Particulates larger than ten microns in the stack gases are removed by two stages of cyclone separators, and regenerative cooling of the gases to below 600° F allows the bulk of the remaining fines to be removed with porous bags made of glass cloth. The MIUS coal fired gas turbine process has the advantage that it provides the required overall thermal efficiency at full load, with little loss of thermal efficiency for part-load operation, the more common operating condition. In addition, the fluidized-bed combustion system operates well with liquid or gaseous fuel, as well as char, low-sulfur coal, or solid organic waste. Therefore, it may also be used as an incinerator. Another advantage is that by keeping combustion temperature at approximately 1600° F, the formation of appreciable amounts of nitrogen oxide is prevented, and agglomerate clinkers are not formed because the ash temperature is below its fusion point.

ORNL has given much attention to basic problems such as:

- Ensuring even distribution of coal and limestone across the fluidized bed
- Minimizing bed pulsations and tube vibrations
- Decrepitation rates and reactivities of various limestones and dolomites after recycling
- Upper limits of gas velocity and bed depth
- Possibility of excessive corrosion on the combustion side of the tubes
- Effectiveness of fly ash removal equipment.

HISTORY OF THE PROJECT

Anticipating the impending energy shortage, HUD, with the assistance of ORNL, is investigating total energy systems for use with new building complexes as a part of the MIUS program. ORNL examined 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 engines, gas engines, or gas turbines, are currently in use 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. This led to the formulation of a program in May 1974, funded and technically directed by the Office of Coal Research (OCR, now part of ERDA), to be carried out at ORNL through HUD.

Phase I of this program, concept and preliminary evaluation, involved the comprehensive review of a wide variety of methods for employing coal in small total energy systems for HUD applications. Completed in July 1974, Phase I demonstrated 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 hot air for expansion in a closed-cycle gas turbine. The thermal efficiency of the closed-cycle turbine is sufficiently high under partial loading, at which MIUS normally operates, to produce power that is economically competitive with power generated by utility companies. The closed-cycle system can convert about 30 percent of the energy in the fuel to electricity and about 50 percent to heat for gas turbine working fluid recuperation and to steam at 250° F or 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 conducted, 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 testing and evaluation. ORNL also has a continuing research and development program in support of this contract.

PROGRESS DURING JULY-SEPTEMBER 1976

Though several bids were received for fabrication of the ORNL-designed furnace, it was decided to permit these bids to expire and later request bids from furnace manufacturers for both design and fabrication. This new approach has the potential advantage of providing a more economical and more nearly commercial design. Efforts expended on the turbine-generator unit involved the analysis of the electronic control package and design of turbine instrumentation and controls.

Fluidizing tests were completed in August using smaller sized limestone in the small cold flow model. The results indicated a considerably lower fluidizing velocity and heat transfer coefficient than had been expected. During subsequent heat transfer tests, coefficients of approximately 70 Btu per square foot per hour per degree Fahrenheit were measured over the velocity range of 1.0 to 2.5 feet per second for ambient temperature air fluidizing the bed.

VI. PRESSURIZED FLUIDIZED-BED COMBUSTION RESEARCH

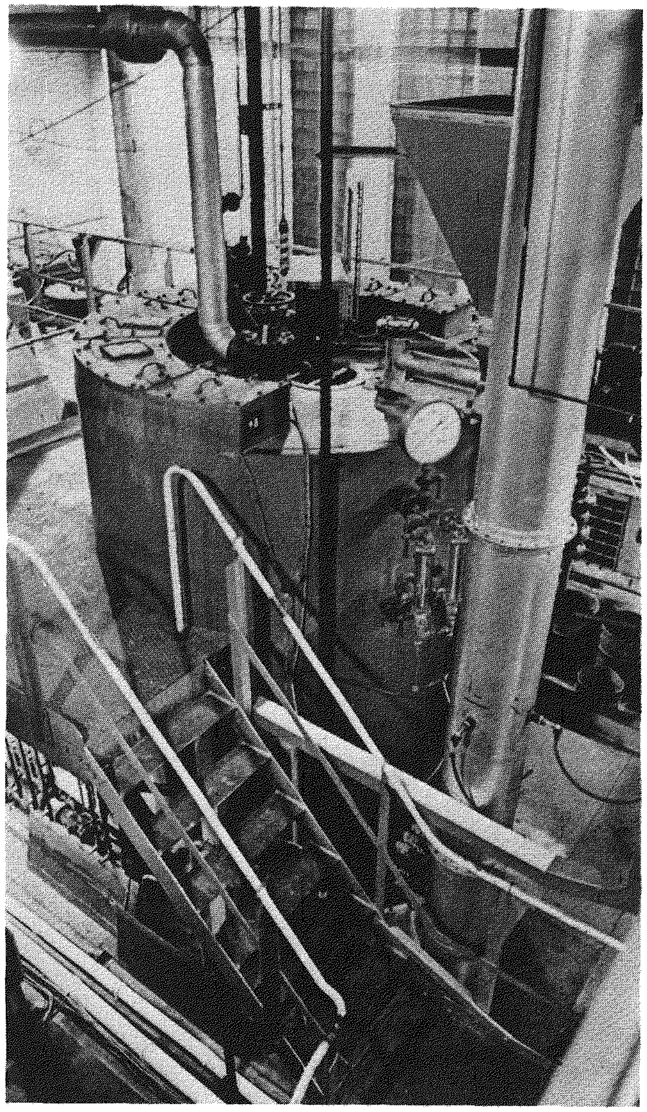
NATIONAL RESEARCH DEVELOPMENT CORPORATION

LONDON, ENGLAND

Plant Site: London, England

Contract No.: E(49-18)-1511

Total Funding: $907,331
(100% ERDA)



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, while obtaining additional research information. The specific purpose of this contract is to establish the effect on performance of:

- Fouling of turbine blades
- Emission of alkalis and sulfur and nitrogen oxides
- Bed behavior (clinker formation) at higher temperatures (1650° F to 1750° F) than previously used for this type of combustor (1470° 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.

PROCESS DESCRIPTION

Figure VI-1 is a schematic of the pressurized fluidized-bed combustor being used in the NRDC test program. The reactor, the principal component of the unit, has a distributor plate in addition to an immersed bank of water-cooled tubes for regulating the bed temperature. Baffle tubes (without cooling) are located

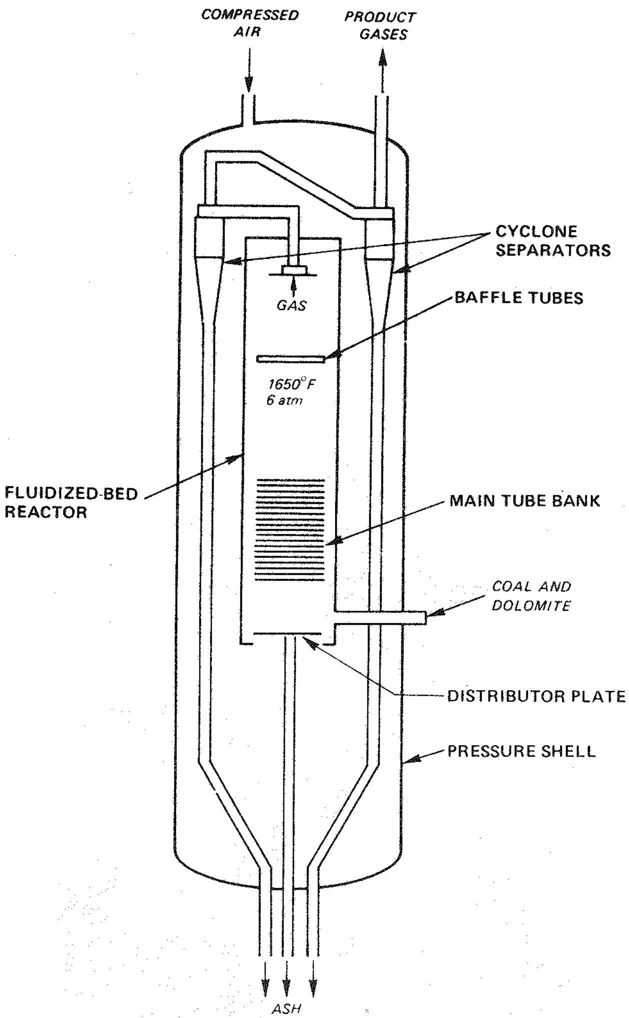


Figure VI-1. NRDC PRESSURIZED FLUIDIZED-BED COMBUSTOR

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 (with an internal diameter of six 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 by NRDC/BCURA on pressurized fluidized-bed combustion involved 1,000 hours of test runs (1968 to 1971) at a bed temperature of 1470° 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 dolomite.

Under the current contract, which began 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, bed temperature and sulfur dioxide acceptor. In these experiments, NRDC/BCURA found that:

- Combustion efficiencies exceeded 99 percent at 1750° F and were only slightly lower at 1650° 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 two.
- 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 1650° F, but were sufficiently extensive at bed temperatures of 1750° 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 is that performance when burning Illinois and Pittsburgh seam coals at bed temperatures of around 1650° F should be as good as the performance achieved in previous tests. 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 operating load range that can be achieved by varying 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 1650° F and an excess air rate of 100 percent, with attention also directed to any primary or secondary cyclone depositions and to cascade erosion, corrosion, and deposition. Currently, contract negotiations are in progress to expand the number of fluidized-bed tests at 1650° F to investigate the effect of various excess air rates, bed depths, and bed velocities on combustion efficiency, sulfur and nitrogen oxides emissions, and circulation. Additional construction materials will be tested for corrosion resistance.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

Though some delays were experienced in July due to labor problems, modifications to the combustor in preparation for Test 6 were completed in September. The delay in July resulted in a three-week setback in the project schedule and equipment problems discovered in September will require two weeks for repair. Test 6 is now scheduled to begin at the end of October.

Other activities included continuation of installation of the combustor by-pass section for Tests 7 and 8 and continuation of negotiations for testing the Curtiss-Wright tube bundle. As currently planned, testing of the bundle will begin in January 1977 with Tests 7 and 8 to follow in April and May.

Discussion of Activities

The major activity continued to be assembly of the combustor in preparation for Tests 6, 7, and 8. Construction was completed in early September. Some delays were experienced in July because of site congestion and labor problems. These were alleviated by increasing shift work, but the delays required revising the project schedule back about three weeks.

Another delay was experienced in September when an equipment fault was discovered during commissioning of the sub-assemblies. The top closure dome of the pressure shell had been installed and instrument lines connected through nozzles in the domes. During commissioning of the temperature measuring systems it was discovered that the pressure seals in the leads through the pressure shell were electrically faulty. The seals will have to be replaced and this will require about two weeks. Following repair of the seals, the combustor will be commissioned, and the refractory baked out. Test 6 is currently scheduled to begin about the end of October.

Negotiations between ERDA, NRDC, and the contractor for ERDA for testing of the Curtiss-Wright tube bundle were nearly completed at the end of September. It is expected that tests with the tube bundle will be carried out at the end of January 1977. Tests 7 and 8 are currently scheduled for April and May 1977.

