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U.S. DEPARTMENT OF ENERGY
Division of Coal Conversion

QUARTERLY REPORT

January-March 1977

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Publication Date: December 1977

**POWER-COSTS
& BUS-LOADS**

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COAL POWER & COMBUSTION

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QUARTERLY REPORT

JANUARY - MARCH 1977

U.S. DEPARTMENT OF ENERGY

Division of Coal Conversion

Washington, D.C. 20545

Publication Date: December 1977

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FOREWORD

This document was prepared by the Energy Research and Development Administration (ERDA) prior to the activation of the Department of Energy (DOE) by P.L. 95-91 on October 1, 1977. Therefore, wherever ERDA is mentioned, it should be noted that its functions have been transferred to DOE.

The technical reviews contained in this document were prepared by Cameron Engineers, Inc., Denver, Colorado, based on information supplied by DOE and its various contractors. The reviews, as they appear herein, have been authorized for publication by representatives of DOE. Cameron Engineers, Inc. assumes responsibility for the accuracy of the reviews but not for the accuracy of the information provided by either DOE or its contractors.

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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 rapidly as possible, ERDA is sponsoring a variety of research and development projects. Responsibility for designing, constructing, and operating a *Multicell Atmospheric Pressure Fluidized-Bed Boiler* at the Monongahela Power Plant in Rivesville, West Virginia, was contracted to Pope, Evans and Robbins, Inc. This improved combustion design is to be used to produce steam for conventional power generation. The system features sulfur removal during combustion and the use of modular "cells" to facilitate construction and improve plant operability and reliability. All of the auxiliary systems subcontract work was completed at the Rivesville facility during the quarter. Laboratory work consisted of continued hot mode testing and evaluation of the Alexandria unit as a Carbon Burnup Cell with flyash. A coal feeder test and evaluation program was also initiated.

The Lewis Research Center, National Aeronautics and Space Administration, through contracts with several corporations, conducted an *Energy Conversion Alternatives Study (ECAS)* wherein performance and economic comparisons were made of advanced power generation technologies. The Evaluation of Phase 2 Conceptual Designs Report, NASA TM X-73515, was published during the quarter.

Combustion Power Company, Inc. completed all of the experimental work for development of a *Pressurized Fluidized-Bed Combustion and Turbine Power Generation* system using high-sulfur coals, and combining desulfurization with combustion. The final report, "Energy Conversion from Coal Utilizing CPU-400 Technology," was published during March.

Supportive Studies of Pressurized Fluidized-Bed Combustion at Argonne National Laboratory included the continuation of the cyclic sorbent utilization experiment on the limestone and coal being used by Pope, Evans, and Robbins in the atmospheric pilot plant at Rivesville. Studies during the quarter were also aimed at providing information on synthetic sorbent development, limestone characterization, trace elements, and emission controls.

The coal feed system for the *Externally Fired Gas Turbine for Modular Integrated Utility Systems (MIUS)* was modified during the quarter. A 1000-hour endurance test was completed by Oak Ridge National Laboratory. Metallographic examination of samples cut from corrosion specimen tubes was nearly completed also.

Test No. 6 in the *Pressurized Fluidized-Bed Combustion Research* program being conducted by National Research Development Corporation was completed during the quarter. The combustor was modified and Test No. 7 was performed at higher fluidizing velocities.

Combustion tests in the 100-HP boiler used in the *Coal-Oil Slurry Combustion Program* were conducted by the Pittsburgh Energy Research Center during the quarter to establish a configuration for the fuel circulating system which would permit stable operation. Based on the projected 18-month architectural and engineering management schedule, the overall project design and construction of the 700-HP Combustion Test Facility is approximately 30 percent complete. Results of tests performed in the *Solvent-Refined Coal (SRC) Combustion Test Program*, also being conducted by the Pittsburgh Energy Research Center, were reported. The agricultural waste char program was completed on the 500-pound-per-hour combustor. Pulverization of coal for the coal-oil slurry combustion program was continued during the quarter.

A rough draft of the anthracite refuse test report was completed by the Morgantown Energy Research Center in conjunction with its *Anthracite Refuse Utilization Program*. Construction of the second 18-inch fluidized-bed combustor was 80 percent complete at the end of the quarter. Construction also continued on the cold model combustor.

The final report of the *High Temperature Dust Control* study was completed by the U.S. Army Construction Engineering Research Laboratory.

The dust-extraction properties of an array of particle precipitating heat transfer surfaces were evaluated.

The final report of Exxon Research and Engineering Company's analysis of *Applications of Fluidized-Bed Combustion Technology to Industrial Boilers* was published in January. The document is available through the National Technical Information Service, Springfield, Virginia 22161, NTIS No. PB264528.