VII. COAL-OIL SLURRY COMBUSTION PROGRAM

ERDA/FE *with in-house technical support of:*
PITTSBURGH ENERGY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA

INTRODUCTION

A coal-oil slurry combustion project is being conducted by the Pittsburgh Energy Research Center (PERC) to provide ERDA with an in-house tehnical capability in support of its coal-oil slurry combustion program. The purpose is to investigate and validate the potential of this near-term retrofit technology for oil conservation and increased coal utilization. PERC is presently operating a 100 Hp firetube oil-fired boiler on coal-oil slurry and 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 objective of the CTF program is to demonstrate the value of using coal-oil slurries in commercial oil-fired boilers without the need for extensive retrofitting modifications. Because coal-oil slurries often demonstrate physical properties and combustion characteristics different from conventional petroleum-based fuels, new burner designs and system requirements will have to be developed. Fuel characteristics affecting the design of feed systems include atomization and mixing of fuel with combustion, air, air preheat requirements, flame characteristics and stability, and heat-transfer properties.

The CTF program will include the following tests:

- Shakedown
- Slurry erosion
- Slurry suspension stability
- Slurry combustion
- Slurry handling
- Slurry characterization
- Flue gas emission control
- Economic analyses of various slurries in retrofitted steam generating plants.

Data collected from the above tests will be used to design combustion systems using various slurries for both industrial and utility boilers.

PROCESS DESCRIPTION

The main components of the CTF include:

- An air cooled steam condenser and condensate unit
- Coal-oil slurry mixing and feed equipment
- Flue gas cleaning equipment
- Fuel storage facilities
- Coal preparation equipment

Raw coal feed is first crushed to —200-mesh and then fed to a slurry mixing tank. Dust is controlled in the crushing area through the use of a pulverizer blower and a cyclone blower and baghouse system. No. 6 fuel oil, heated to 100° F by a suction heater, is mixed with the pulverized coal in the slurry mixing tank. The slurry is then conveyed to a slurry holding tank mounted on a weigh scale. As required, the feed slurry is pumped to a preheater, heated to 300° F, and injected into the air-blown combustor.

Hot flue gas from the combustor is cooled and mixed with pulverized sodium bicarbonate, which absorbs significant quantities of sulfur dioxide present in the flue gas. After the particulates are removed in a baghouse, the clean flue gas is discharged to a 60-foot stack.

The steam produced by the test boiler is condensed in an air-cooled heat exchanger. The condensate is then deaerated, conditioned with chemicals, and recycled to the boiler.

HISTORY OF THE PROJECT

The difficulties of converting oil-fired facilities to coal-firing are well documented. One alternative which has been studied to some extent is the supplementing of fuel oil with pulverized coal-oil slurries. Preliminary studies have shown that this approach would cost less than firing oil exclusively and would require only minimum changes to existing boilerhouse facilities. The development of viable slurry-firing processes poses a short-term solution to restrictions on fuel supplies by reducing oil consumption by up to 40 percent in applicable units now firing with oil. The markets which could make use of this plan include both large and small industrial units and utility companies.

The CTF was designed under the constraints and conditions of a commercial packaged boiler and auxiliaries so as to permit the test results to be applied directly to industrial situations. The CTF will, however, be extensively instrumented and contain a computer-controlled data acquisition system to allow for on-line, real-time, analyses and computations. With this equipment, the operating characteristics will be defined with a minimum of experimental tests.

PROGRESS DURING JULY-SEPTEMBER 1976

A 1000-hour coal-oil slurry combustion test was completed in the 100 HP firetube boiler and several efficiency tests of short duration were conducted. A calculated efficiency of 83 percent was determined for the boiler when firing coal-oil slurry. Measurements of bulk gas temperature were made to define the local thermal environment in those tubes selected for metallographic analysis. Upon completion of the test, the tubes were given a metallographic analysis to determine the erosive and corrosive effects of slurry combustion. Visually, only a light, evenly distributed coating of ash was found in the tubes.

Initially, the 100 HP combustion system was assembled by intentionally using existing or readily available equipment typical of oil-fired combustors. The 1000-hour test served to identify areas where improved control and measurement were required. From the operating experience gained during the test, a number of modifications are planned on the 100 HP boiler, which will improve the operation of the present unit and establish the unit as a quantitative diagnostic tool. As a diagnostic tool, the unit can examine problem areas common to coal-oil slurry combustors and generate guidelines for the instrumentation and control of other facilities.

During the next quarter, redundant measurement, either directly or through calculations based on a related parameter, will be provided for the major flows, i.e., steam, fuel, and air. Improved control of pressure and temperature in the fuel feed train will be provided. A program of temperature measurement will be implemented to permit heat transfer studies between the gas phase and the boiler water in each of the four boiler passes. A study will be started on the flow properties of the slurry, oriented toward slurry settling and the ability of various stabilizers to prevent this settling.

VIII. SOVENT-REFINED COAL (SRC) COMBUSTION TEST PROGRAM

PITTSBURGH ENERGY RESEARCH CENTER
PITTSBURGH, PENNSYLVANIA

INTRODUCTION

As part of the overall ERDA program to increase coal utilization, combustion tests on Solvent-Refined Coal (SRC) are being conducted by the Pittsburgh Energy Research Center (PERC). SRC is a low-ash, low-sulfur, coal-derived fuel having a melting point of less than 300° F and a heating value of approximately 16,000 BTU per pound. Although the process of solvent refining is fairly well defined, there has as yet been no effective evaluation of SRC as a utility boiler fuel. The specific purpose of this project, therefore, is to study the handling, pulverizing, combustion, and fouling characteristics of SRC.

PROCESS DESCRIPTION

The SRC combustion test program uses a multi-burner, water-wall furnace designed to burn pulverized coal at a nominal rate of 500 pounds per hour. The SRC being used in the project was obtained from the six-ton-per-day pilot plant in Wilsonville, Alabama. The material was produced from a high-sulfur Illinois coal. The SRC contains 0.8 percent sulfur, 0.3 percent ash, has a heating value of 15,400 BTU per pound, and has a fluid temperature of less than 300° F.

In the test program, the SRC is air dried, transported to a feed hopper, and then conveyed to a pulverizer by a screw feeder. It is then pulverized in an impact mill with integral classification. Previous studies were conducted on hammer mills and ball-and-race type mills, but heat generated by the processes caused the SRC to soften and agglomerate. The possibility still exists, however, that these difficulties could be overcome by strict temperature control of the material in the mill.

After being pulverized, the SRC is pneumatically transported to a recycle loop in the primary air-fuel transport line. This recycle loop minimizes fluctuations in the primary air-fuel ratio. The fuel is then injected through four burners into the furnace, which is seven feet wide, twelve feet high, and five feet deep. In the combustion chamber, the burners impart a swirl to both the primary and secondary air streams.

PROGRESS DURING JULY-SEPTEMBER 1976

During this report period, additional combustion tests were conducted on a combination of solvent-refined coal (SRC) produced at the Fort Lewis, Washington, pilot plant and an Illinois No. 6 coal. A test using 15 percent excess air was conducted to determine the effect of burner operation and combustion efficiency. Combustion appeared to be quite stable; however, some burner deposits were formed. The deposits were not massive, and did not affect combustion during a three-hour test; however, they were more evident than the slight deposits formed during tests at higher excess air levels. Primary air for all SRC combustion tests was held constant to maintain a velocity in the primary stream of 100 feet per second. Excess air was varied by adjusting the secondary air supply.

The pulverizing system of the 500-pound-per-hour combustor was used to prepare pulverized coal for the coal-oil slurry program and resulted in processing more than 22 tons of coal to 90 percent through 200-mesh. It also included frequent screening of samples to monitor size consist. In addition, rescreening was used to verify the final product size. The 90 percent through 200-mesh size consist was of extreme importance in the coal-oil slurry combustion program.

A motion picture is being prepared on solvent-refined coal combustion. This film will include pictures of flames obtained during the combustion tests after each of several modifications of burner design.

In the next quarter, the effect of turndown on combustion stability, burner fouling, and NO_x emissions with Fort Lewis SRC will be examined. The burner will be further modified to decrease fouling. The uncooled burners normally used when firing coal will be installed to study combustion characteristics of Georgia Tech char and charcoal blends.

IX. ANTHRACITE REFUSE UTILIZATION

MORGANTOWN ENERGY RESEARCH CENTER
MORGANTOWN, WEST VIRGINIA

INTRODUCTION

Anthracite refuse and silt bank materials which have resulted from the mining and cleaning of anthracite coal in the northeastern section of Pennsylvania are potential sources of low-carbon, high-ash fuel. The mining region in which the material is located covers only about 480 square miles and is fairly densely populated. The U.S. Bureau of Mines has estimated that within the area there are 800 banks containing a total of 910 million cubic yards of refuse. This material has been deposited by mining operations and reject streams from preparation and cleaning plants over the history of the region. The deepest layers of material were deposited over 100 years ago when preparation methods were crude, whereas the surface layers have resulted from much better washing procedures and are therefore essentially depleted of coal. Some of the older banks have been reworked in recent years using better cleaning methods to recover the coal and consequently the characteristics of the refuse varies widely from bank to bank and even within a single bank.

The Morgantown Energy Research Center (MERC) is investigating the combustion characteristics of the refuse materials in a fluidized-bed combustor. Due to the declining mining activity in the area and the subsequent growing dependence on oil, the value of the refuse as a fuel is becoming increasingly important. In addition, the refuse banks are aesthetic eyesores in the community, are occupying valuable land which could be used for other purposes, and constitute a potential health and safety hazard due to the likelihood of spontaneous combustion. The use of the material as a fuel in fluidized-bed combustors would not only provide a needed energy source in the area, but would also reduce some of the problems currently associated with the banks.

PROCESS DESCRIPTION

The MERC atmospheric pressure fluidized-bed combustor is a refractory-lined cylindrical combustor with an 18-inch internal diameter in the bed region and 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 ¼-inch 310 stainless steel pipe with individual water flow controls were installed.

Fuel is pneumatically injected into the base of the combustor with ambient-temperature air. Fluidizing air is supplied through a plenum which feeds several orifices in the conical distributor. Solids which are removed from the exiting flue gas in the primary cyclone are reinjected into the bed by an air injector for carbon burnup. Flue gases leaving the cyclone are further cleaned by a secondary cyclone and parallel bag filters prior to discharge through the stack. Gases are sampled at the combustor outlet for on-line analysis purposes. Excess spent bed material is withdrawn through the apex of the inverted conical air distributor by a screw feeder.

A five-day operating period is typical for the combustor. Startup begins by preheating the empty combustor vessel with a premixed natural gas-air flame through the air distributor. Upon reaching operating temperature, the fluidized bed is built by feeding either a 50-50 mixture (by weight) of anthracite coal and inert material (such as limestone) or with refuse directly. When the planned depth has been achieved, the natural gas flow is curtailed and the temperature of the bed is stabilized by adjusting water flow in the submerged heat exchanged followed by reinjection of the primary cyclone ash. The complete startup procedure requires two to four hours from cold lightoff to stabilization of temperatures with normal feeding of refuse and reinjected ash.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

Using the MERC 18-inch fluidized-bed combustor, four tests were conducted on refuse material from the Butler Colliery Bank and one test was conducted using Kaminski No. 14 bank anthracite refuse (culm). Sulfur dioxide emission levels from the tests using material from the Butler Colliery Bank were low enough that limestone addition was not required. Though some clinkering was encountered during the tests, the operation of a newly-installed overflow tube averted a shutdown. A final report on anthracite refuse utilization is being prepared and plans are being made to test both oil shale and subbituminous coal in the fluidized-bed unit.

Discussion of Activities

Four combustion tests were conducted during the quarter on refuse material from the Butler Colliery Bank in Lucerne County, Pennsylvania using the MERC 18-inch fluidized-bed combustion. The analysis of this refuse was:

moisture	2.11 wt. percent
ash	60.34
sulfur	0.45
hydrogen	2.04
total carbon	29.56
nitrogen	0.62
oxygen	4.88
heating value	4950 Btu/lb
ash fusion	IDT >2605° F

Operating temperatures during the runs were 1450°, 1600°, and 1750° F and superficial velocities were three and six feet per second. Feed rate was held fairly constant at 90-95 pounds per hour and U-tube heat exchangers immersed in the bed were used to control temperature. During all four runs it was not necessary to add limestone to control the sulfur dioxide emissions, as these levels ranged from 0.5 to 1.0 pounds of sulfur dioxide per million Btu, well below the standard of 1.2 pounds per million Btu.

During the first two runs, the ash reinjection system did not operate due to a pinched-off air supply to the nozzle; however, the unit was operational during the second two runs. In order to alleviate the problem of overheating and destruction of the ash screw, an overflow tube was installed on the unit. Although some clinkering was encountered in the later tests, drainage of the bed by use of the overflow tube averted a shutdown.

A 4½-day run was conducted in September to determine the burning characteristics and heat release capabilities of Kaminski No. 14 bank anthracite refuse (culm). Three test periods were completed during the run. The operating conditions were:

- bed temperature 1600° F
- coal rate 95-96 lb/hr.
- superficial velocity 3 feet per second
- limestone addition rate 0.5 lb/hr.

All operating parameters were the same except that two test periods were run without recycle of the dust from the primary cyclone.

A final report on the fluidized-bed combustion of anthracite refuse and culm is being prepared and will be completed in late October or early November. A firm date for the Battelle-EPA sampling run, previously scheduled for August, has not yet been established. Initial planning is also underway for the installation of a six-foot by six-foot cold model. The unit is to be delivered in November. Efforts are also being made to acquire oil shales and subbituminous coal samples for feasibility tests in the 18-inch combustor.

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: $67,302
(100% ERDA)

INTRODUCTION

Under the sponsorship of ERDA, the Construction Engineering Research Laboratory (CERL), U.S. Department of the Army, is evaluating the efficiency of a patented (U.S. Patent No. 3,815,336) Particle Precipitating Heat-Transfer Surface (PPHTS) device in removing dust particles from the high-temperature exhaust gas streams of fluidized-bed combustors. The fluidized-bed combustor being used in the project 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, which began in July 1975, is scheduled for completion by mid-1976. The tasks included in the project are:

- 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

PROGRESS DURING JULY-SEPTEMBER 1976

The principal program effort has been directed toward compiling, preparing, and drafting the various component sections of the final report. Certain relatively minor and unforeseeable operational and procedural problems have resulted in delays in completing the final report; however, these problems reportedly are being resolved and it is believed that the report will progress at a smoother pace in the coming reporting period.

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: $112,000
ERDA: $100,000
FEA/EPA: $12,000

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 greatest possibility of near-term implementation. Therefore, Exxon Research and Engineering Company is conducting a research program to study the diverse industrial applications of fluidized-bed combustion technology. The project is being sponsored jointly by ERDA, the Environmental Protection Agency (EPA), and the Federal Energy Administration (FEA).

The objective of this study is to conduct economics, energy, and environmental analyses of the industrial applications of atmospheric and pressurized fluidized-bed technologies as methods 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. In addition, fluidized-bed combustion systems are expected to surpass air quality standards for stationary source emissions.

PROGRAM DESCRIPTION

The program was initiated in January 1975 and is scheduled for completion in late 1976. The study will consider both new and retrofitted atmospheric fluidized-bed boilers with steam output capacities ranging from 10,000 to 400,000 pounds per hour. The effects of fluidized-bed combustion technology will be evaluated for each industrial sector, a composite of all industries, localized geographic regions, and the entire nation. The key dates for which these effects will be predicted are 1980, 1985, 1990, 1995, and 2000. The tasks involved in the project are:

- Determination of the applicability of fluidized-bed combustion technology for meeting industrial boiler requirements based on:
  - —life-cycle cost
  - —energy conversion efficiency
  - —reliability
  - —maintenance requirements
  - —stack gas emissions
  - —waste disposal and utilization
  - —required plant characteristics
  - —fuel flexibility
  - —ease of installation and operation
- 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 speci-

fications 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, 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 numbers of fluidized-bed boilers that will be required by industry 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 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.

PROGRESS DURING JULY-SEPTEMBER 1976

Efforts during this review period were concentrated on the preparation of the final project report. The draft of the report was prepared during July and August and was forwarded to ERDA for technical review. This review was in progress throughout the remainder of the quarter.

XII. ON-LINE PARTICULATE ANALYSIS INSTRUMENTATION

LEEDS & NORTHRUP COMPANY
NORTH WALES, PENNSYLVANIA

Contract No.: E(49-18)-2412

Total Funding: $75,816
(100% ERDA)

INTRODUCTION

An on-line particulate analysis instrument is being developed by Leeds & Northrup Company, under ERDA sponsorship, for pressurized fluidized-bed combustion systems. The objective of this project is to design and construct a prototype instrument to measure particulate loadings and particle size distributions in high temperature gas streams and to evaluate this instrument on pressurized fluidized-bed combustion systems. This type of instrumentation will enable near real-time monitoring and analysis of gas entrained particules to evaluate performance of particle separators and to record the size and concentration of particles at the inlet to gas turbines in direct combustion systems. This capability will provide critically needed information relative to analysis of turbine blade erosion problems.

The instrument development work is based on Leeds & Northrup's prior work in low-angle forward scattering of light by suspended particles. The development phase of this project involves extending the method to instrumentation compatible with large gas ducts and applicable to high temperature (1500°-2000° F) and high pressure (up to 10 atm.) gas streams. Following the development phase, a prototype instrument will be delivered to Argonne National Laboratory for initial evaluation on its six-inch fluidized-bed combustor.

MEASUREMENT METHOD

When small particles are illuminated by a laser light source, a diffraction pattern is produced in the Fraunhofer plane of a collection lens. The intensity and angular distribution of the diffracted flux is related to the size of the particle in the illuminating beam. Large particles produce a narrowly defined flux pattern, while smaller particles diffract flux over wider angles and with lower flux intensity. The angular extent of the diffraction pattern is given by the question:

$$\text{Sin } \theta = (1.22/d)\lambda$$

where: θ = half angle to the first minimum of the pattern
λ = wavelength of light source
d = particle diameter

The total intensity of the scattered flux is given by:

$$I = Knd^2,$$

where: I = total diffracted light
K = instrument calibration constant
n = number of particles
d = particle diameter

If a specially shaped spatial filter is placed in the Fraunhofer plane of the collection lens, the intensity of the transmitted scattered light can be made proportional to any power of the particle diameter. In particular, a disk-shaped spatial filter has been designed and constructed to produce signals proportional to the fourth, third, and second power of the particle diameters in the illuminating beam. The three functions are separated in angular extent and rotated to allow serial extraction of information.

The transmission characteristics are optimized through a special computer program based on the mathematical expression (Bessel function) for the intensity distribution of the diffracted flux. The exact spatial filter characteristic design or shape is adjusted so that the response per unit function (d^4, d^3, d^2) is constant for all particles sizes within the range of the measurement. The three signals generated by a rotating disk are collected and averaged over many rotations of the spatial filter. Ratios are computed to find the mean diameter of the particle distributions as well as the variance of the distribution. The d^3 signal is proportional to the volume of particles illuminated and thus can be calibrated for concentration of particles in the fluid stream.

To apply such measurement to hot gas streams requires optical filtering to eliminate infrared radiation emitted by the particles and from the walls of the duct, scaling the size of the optical components for across-the-duct sampling, and working out means for air purge to keep the quartz windows on the duct clear of any deposits. Since it is believed that any particles larger than four microns in diameter are detrimental to turbine blade life, the size range of interest for this instrumentation is 1-50 microns. This range of particle size can be measured using a helium-cadmium laser having a wavelength of 0.325 micron.

PROGRESS DURING JULY-SEPTEMBER 1976

During July, a meeting was held with Argonne National Laboratory (ANL) personnel to discuss measurement and interface requirements. Loading information acquired at the meeting indicated that af the final output filter the particle size is less than 1 microns and the total loading is typically between 0.001 and 0.089 grains per standard cubic foot (70° F, 1.0 atm., dry). At these loadings, multiple scattering should not be a problem.

Additional work was also performed to increase the applicability of the instrument to larger duct sizes and provide greater sensitivity to small particles. The current instrumentation can accommodate duct sizes up to ten inches in diameter. This capability will make the unit compatible with both ANL and Curtiss-Wright combustion systems—one inch and ten inches ID, respectively. A revised instrument configuration was also defined using a folded optical system. This system offers the following advantages:

- Almost 50 percent smaller in size than a linear configuration
- Fits around sample duct close to walls (as little as five inches of clearance required)
- Simplified alignment in the field

Discussions with ANL also revealed that the sample cell being designed by ANL will meet all requirements for a satisfactory interface with the exception of the optical coating on the windows. New windows will be required with the coating appropriate for ultra-violet transmission (325 nm) rather than visible (~550 nm).

During September, the instrument layout was completed and detailed design of mechanical parts was 80 percent completed. The electronics design was 50 percent complete and approximately 80 percent of the hardware was released for fabrication or procurement.

XIII. PARTICLE MEASUREMENT IN FLUIDIZED-BED COMBUSTION SYSTEMS

SPECTRON DEVELOPMENT LABORATORIES, INC.
COSTA MESA, CALIFORNIA

Contract No.: E(49-18)-2413
Total Funding: $17,219
(100% ERDA)

INTRODUCTION

The primary objective of this program is to assess the capability of an advanced diagnostic technique to make required particle field measurements in fluidized-bed combustion (FBC) systems. These measurements are needed, for example, to determine efficiencies of particle separators and filters, and to monitor particle environments at gas turbine inlets of combined cycle systems. Measurements will be made at the Argonne National Laboratory (ANL) FBC facility, and will provide data on particle size and velocity distributions in the combustion gas flows. Currently available SDL laser instrumentation will be used for data acquisition.