Leeds and Northrup Company has developed an instrument for *On-Line Particulate Analysis Instrumentation* experiments for fluidized-bed combustion systems. Problems with the laser developed in March, thus delaying shipment of the particle analyzer to Argonne National Laboratory (ANL).

Spectron Development Laboratories completed a report concerning the Particle Morphokinometer System for the *Particle Measurement in Fluidized-Bed Combustion Systems* used at Argonne National Laboratory.

The scope of the *Boiler Tube Bundle and Burner Module Tests With Potassium* being conducted by Oak Ridge National Laboratory was redefined during the quarter. The primary effort was concentrated on a parametric analysis of various plant arrangements with both cesium and potassium as the working fluid, and the design and analysis of a vertical tube natural circulation boiler for a pressurized furnace.

Work continued on the *Industrial Application of Fluidized-Bed Combustor Processes*. In the development of an industrial superheated steam boiler, Combustion Engineering, Inc. continued activities within Phase I of the program, completing the initial testing of the two-dimensional model. Georgetown University and Battelle Memorial Institute, Columbus Laboratories, continued their work on industrial boilers. Work on the development of an industrial boiler with all natural circulation boiler circuitry was in progress at Georgetown University. Design of the subscale experimental unit was completed by Battelle and construction began in February. Exxon Research and Engineering Company and Fluidyne Engineering Corporation continued their work on indirect-fired heaters. Exxon's efforts were directed toward the planning and design of the laboratory units which are to be a part of the Phase I program. Construction of the two-dimensional flow visualization unit continued during the quarter. Assembly of the coking unit test facility began in March. Planning and design of a high temperature heat flux unit was also started. Fluidyne Engineering Corporation completed the conceptual design of an atmospheric-pressure fluidized-bed combustion system during the quarter.

The *Modeling of Fluidized-Bed Combustion Processes* included the continuation of the study of gas solid reaction kinetics throughout the quarter.

A desulfurization program was also developed, designed to predict the sulfur dioxide effluent gas concentration as well as the sulfur acceptor stone utilization in a continuously operated fluidized-bed combustor.

Four separate contractors are investigating the potential of *Fluidized-Bed Waste Material Utilization*. A three-year study of the application of the material to farm acreage was completed in March at the Virginia Polytechnic Institute and State University. The Tennessee Valley Authority continued studies to measure liming effects of the material. Additional agriculture-related studies were conducted by the Agricultural Research Service. The Federal Highway Administration assessed the chemical composition of the material and its value for use in soil stabilization applications.

Combined-Cycle Electric Power Generation Using Pressurized Fluidized-Bed Combustion is the objective of a study conducted by the Curtiss-Wright Corporation. Preliminary design of the pressurized fluidized-bed pilot plant continued during the quarter.

Burns and Roe Industrial Services is preparing an *Evaluation of a Pressurized Fluidized-Bed Combustion (PFBC) Combined-Cycle Power Plant Conceptual Design*. During the quarter, it was decided to concentrate all future work on the cycle containing pressurized fluidized-bed combustors exhausting to gas turbines followed by a steam-cooled atmospheric pressure fluidized-bed boiler.

The *Coal-Fired Combined-Cycle Development Program* is being developed under a contract with General Electric Energy Systems. The commercial plant design study continued during this quarter with primary emphasis upon trade-off studies not dependent on tube bundle testing.

A *Diagnostics Assessment for Advanced Power Systems* is being prepared by Sandia Laboratories. The techniques for the determination of particle size distribution, particle mass loading density, gas velocity, gas temperature and species concentrations were investigated during the quarter.

A *Combined Cycle Research Program* is underway by Massachusetts Institute of Technology to provide essential data for the future development of combined cycle power plants. During the quarter, the waste cooling facility was successfully operated under pressure. Cascade operating parameters and airfoil instrumentation location were established. Corrosion studies also continued.

A stacked bed *Atmospheric Fluidized-Bed Combustor/Component Test and Integration Unit* being built by Morgantown Energy Research Center will address and resolve a number of key fluidized-bed combustor/boiler

development technical issues. Forty percent of the engineering design work for the facility was completed by the end of the quarter.

A conceptual design for a 3 MW *Pressurized Fluidized-Bed Component Test and Integration Unit* was completed by Argonne National Laboratory. The unit is intended to support the pressurized fluidized-bed combustor development program by providing the flexibility to investigate alternative and advanced concepts of fluidized-bed combustion.