PROGRAM DESCRIPTION

Instrument Description

The SDL equipment to be used in this program is a laser light scattering instrument called a Particle Morphokinetometer (PM) system. Key features of the instrument for the FBC application include:

- In-situ measurement
- Simultaneous size and velocity measurement
- Electronic data processing and management
- Continuous and real time data output
- Easy interface with user computer and control systems

The system is shown schematically in Figure XIII-1. The light beam emitted from a continuous wave (CW) laser is divided in two and subsequently re-mixed by optical components. The region where the two beams cross contains the measuring probe volume, remote from instrument hardware. In the probe volume, light from the two beams interfere, resulting in a set of interference fringes as illustrated in the sketch. As particles pass through the probe volume, the interfered light is scattered and collected into a photomultiplier tube (PMT), either in the forward or backscatter mode. The PMT output, shown in the sketch (lower right), is then processed electronically to determine individual particle size and velocity. Velocity is measured by ratioing the fringe period, δ, to the signal time period, τ. Size is determined by a function of the signal AC to DC ratio. Individual measurements can then be displayed one at a time, stored in a histogram generator, or input to user computer or control systems.

PM systems similar to the one to be used at ANL have been employed successfully to measure particle size and velocity distributions in various other applications. These include air pollution particules from airborne platforms, cloud chambers, furnaces, and erosion test facilities.

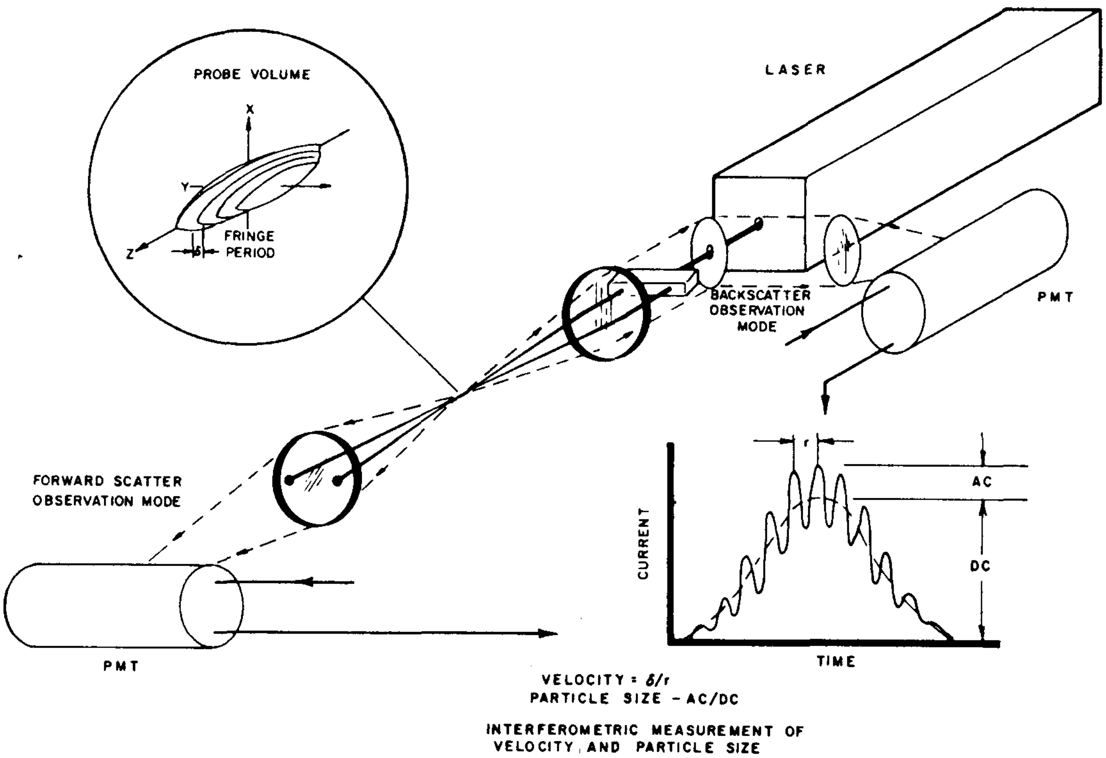


Figure XIII-1. PARTICLE MORPHOKINETOMETER SYSTEM

ANL Application

An SDL PM system will be installed at the ANL FBC facility to measure particle size and velocity in the combustion gas at several different stations. The system will be used in the backscatter mode at ANL. Optical access to the flow will be made through optical windows designed by SDL and installed by ANL.

PROGRESS DURING JULY-SEPTEMBER 1976

During most of this reporting period, there was no SDL activity on the subject contract because windows were not yet installed in the Argonne National Laboratory fluidized-bed combustion facility. Initial tests with the particle morphokinetometer began in late September, however, no results are yet available.

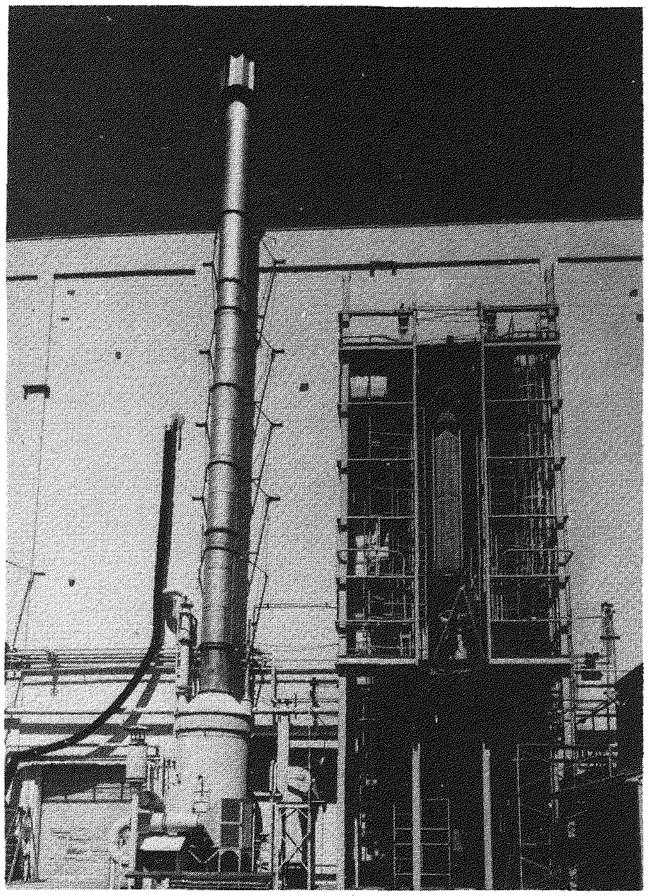
XIV. BOILER TUBE BUNDLE AND BURNER MODULE TESTS WITH POTASSIUM

OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE

INTRODUCTION

Boiler fuel consumption can be reduced by increasing the efficiency of thermodynamic cycles. Little has been done to increase efficiencies since the upper practicable temperature limit (about 1000° F) for the steam cycle was reached more than 25 years ago. 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.

The approach proposed by ORNL involves raising the peak temperature of the thermodynamic cycle by using 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 boiler water of the steam cycle. The combined cycle is similar to the mercury-steam binary vapor cycle used 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 1920's, but by the late 1930's 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 proposed power plant is shown in Figure XIV-1. Three basic systems are combined 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

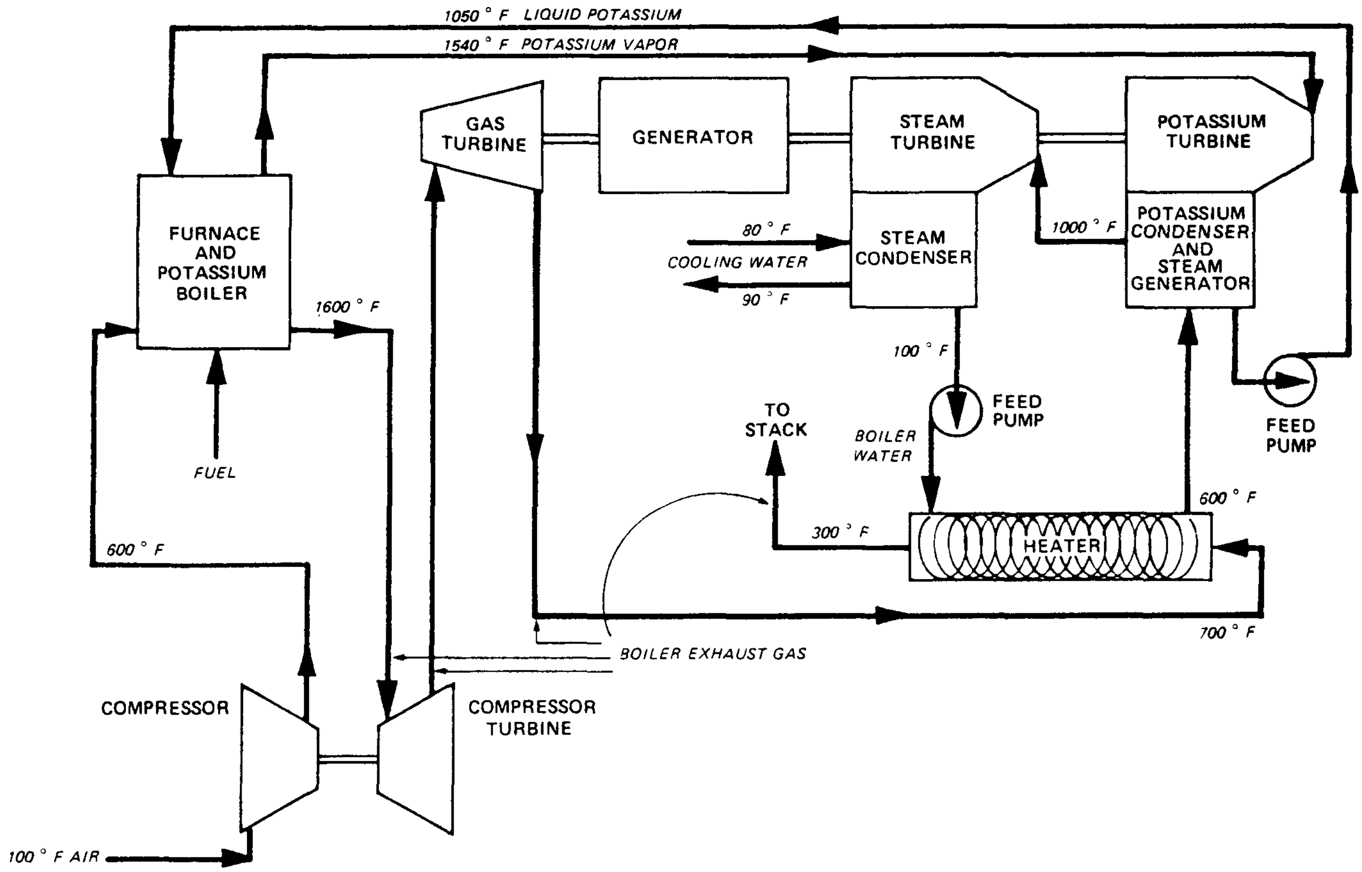


Figure XIV-1. SCHEMATIC OF POTASSIUM VAPOR COMBINED-CYCLE SYSTEM

important components involving new technology are the furnace-potassium boiler and the potassium condenser-steam generator. Both use tube bundle modules as their basic unit of construction.

The ORNL gas- or oil-fired potassium boiler concept employs a basic bundle module composed 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 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 six to ten atmospheres. This is substantially above the two atmospheres 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 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 power plant.

The boiler tube bundles would be mounted in four to eight 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 t' top or the bottom of the furnace.

HISTORY OF THE PROJECT

Potassium Boiler

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, in the course of which ~200,000 hours of boiling potassium system operation was obtained in the early and middle 1960's. When the pressing 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 conducted under National Science Foundation (NSF) sponsorship. 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 the 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 the work were made available by NSF in July, 1972 and NSF funding was continued in 1973. When ERDA was proposed in June, 1973, NSF responsibility for the potassium vapor cycle work became uncertain, with other federal agencies also having claims in this area. As a consequence of these uncertainties, the program remained unfunded through 1974, until some interim funds were made available from NSF, and funds from ERDA-FE finally became available at ORNL for the program in December 1975.

An indication that the potassium boiler presents by far the most important set of uncertainties of any component in the plant, including the turbine, is indicated by the fact that in a study of advanced power systems being conducted for ERDA-FE, the initial capital cost estimate for a potassium vapor topping cycle plant yielded a cost for the potassium boiler that was greater than the sum total for all of the rest of the plant. The ORNL design yields a boiler with a much less expensive material, a weight about half as great, and a potassium liquid inventory less than 1/20 as great as was premised in the study, hence the cost should be much lower. The reason for these large differences is that the other study based the design on conventional, low pressure, horizontal tube, forced convection, steam boiler design practice, whereas the ORNL design is based on a vertical tube, natural thermal convection boiler concept that goes well beyond established practice, although it employs a wealth of experience gained under the space power plant program.

The test program is designed to resolve the many uncertainties that have become evident in the course of the design. These uncertainties fall into four major problem areas:

- Burner performance
- Gas flow, with the associated heat transfer and temperature distribution uncertainties
- Two-phase potassium liquid-vapor flow and temperature distribution
- Vapor separator effectiveness.

All of these characteristics will be very dependent on the heat load. In many cases, the cumulative uncertainties in the analysis are substantial and can be resolved only by obtaining test data.

It is expected that data will be obtained that will give a detailed insight into these problem areas in the course of test with water that were begun in July. In the first phase of the tests, the top of the boiler drum is open so that visual observation of the flow from the boiler tubes is possible. The boiler drum being open will make it much easier to install instrumentation that will yield a detailed picture of the flow distribution in the boiler tubes than will be the case in later tests with potassium.

Potassium Boiler Coupled to a Fluidized-Bed

It has been evident for some time that a particularly attractive system could be obtained by coupling a potassium vapor cycle to a fluidized-bed coal combustion system. The design of a fluidized-bed coal combustion system differs in many vital respects from the design of any of the conventional types of coal-fired furnace. For good fluidization and acceptable stability of the two-phase gas-solid particle flow in the bed, the combustion air must be supplied to the base of the bed through a large number of relatively closely spaced ports orificed so that about one-third of the total pressure drop across the bed will occur at these inlet orifices. To keep the pumping power for the combustion air to a reasonable value, (around two percent of the net power output) the depth of the bed, if it is operated at atmospheric pressure, should not exceed about three feet. This in turn favors the use of horizontal tubes for the heat transfer matrix. If the furnace is supercharged and the combustion air pumping power requirement is kept fixed, the depth of the bed can be increased in direct proportion to the furnace operating pressure. Increasing the bed depth has the advantage from the combustion standpoint of providing more time for fine particles of coal to burn; hence the amount of unburned carbon in the fines blown out of the bed can be reduced as the bed depth is increased. Increasing the bed depth also has the advantage that it makes possible the use of vertical tubes, which is particularly desirable for steam or potassium boilers where it is advantageous to employ natural thermal convection for recirculation of the liquid in the boiler. If the bed is too shallow, the tubes will be too short, the required number of tubes will increase, and the cost of making the tube-to-header joints becomes excessive.

In recent years, much attention has been given to furnaces pressurized to around ten atm, in which case pumping power requirements have been kept reasonable by making the furnace the combustion chamber for an open cycle gas turbine. Design studies of such systems have usually contemplated turbine inlet temperatures of approximately 1600° F. Unfortunately, over 30 years of experience with coal-burning gas turbines indicates that turbine bucket erosion, corrosion, and deposition have proved to be so serious that no one has yet succeeded in operating such units for more than a few hundred hours prior to a forced outage for at least a cleaning operation. This work has also shown that, if the turbine inlet temperature can be reduced to about 1000° F the problems with turbine bucket erosion, corrosion, and deposition become tractable and long turbine operating lives can be obtained. The best evidence to support this is the fact that dozens of gas turbines are in use for pressurizing blast furnaces, and these have demonstrated operating lives of the order of 100,000 hours without a need for major maintenance work.

Recent studies at ORNL indicate that a promising compromise is to operate the fluidized-bed at a pressure of three atm with a bed depth of about eight feet and an eight-foot-high plenum chamber above the bed to permit particles lifted out of the bed an opportunity to fall back into the bed and recirculate. The hot gases leaving the bed can be cooled to approximately 1000° F before being admitted to a gas turbine to give a power output just sufficient to drive the compressor. This arrangement has the additional control advantage that the gas turbine need not run at synchronous speed but rather can operate at much reduced speeds during the startup or intermediate power conditions.

The ORNL fluidized-bed potassium boiler concept proposed follows the above approach in part for the reasons cited above, and in part to avoid the difficult creep-buckling problems associated with operati tubes, header drums, and manifolds at high temper ture and under a large external pressure. This was a major factor in the large estimated boiler weight and cost in the study cited above.

PROGRESS DURING JULY-SEPTEMBER 1976

Summary

The installation of the gas-fired potassium boiler module was completed and boiling tests using water were begun. The boiler has been operated at various power levels up to about 2 x 10^6 Btu/hr. The major part of the mechanical design of the potassium fill and drain system and the potassium condenser was completed. The work statement for a reference design study of a 200 Mw coal-fired fluidized-bed alkali metal boiler power plant for potassium and cesium was prepared.

Water Tests

The installation of the gas-fired boiler module system for water tests was completed about mid-July. After the system installation was completed, the boiler was flushed with demineralized water several times.

During the checkout of the system, the pilot lighted several times and then became inoperable. This was found to be the result of faulty insulation around the pilot ignitor electrode, thus allowing the spark current to leak off before it reached the spark gap. The insulation design was modified to prevent this and the pilot burner would then light reliably.

Efforts to light the main burner were at first unsuccessful and this led to the conclusion that part of the combustion air was bypassing the main burner and leaking directly to the exhaust duct across the sliding seal between the burner housing and the boiler shroud. Several tests were conducted to determine the magnitude of this leakage. The main gas line was disconnected and an argon supply was connected in its place. The flame detector was removed from the pilot system and a ⅜-inch OD sample tube was inserted through the pilot tube to a point about eight feet above the burner cup. With a known quantity of argon flc ing into the system through the burner, varyi amounts of air were admitted to the furnace through the main combustion air lines. Samples of the air/gon mixture were taken from the sample tube over the burner and also from a sample port in the exhaust duct. Analysis of these samples for argon concentration and subsequent calculations indicated that about 40 percent of the combustion air entering the furnace bypassed directly to the exhaust duct and did not go through the burner. The combustion air flow was increased to compensate for the leakage and the main burner then lit reliably. This modification will make it possible to complete the water tests without modifying the seal.

Argon is supplied at two points in each of the bottom liquid headers to promote boiling nucleation when operating with potassium in the boiler. One of the objectives of the water tests was to determine if the argon was properly distributed so that the flow in each tube was sufficient to promote nucleation. Visual observation of the argon bubbles in the water leaving the boiler tubes without the burner in operation indicated that the argon was not being distributed uniformly to the boiler tubes, with most of the argon going up the tubes adjacent to the injection point. With the burner operating, visual observation was difficult due to steam generation. A method was devised for measuring the argon flow rate to the individual tubes of the boiler. Water and argon are removed from a point about ten feet down in the boiler tube and passed through a flask where the argon is separated from the water and the collection rate is measured. The water is returned to the boiler tube so that there is essentially no net disturbance in flow at the entrance or exit of the boiler tube. Using this system, tests are being made to determine the argon flow rate to the individual tubes. Results from a representative sample of the tubes are very encouraging in that they indicate that an adequate argon flow is present in each of the tubes.

One matter of concern that can affect the integrity of the boiler is the temperature distribution in the tube bundle as the burner is turned on and the system is brought up to boiling. Analysis of the startup conditions had indicated that once the temperature of the liquid in the boiler tubes was only slightly higher than the liquid temperature in the downcomers, a thermal circulation current would be set up if the boiler drum were filled with liquid to a level above the outlet of the boiler tubes. This liquid flow would tend to equalize the temperatures in the tube bundle and prevent any high thermal stresses from differential thermal expansion. The temperature distribution observed during startup of the boiler indicated that good liquid circulation was present and the maximum temperature difference between the tubes in the outer row and the tubes in the inner row was only about 45° F, with the downcomer temperature running between the temperatures of the inner and outer tube row. The temperature of the outer tube row gradually came up to about the same temperature as the inner row as the water temperature came up to the boiling point.

Potassium System Design and Fabrication

Very good progress was made on the design of the components and system modifications that are required for the potassium test and fabrication work was begun. The potassium system instrumentation flowsheet was completed and is near approval for release.

The majority of the mechanical design work on the potassium fill and drain system and the air-cooled condenser was completed. Six drawings of the potassium fill and drain system and ten drawings of the condenser and its enclosure were completed and released. Drawings of the condenser outlet air plenum are underway.

Fabrication work was initiated on the fill and drain tank, the vapor piping connection to the condenser, the condenser enclosure, and the air ducts.

Fluidized-Bed Furnace—Alkali Metal Boiler design

The work statement for a reference design study of a 200 Mw power plant employing a coal-fired fluidized bed alkali metal boiler was prepared. The study will include designs for potassium and cesium boilers at three levels of operating pressure in the fluidized-bed furnace. The objectives of the study are to choose potassium or cesium as the working fluid and select a reference design.

XV. INDUSTRIAL APPLICATION OF FLUIDIZED-BED COMBUSTION PROCESSES

INDUSTRIAL SUPERHEATED STEAM BOILERS

COMBUSTION ENGINEERING COMPANY

Sub-scale Unit Site:	*Windsor, Connecticut*
Demonstration Unit Site:	Great Lakes, Illinois
Contract No.:	No. E(49-18)-2473
Total Funding:	*Under Negotiation*
Projected Start-up:	February 1980

INDUSTRIAL BOILERS

GEORGETOWN UNIVERSITY

WASHINGTON, D.C.

Project Site:	Washington, D.C.
Contract No.:	No. E(49-18)-2461
Total Funding:	*Under Negotiation*
Projected Start-up:	October 1978

BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES

COLUMBUS, OHIO

Project Site:	Columbus, Ohio
Contract No.:	No. E(49-18)-2472
Total Funding:	$5,256,355 *ERDA: $3,397,131* *Industry: $1,859,224*
Projected Start-up:	October 1979

INDIRECT FIRED HEATERS

EXXON RESEARCH AND ENGINEERING COMPANY
FLORHAM PARK, NEW JERSEY

Sub-scale Unit Site:	Florham, Park, New Jersey
Contract No.:	No. E(49-18)-2471
Total Funding:	$4,008,375
	ERDA: $3,274,757
	Industry: $ 733,618
Projected Start-up:	June 1979

FLUIDYNE ENGINEERING CORPORATION

Sub-scale Unit Site:	Minneapolis, Minnesota
Demonstration Unit Site:	Owatonna, Minnesota
Contract No.:	No. E(49-18)-2463
Total Funding:	$4,415,612
	ERDA: $2,878,385
	Industry: $1,537,227
Projected Start-up:	October 1979

SUPPORT STUDIES

ARTHUR G. McKEE AND COMPANY

Contract No.: EX-76-C-01-2418
Total Funding: $483,400

INTRODUCTION

During the past decade, the federal government has evaluated direct combustion of coal by the fluidized-bed combustion process. As a result of these evaluations, it has been determined that the fluidized-bed combustion process can efficiently convert coal to usable power in an environmentally acceptable manner. In order to develop the fluidized-bed combustion concept for demonstration in the industrial sector, ERDA issued Program Opportunity Notice (PON) FE-1, a part of the National Energy Research, Development, and Demonstration Program. Four categories of application were identified and defined:

Category I—An industrial steam generator capable of producing steam of the quality and quantity for back pressure turbines, industrial processes, and heating requirements.

Category II—An industrial boiler with the capability of producing steam of the quality and quantity suitable for process heating and space heating requirements of industrial or institutional facilities.

Category III—An indirect-fired heater, utilizing tubes or other heat exchange devices, designed to heat process liquids or gases.

Category IV—A direct-fired heater capable of heating process materials by direct contact between the combustion gases and the process materials.

In each of the PON contracts, the program objectives as stated in the PON are:

- Identify and conduct evaluations of industrial boiler or process heater requirements to determine the applications in which fluidized-bed combustion is technically, economically, and environmentally feasible.
- Design, construct, operate, test, and demonstrate prototype boilers or heaters to burn coal and other fuels in an environmentally-acceptable manner.
- Obtain sufficient data from prototype operations to design and construct a commercial-size unit.

PROGRAM DESCRIPTION

General

In the fluidized-bed combustion process, crushed coal is burned in a bed of granular particles which are maintained in suspension by an upward flow of air. Heat energy from the bed is transferred to another fluid through tubes immersed in the bed of hot granules. The overall heat transfer obtained in this manner is greater than in conventional combustion processes. If limestone is used as the granular bed material, the sulfur liberated from the coal combines with the available calcium and forms calcium sulfate, thus reducing the flue gas desulfurization requirements.

Industrial Superheated Steam Boilers

Nearly half of the fuel used by industry is consumed in the firing of boilers for process steam, space heating, and on-site power generation. Nearly an equal amount is consumed in the generation of electricity by utilities. Coal was once the dominant fuel used for industrial boilers, but presently accounts for only about one-quarter of boiler fuel demand. Under contract No. E(49-13)-2473, Combustion Engineers will design, construct, operate, test, and demonstrate a fluidized-bed boiler incorporating natural circulation.

Industrial Boilers

Supplementing the general objectives of the PON, Georgetown University will design, construct, and operate an atmospheric fluidized-bed boiler using high-sulfur coal designed to function as a source of steam Georgetown University. Also supplementing the general objectives of the PON, under Contract No. (49-13)-2472, Battelle will determine the feasibility of using fluidized-bed combustion techniques to decrease oil and gas consumption. In addition to the general objectives as expressed in the PON, the specific objectives of this contract are to:

- Extend the state-of-the-art of fluidized-bed coal combustion to higher heat release rates and air velocities by use of the multi-solids fluidized-bed concept.
- Design, construct, operate, test, and demonstrate a prototype high-velocity fluidized-bed steam generator which will burn high-sulfur coal in an environmentally-acceptable manner. The steam generator will be operated as a lead steam generator in an industrial steam plant.

Indirect-Fired Heaters

Between four and eight percent of the crude oil processed in oil refineries is consumed to maintain the refinery operations. Under contract No. E(49-13)-2471, Exxon will determine the feasibility of using coal combustion processes to satisfy this energy requirement, resulting in a decrease in oil consumption. In addition to the general objectives as expressed in the PON, the specific objectives of this contract are to:

- Extend the state-of-the-art of fluidized-bed coal combustion to applications wherein oil passing through tubes immersed in the bed will absorb heat energy for subsequent refining and processing.
- Design, build, operate, test, and demonstrate a fluidized-bed indirect-fired process heater operating as an integral part of a petroleum refinery.

Supplementing the general objectives of the PON, FluiDyne will design, construct, test, operate, and evaluate an atmospheric fluidized-bed air heater and distribution system using high-sulfur coal and secondary fuels, designed to generate 900° F air in a metalworking manufacturing plant.

Support Studies

Arthur G. McKee and Company was awarded a contract which is not part of the PON contracts, but is directly related to them. McKee will provide general and technical assistance to ERDA in the areas of scheduling, specification evaluation, and program review.

XVI. MODELING OF FLUIDIZED-BED COMBUSTION PROCESSES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Contract No.: No. E(49-18)-2295
Total Funding: $945,000

INTRODUCTION

The modeling of the fluidized-bed combustion of coal is planned by the Massachusetts Institute of Technology (MIT) under this program sponsored by ERDA. The specific objective of the contract is to develop a phenomenologically-based system model for the coal-fired fluidized-bed combustion process.

PROGRAM DESCRIPTION

The 21-month program began in May 1976. Three main tasks are included in this program:

Task I—Data Base Establishment

A data base will be established containing all information available on fluidized-bed combustion, with emphasis directed to the use of coal as the primary fuel. All information acquired will be stored using an established, comprehensive, well-documented data storage and retrieval system.

Task II—Modeling

Using the data base established in Task I, a comprehensive model of the coal-fired fluidized-bed combustion process will be designed and implemented. The model will consist of four sub-models: combustion, fluid dynamics/heat transfer, desulfurization, and materials.

Deficiencies of data will be documented for Task III action. Reasonable estimates will be made for information not available.

Task III—Documentation

Three final documents will be prepared:

- The model document will describe the status, capabilities, and deficiencies of the model developed for the coal-fired fluidized-bed combustion process.
- The planning document will provide detailed data deficiencies, the most likely sources of that data, and the rationale for the course of action and the necessary timing.
- A manual of instructions will be prepared for prospective users of the data base and computer model.

XVII. FLUIDIZED-BED WASTE MATERIAL UTILIZATION: SOIL MODIFICATION

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Total Funding: $1,500

TENNESSEE VALLEY AUTHORITY

Contract No.: E(49-18)-2411

Total Funding: $29,000

UNITED STATES DEPARTMENT OF AGRICULTURE

Contract No.: E(49-18)-2488

Total Funding: $1,766,548

UNITED STATES DEPARTMENT OF TRANSPORTATION

Contract No.: E(49-18)-2491

Total Funding: $42,750

INTRODUCTION

When coal, containing three percent sulfur and 12 percent ash, is burned in fluidized-bed boilers along with a quantity of limestone sufficient to maintain a molar ratio between 2:1 and 3:1 of calcium to sulfur, between 400 and 600 pounds of waste bed material is generated for each ton of coal burned. About 50 percent of this waste material is drawn from the fluidized-bed, the rest being discharged as fly ash. The material drawn from the bed usually consists of 25 to 35 percent unhydrated lime, 50 to 60 percent calcium sulfate, and varying amounts of silica, aluminum, iron, and magnesium oxides. ERDA has funded ous studies to demonstrate the effectiveness of using this fluidized-bed combustion (FBC) waste for agricultural purposes, as a liming material, and as a soil stabilizer.

PROGRAM DESCRIPTION

Virginia Polytechnic Institute and State University will continue studies which began two years ago using the atmospheric FBC waste bed material as a nutrient source of calcium for crops.

The Tennessee Valley Authority will demonstrate the use of FBC waste bed material in agriculture and as a liming source in a program consisting of four tasks:

- Field experiments studying the utilization of FBC waste material as a nutrient source of calcium and sulfur for crops.
- Pot experiments evaluating FBC waste as a source of sulfur and micronutrients, and as a liming material.
- Field experiments determining the maximum non-toxic loading rates for soils having various textures and for selected crops.
- Field experiments determining the amount of waste material required to neutralize acid mine spoils and the subsequent effect on plant growth.

The Agriculture Research Service, United States Department of Agriculture, will evaluate the solid wastes from FBC processes for potential use in agriculture by detailed chemical and physical analysis of the material, followed by extensive greenhouse, growth chamber, and field studies.

The Federal Highway Administration, United States Department of Transportation, will assess the utilization of FBC waste bed material for remedial treatment of soils. The objective of this study is to determine whether FBC waste bed material can be used for soil stabilization. The program consists of four tasks:

- Physical, chemical, and mineralogical properties of FBC bed waste material will be determined.
- Twenty soil samples will be selected from areas where FBC installations will likely be located.
- Various mixtures of the soils and the waste material will be tested to evaluate the effectiveness of this waste material relative to conventional stabilization additives.
- Tests will be performed as in the previous tasks, but various additives such as flyash, lime, and waste cement kiln dust will also be tested.

XVIII. COMBINED-CYCLE ELECTRIC POWER GENERATION USING PRESSURIZED FLUIDIZED-BED COMBUSTION

CURTISS-WRIGHT CORPORATION
WOOD-RIDGE, NEW JERSEY

Plant Site: Wood-Ridge, New Jersey
Contract No.: E(49-18)-1726
Total Funding: $27,500,000

INTRODUCTION

Curtiss-Wright Corporation, under the sponsorship of ERDA, is conducting a program to design, construct, operate, and evaluate a coal-fired combined-cycle pilot plant for electric utility power plant applications using pressurized fluidized-bed (PFB) technology and high-sulfur coals. The program was initiated on March 1, 1976. The pilot plant program is a five-year, four-phase effort. Phase I is a 14-month program to provide:

- Conceptual design of a commercial coal-fired 300-500 Mw combined-cycle generating station using the PFB combustion technique.
- Pilot plant design which is representative of the commercial concept.
- Pilot plant site and environmental assessment study.
- Technology support programs which provide data on the performance of the selected PFB design.

Phase II is an eight-month effort to complete the detail design drawings and specifications of the pilot plant, prepare a construction bid package, and obtain bids for evaluation. Phase III is a 20-month construction period for the manufacturing, buildup, and installation of the pilot plant. The final phase is a month effort to operate the pilot plant and to evalu- operating parameters and durability using several coal types. At the conclusion of this phase, a reassessment of the commercial plant conceptual design will be conducted.

PROCESS DESCRIPTION

The pilot plant will be designed and constructed by converting an existing power generating station located at Curtiss-Wright's Wood-Ridge, New Jersey facility. This station consists of a gas turbine-driven alternator and a waste heat recovery boiler. The station currently provides the facility's requirement for electric power and steam for processing and heating. The gas turbine's liquid or gas fuel combustor will be replaced with a pressurized fluidized-bed combustor capable of operating on crushed coal feed.

A flow diagram of the projected pilot plant is shown in Figure XVIII-1. The PFB process involves the combustion of coal in the presence of a sulfur sorbent material, such as limestone or dolomite, at a temperature below 1750° F. Bed temperature is controlled by extracting heat from the bed with a tubular heat exchanger using air as the coolant in the tubes. Approximately one-third of the air flow from the compressor is used for combustion and the remainder is used as the bed coolant. The coolant air is heated nearly to bed temperature and is mixed with the com-

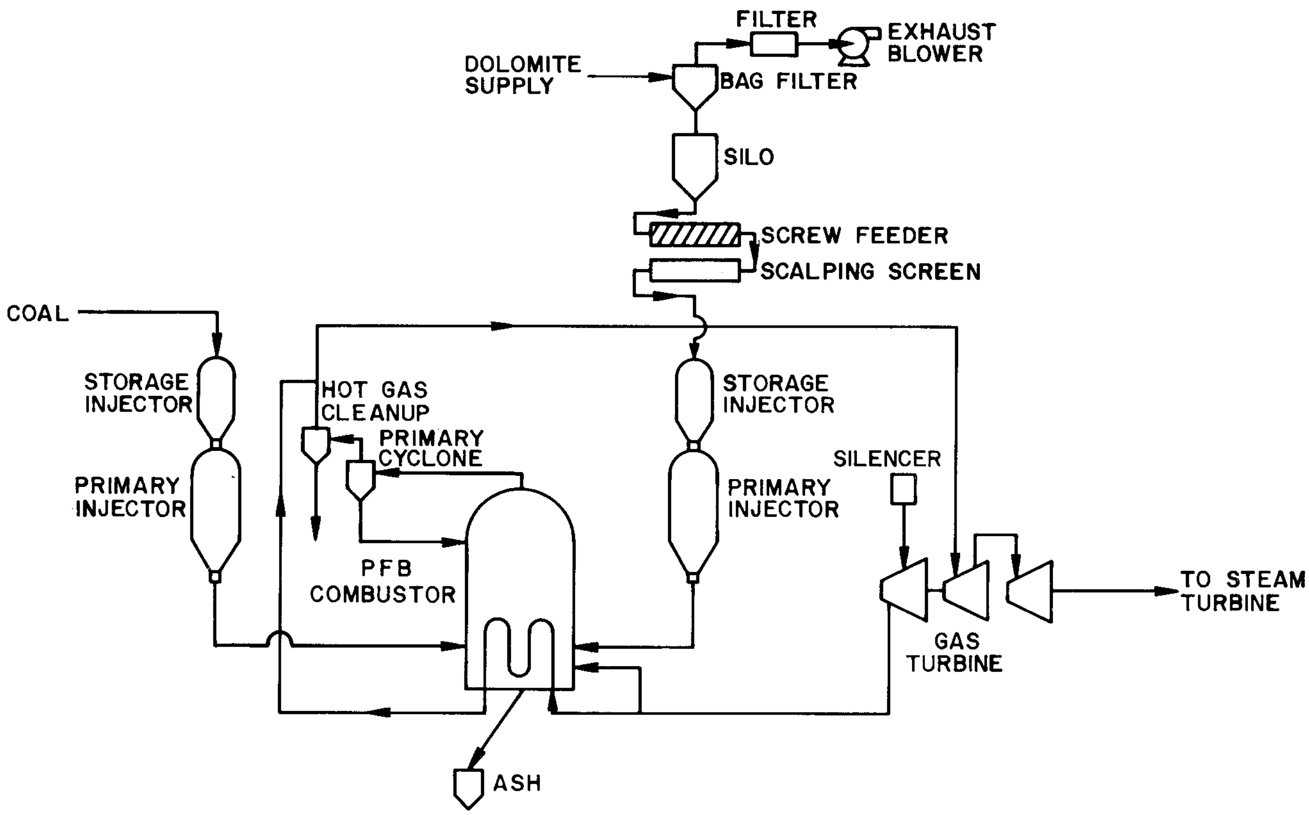


Figure XVIII-1. SCHEMATIC OF CURTISS-WRIGHT PRESSURIZED FLUIDIZED-BED COMBUSTION/COMBINED-CYCLE PILOT POWER PLANT

bustion gas from the bed prior to entering the turbine. The large quantity of air flow which bypasses the direct combustion process improves turbine durability by minimizing the corrosive and erosive effects of particulates and alkali salts in the combustion gas stream.

The bed and heat exchanger are supported by a distributor plate which is used for injecting the fluidizing air from the compressor. Coal and sorbent material are separately metered by a pressurized lock-hopper injector system and are fed into the combustor bed zone. The bed level is maintained by periodically removing spent material from the bottom of the bed. This ash is fed into a solids cooler and lock-hopper system for eventual disposal.

Ash entrained in the combustion gas leaving the bed is removed in the primary and secondary cyclones. The ash from the primary unit is recycled to the PFB and that from the secondary unit is directed to the solids cooler for disposal.

Plant start-up is accomplished by operating the gas turbine on a liquid or gaseous fuel fed to an auxiliary combustor. Another auxiliary combustor is operated to heat the PFB. When the bed temperature is sufficiently high, coal is injected into the PFB and ignition and combustion occurs. The auxiliary combustors are gradually shut off as the coal flow is increased to full operating conditions.

A power turbine, not mechanically coupled to the gas turbine, drives a 50 or 60 Hz alternator and produces approximately two-thirds of the combined-cycle total power. The gas leaving the power turbine enters a waste heat recovery boiler in which steam is generated to drive a steam turbine/alternator set. The total power generated by the combined-cycle system is produced at a thermal efficiency significantly higher than either the gas turbine cycle or the steam turbine cycle can provide separately.

Because of the relatively low combustion outlet temperatures, emissions of oxides of nitrogen can be controlled to a level below the current emission stanc of 0.7 pounds of NO_2 per million Btu. In additic.., the use of the sulfur sorbent material in the bed allows ›issions of sulfur oxides to be below the current .ndards of 1.2 pounds of SO_2 per million Btu.

HISTORY OF THE PROJECT

Fluidized-bed technology was first used commercially in the fields of mining and metallurgy in the 1940's, and more recently in chemical processing, heat-treating, and combustion systems. During the 1960's, work was initiated in both Britain and the United States on the development of fluidized-bed coal combustion systems for the generation of electric power. The systems under development are:

- Atmospheric—in which the combustion takes place at or near atmospheric pressure.
- Pressurized—in which combustion occurs at pressures up to ten atmospheres.

First generation fluidized-bed combustors have been used primarily as steam boilers. The steam produced is used to drive a conventional steam turbine coupled to an electric generator. More advanced power systems, which offer higher thermal efficiency in converting heat energy to electrical power, are currently under investigation. The most technically developed by these advanced systems is the combined gas turbine-steam turbine cycle. Combined-cycle systems are currently in use by utilities, burning petroleum fuels, to provide intermediate and peaking electrical load service.

Recognizing that the combination of pressurized fluidized-bed technology and the gas turbine-steam combined-cycle power system offers the opportunity for the production of clean, cost-competitive electric power from the combustion of high-sulfur coal, ERDA contracted with the Curtiss-Wright Corporation to design, construct, and operate a pilot electric power plant. Phase I of the program, initiated on March 1, 1976, includes the following tasks:

- Task 1—Preliminary Engineering
- Task 2—Pilot Plant Preliminary Design
- Task 3—Site Evaluation
- Task 4—Pilot Plant Environmental Analysis
- Task 5—Technology Rigs
- Task 6—Management
- Task 7—Reliability and Quality Assurance
- Task 8—Documentation and Reporting

PROGRESS DURING JULY-SEPTEMBER 1976

During this quarter, the conceptual design of the commercial electric power generation plant continued for the 300-500 Mw central station. Off-design performance analysis for the gas turbine and overall power plant was completed for 20 to 100 percent gas turbine power and a range of ambient temperatures. The design of the gas turbine power train, fluidized-bed combustor, and heat exchanger is nearing completion. Work is also continuing on the commercial plant environmental engineering and the capital and operating costs estimates for the plant.

Pilot plant site evaluation continued and reports were prepared on real estate description, topographic analysis, soil boring sampling, and meteorologic/climatologic analyses. Development work continued on brazing techniques for fabricating PFB heat exchanger finned tubes. Ultrasonic inspection methods were also developed to confirm fin attachment to the tubes.

The initial heat exchanger tube specimens for testing in the existing Dorr-Oliver 12-inch atmospheric fluidized-bed combustor were made and installed in the rig at Dorr-Oliver's Springdale Laboratory. Testing was initiated and will continue throughout the next quarter. In preparation for commercial fluid bed corrosion/erosion material tests, arrangements were made to install test fixtures of various materials in two Dorr-Oliver fluidized-beds at existing commercial facilities. The fluidized-bed erosion rig for testing tubing materials was modified to provide 1600° F bed temperature and the machining of specimens was begun.

Small gas turbine/PFB combustor and heat exchanger test rig system performance and process analyses were initiated to establish combustor design and material handling requirements. Preliminary design studies of the combustor vessel, first-stage clean-up cyclone filter, ash return, and ash removal systems was also started. Performance specifications for the coal and dolomite material handling equipment were prepared and the existing coal storage facility was prepared for receiving rail shipments of unprepared coal.

GLOSSARY

absorption—an imprecise term suggesting the taking up of one substance by another by either a physical process or a chemical combination.

acceptor—calcined carbonate that absorbs carbon dioxide evolved during gasification, liberating heat.

acid gas removal—the process of selectively removing hydrogen sulfide and carbon dioxide from a 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 process by which the surface of a solid or liquid attracts and holds any atom, molecule, or ion from a solution or gas with which it is in contact.

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

anthracite coal—hard coal containing 86 to 98 percent fixed carbon and small percentages of volatile material and ash.

API—American Petroleum Institute.

API gravity—a scale adopted by the API for measuring the density of oils; $° \text{API} = \dfrac{141.5}{\text{Specific gravity, } 60°\text{F}/60°\text{F}} - 131.5$

aromatic hydrocarbon—a cyclic hydrocarbon containing one or more six-carbon (benzene) rings.

ash—solid residue remaining after the combustion of coal.

ASTM—American Society for Testing Materials.

autoclave—a vessel, constructed of thick-walled steel, for carrying out chemical reactions under high pressures and temperatures.

bench-scale unit—a small-scale laboratory unit for testing process concepts and operating parameters 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 non-coking coals.

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

blow down—periodic or continuous removal of water from a boiler to prevent accumulation of solids.

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.

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

nation—the process of heating a solid to a high temperature .o cause the decomposition of hydrates and carbonates.

calorific value—the quantity of heat obtained by the complete combustion of a unit mass of a fuel under prescribed conditions.

carbon fiber—fine filaments of carbon about eight microns in diameter which are used in composite materials, being bound with resins.

carbonization—destructive heating of carbonaceous substances with the production of a solid, porous residue, or coke, and the evolution of a number of volatile products. For coal, there are two principal classes of carbonization, high-temperature coking (about 900° C) and low-temperature carbonization (about 700° C).

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 which utilizes the centrifugal force generated to separate materials of different densities, e.g., undissolved residue from coal solution in the SRC process.

char—the solid residue remaining after the removal of moisture and volatile matter from coal.

Claus process—industrial method of obtaining elemental sulfur through the partial oxidation of gaseous hydrogen sulfide in air followed by catalytic conversion to molten sulfur.

coal—a readily combustible rock containing more than 50 weight percent and more than 70 volume percent of carbonaceous material including inherent moisture, formed from compaction and induration of variously altered plant remains similar to those in peat.

coalification—metamorphosis of vegetable debris into coal.

coke—strong porous residue consisting of carbon and mineral ash formed when bituminous coal is heated in a limited air supply or in the absence of air. Coke may also be formed by thermal decomposition of petroleum residues.

coke breeze—the fine screenings of crushed coke usually passing a ½-inch or ¾-inch screen opening.

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

combustion gas—gas formed by the combustion of coal, e.g., burning.

combustor—a vessel in which combustion takes place.

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—impure gas produced in a gasifier.

culm—the waste or slack from anthracite mines or preparation plants consisting of fine coal, coal dust, and dirt.

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 removing naturally occurring methane from coal seams.

delayed coking—a process wherein coal is subjected to a long period of carbonization at moderate temperatures to form coke.

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

depolymerization—the change of a large molecule into simpler molecules usually accompanied by the substitution of hydrogen for oxygen in the molecular structure.

destructive distillation—the distillation of coal accompanied by its thermal decomposition.

desulfurization—the removal of sulfur from hydrocarbonaceous substances by chemical reactions.

devolatilization—the removal of a portion of the volatile matter from medium- and high-volatile coals.

diatomaceous earth—a yellow, white, or light-gray, siliceous porous deposit made up of opaline shells of diatoms; used as a filter aid, paint filler, adsorbent, abrasive, and thermal insulator. Also known as kieselguhr.

diatomite—See Diatomaceous Earth.

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

distillation—a process of vaporizing a liquid and condensing the vapor by cooling; used for separating liquids into various fractions according to their boiling points or boiling ranges.

dolomite—a carbonate of calcium and magnesium having the chemical formula $CaMg(CO_3)_2$.

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

ebullated bed—gas containing a relatively small proportion of suspended solids, bubbles through a higher density fluidized phase with the result that the system takes on the appearance of a boiling liquid.

economizer—heat exchanging mechanism for recovering heat from flue gases.

effluent gas—gas given off from a process vessel.

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

endothermic reaction—a process in which heat is absorbed.

enthalpy change—the increase or decrease in heat content of a substance or system which accompanies its change from one state to another under constant pressure.

entrained bed (flow)—a bed in which solid particles are suspended in a moving fluid and are continuously carried over in the effluent stream.

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

exothermic reaction—a process in which heat is liberated.

extraction—a method of separation in which a solid or solution is contacted with a liquid solvent (the two being essentially mutually insoluble) to transfer components into the solvent.

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

filter aid—finely divided solids used to increase efficiency of filtering.

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, diatomaceous earth.

Fischer assay—method for determining the tar and light yields from coal or oil shale; conducted in a retort under an inert atmosphere with a prescribed increase in temperature to 500° C.

Fischer-Tropsch catalyst—catalysts developed for the catalytic synthesis of liquid fuels from coal-derived synthesis gas; catalysts contain principally iron, cobalt, nickel, or ruthenium.

Fischer-Tropsch process—method of hydrogenating mixtures of carbon monoxide and hydrogen produced from coal, lignite, or natural gas by means of steam, at 1–10 atmospheres and 360–410° F to yield liquid and gaseous fuels, and a wide spectrum of industrial chemicals.

fixed-bed—stationary solid particles in intimate contact with fluid passing through them.

fixed carbon—the solid residue, other than ash, obtained by destructive distillation; determined by definite prescribed methods.

flash carbonization—a carbonization process characterized by short residence times of coal in the reactor to optimize tar yields.

flue gas—gaseous combustion products.

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)—gas-solid contacting process in which a bed of finely divided solid particles is lifted and agitated by a rising stream of gas.

fluidized-bed—assemblage of small solid particles maintained in balanced suspension against gravity by the upward motion of a gas.

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.

freeboard—the space in a fluidized-bed reactor 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.

Friedel-Crafts reaction—a substitution reaction, catalyzed by aluminum chloride in which an alkyl (R-) or acyl (RCO-) group replaces a hydrogen atom of an aromatic nucleus to produce a hydrocarbon or a ketone.

fuel cell—a galvanic cell in which the chemical energy of a conventional fuel is utilized to produce electricity.

fuel gas—low heating value (150–350 Btu/scf) product generally utilized on site for power generation or industrial use.

gasification of coal—the conversion of solid coal into a gaseous form by various chemical reactions with steam.

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

heat capacity—quantity of heat required to raise the temperature of one pound of a substance one degree Fahrenheit.

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

higher-heating value (HHV)—the heat liberated during a combustion process in which the product water vapor is condensed to a liquid and the heat of condensation is recovered.

hydroclone—a small cyclone extractor for removal of suspe 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.

:oking—coking of tars, SRC, etc., under hydrogenating onditions to form liquid products.

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

hydrogasification—gasification that involves the direct reaction of fuels with hydrogen to optimize formation of methane.

hydrogenation—chemical reactions involving the addition of gaseous hydrogen 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 conversion to liquid products of lower boiling range which are then dissolved by the solvent.

hydrotreating—a process to catalytically stabilize petroleum or other liquid hydrocarbon products and/or remove objectionable elements from products or feedstocks by reacting them with hydrogen.

ideal gas—any gas whose equation of state is expressed by the ideal gas law, namely $PV = nRT$ where P is the pressure, V is the volume, R is the gas constant, T is the absolute temperature, and n = number of moles.

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

industrial gas—See Fuel Gas.

inerts—constituents of a coal which decrease its efficiency in use, e.g., mineral matter (ash) and moisture in fuel for combustion.

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

intermediate-Btu gas—synthesis gas product with a higher heating value between 350 and 500 Btu per standard cubic foot.

lignite—brownish-black coal containing 65–72 percent carbon on a mineral-matter-free basis, with a rank between peat and subbituminous coal.

limestone—sedimentary rock containing 50 percent carbonate (CO_3) of lime or magnesia. Chemical formula (for culcite limestone) is $CaCO_3$.

liquefaction—conversion of a solid to a liquid; with coal, this appears to involve the thermal fracture of carbon-carbon and carbon-oxygen bonds, forming free radicals. These radicals abstract hydrogen atoms yielding low molecular weight gaseous and condensed aromatic liquids.

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 up to 350 Btu per standard cubic foot.

lower heating value—the heat liberated by a combustion process assuming that none of the water vapor resulting from the process is condensed, so that its latent heat is not available.

MAF—moisture and ash-free; a term that relates to the organic fraction in coal.

mesh—measure of fineness of a screen, e.g., a 400-mesh sieve has 400 openings per linear inch.

ation—the production of methane (CH_4) from carbon onoxide or dioxide and hydrogen.

methane—CH_4, a colorless, odorless, and tasteless gas, lighter than air; the chief component of natural gas.

methanol—methyl alcohol, CH_3OH.

micron—a unit of length equal to one millionth of a meter; 10^{-6} meter.

moving bed—particlized solids in a process vessel that are circulated (moved) either mechanically or by gravity flow.

natural gas—naturally occurring gas extracted from sedimentary structures consisting mainly of methane and having a higher heating value of approximately 1,050 Btu per standard cubic foot.

noncoking coal—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.

peat—an unconsolidated, hydrophilic, yellowish-brown to brownish-black, carbonaceous sediment, formed by accumulation of partially fragmented and decomposed plant remains in swamps and marshes which retains more than 75 percent inherent moisture and less than 12 percent mineral matter in saturated natural deposits.

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 (OH) group directly attached to the benzene ring.

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 technical and economic feasibility of the process.

pipeline gas—a methane-rich gas that conforms to certain standards and has a higher heating value between 950 and 1,050 Btu per standard cubic foot.

plenum chamber—an enclosed space through which air is forced for slow distribution through ducts.

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 system used to study the effects of process variables on performance; sized between a bench-scale unit and a pilot plant.

proximate analysis—analysis of coal based on the percentages of moisture, volatile matter, fixed carbon (by difference), and ash, using prescribed methods. Reported on different bases, such as as-received (or as-fired), dry, mineral-matter-free (mmf), and dry mineral-matter-free (dmmf).

purification—removal of a wide range of impurities present in gases from coal gasification.

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

quenching—cooling by immersion in oil, water bath, or water spray.

Raney nickel catalyst—specially prepared nickel catalyst used in the hydrogenation of organic materials and the methanation of synthesis gas to methane.

raw gas—See Crude Gas.

reactivity—susceptibility to chemical change; for example, in coal liquefaction, the reactivity of the coal for conversion to liquid products is a function of the coal rank, among other things.

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 componds, hydrogen cyanide, and carbon dioxide are removed from the gas stream by the methanol at temperatures below 0° C.

reducing gas—a gas which, at high temperatures, lowers the state of oxidation of other chemicals.

reforming processes—a group of proprietary processes in which low-grade or low molecular weight hydrocarbons are catalytically converted 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 a relatively low thermal conductivity.

residence time—time spent by a typical particle in a particular zone.

saturated hydrocarbon—a carbon-hydrogen compound with all carbon bonds filled; that is, there are no double or triple bonds as in olefins and acetylenes.

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

seam coal—coal which is intermediate in rank between bituminous coal and anthracite; contains 8 to 22 percent volatile matter and from 91 to 93 percent carbon.

semi-water gas—a mixture of carbon monoxide, carbon dioxide, hydrogen, and nitrogen, obtained by passing an air-steam mixture through a hot bed of coke, having a higher heating value of 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 scrubber employing a suitable sorbent.

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

slag—molten coal ash composed primarily of silica, alumina, iron oxides, and calcium and magnesium oxides.

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; liquid used to dissolve a substance.

solvent extraction—selective solution of 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) [illegible]taining about 0.1 percent ash and about 10 percent [illegible] 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—volume of a gas (measured at standard temperature and pressure) or liquid passing through a given volume of catalyst in a unit time.

specific gravity—ratio of the weight of any volume of a substance to the weight of an equal volume of water at 4° C.

specific heat—heat capacity of a substance as compared with the heat capacity of an equal weight of water.

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 moisture and mineral-matter-free basis.

substitute natural gas (SNG)—a gas produced from coal, oil sands, or oil shale 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, coal extracts, oil sands, or oil shale, which is similar to petroleum crude.

synthesis gas—a mixture of hydrogen and carbon monoxide which can be reacted to yield 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.

turndown ratio—the minimum ratio of actual flowrate to design flowrate at which a process unit can be operated.

ultimate analysis—the determination by prescribed method of carbon and hydrogen in the material as found in the gaseous products of its complete combustion, the determination of sulfur, nitrogen, and ash in the material as a whole and the estimation of oxygen by difference; may be reported on different bases, such as as-received (or as-fired), dry, mi[illegible] matter-free (mmf), and dry mineral-matter-free (dmmf).

Venturi scrubber—a gas cleaning device which involves the injection of water into a stream of dust-laden gas flowing at high velocity through a contracted portion of a duct, thus transferring the dust particles to the water droplets which are subsequently removed.

volatile matter—those constituents of coal, exclusive of moisture, that are liberated from a sample when heated to 1750° F for seven minutes in the absence of oxygen.

water gas—gas produced by the reaction of carbon (in coal or coke) and steam to yield 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.