The *High Temperature Turbine Technology (HTTT) Program* addresses many of the critical problems concerning gas turbines in a coal-fuel combustion environment. Because of the scope of the engineering involved, four companies were awarded contracts under the program. Curtiss-Wright Corporation, General Electric Company, United Technologies Corporation, Westinghouse Electric Corporation.

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
Contract 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 an 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 fluidized-bed, with two additional horizontal bundles, the evaporator and

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

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 tubes 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 is expected to contain approximately 0.1 pound of carbon per pound of coal feed and is, therefore, 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 this carbon burnup cell whereas coal is burned at 1550°F in cells A, B, and C. The mixing tendencies of the fluidized bed are enhanced 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 ingredient 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 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 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. Champion and PER jointly review and approve structural drawings prior to fabrication. Construction of the Rivesville facility was nearly completed in 1976. Equipment was tested for acceptance and cold mode test operations performed. Coal was first combusted successfully in December.

Concurrent with work on the 30 Mw boiler, PER has continued its laboratory research program, including cold-model and fluidized-bed module tests. Construction to operate the fluidized bed as a carbon burnup cell (CBC) was completed and testing began.

PROGRESS DURING JANUARY-MARCH 1977

Summary

All of the auxiliary systems subcontract work was completed at the Rivesville facility during the quarter. The first light-off of Cell C was accomplished in February as was further operation of Cells C and D. Laboratory work consisted of continued hot mode testing and evaluation of the Alexandria unit as a Carbon Burnup Cell (CBC) with fly ash. A coal feeder test and evaluation program was also initiated in the laboratory.

Plant Activities

The major portion of the Rivesville MFB plant activities in January was concentrated on sustaining coal combustion in Cell D and preparation for light-off of Cell D. The first light-off of Cell C was accomplished in February, as was further operation of Cells C and D.

A series of cold-mode air-flow tests were completed in March. In addition, a detailed light-off procedure for all four cells was developed for use by MFB operations personnel. All of the auxiliary systems subcontract work was also completed in March.

Laboratory Research

During January, laboratory activity concentrated on operation of the Alexandria, Virginia unit as a Carbon-Burnup Cell (CBC), burning high carbon content flyash. The objective of the testing was to find combinations of operating conditions which would give both a 2000°F bed temperature and five percent residual oxygen in the flue gas. The desired combustion conditions were achieved by operating with both a shallow bed and low gas velocity.

Activities in February concentrated on operation of the unit in a continuous mode. One purpose of these tests was to generate sufficient spent bed material, approximately 20 tons, to satisfy requirements of other ERDA contractors.

A coal feed evaluation program was started during March. The Petrocarb, Inc. flyash injection system was modified for use as a coal injection system with various coal feeding arrangements. Two light-off procedures were developed for the Rivesville multicell fluidized-bed boiler. One procedure used No. 4 heating oil to heat the bed to ignition temperatures. The other involved a normal light-off procedure on a partially slumped bed, accomplished by partially blocking off a portion of the bed plate.

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II. ENERGY CONVERSION ALTERNATIVES STUDY (ECAS)

LEWIS RESEARCH CENTER, NATIONAL
AERONAUTICS AND SPACE ADMINISTRATION
CLEVELAND, OHIO

Contract No.: E(49-18)-1751
Contract 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 (performances, economics, en-

- 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

The study was conducted in two phases. Phase 1 consisted of parametric analysis and was completed in 1975. Phase 2 treated conceptual design of certain selected power plants together with development plans and an implementation assessment.

In Phase 1, emphasis was placed on a broad coverage of the energy conversion systems over wide ranges of parametric conditions. Approximately 900 parametric points were calculated by contractor teams led by the General Electric Co. and the Westinghouse Electric Corp. The results were compared and evaluated by NASA. Systems studied in Phase 1 included steam plants with advanced furnaces, open-cycle recuperated and combined gas turbine/steam turbine cycles, helium and supercritical carbon dioxide closed-cycle gas turbine systems, liquid metal Rankine topping cycles, open-cycle and closed-cycle inert gas and liquid metal magneto-hydrodynamic (MHD) systems, and high- and low-temperature fuel cells.

Based on the results of the Phase 1 parametric analyses the Interagency Steering Committee selected 11 concepts for more-detailed evaluation in Phase 2. These included steam systems with both atmospheric- and pressurized-fluidized-bed boilers; combined-cycle gas turbine/steam systems with integrated gasifiers or fired by semiclean fuel; a potassium/steam system with a pressurized-fluidized-bed boiler; a closed-cycle gas turbine/organic system with a high-temperature atmospheric-fluidized-bed furnace; a direct-coal-fired open-cycle MHD/steam system; and a molten-carbonate fuel cell/steam system with an integrated gasifier.

The Phase 2 contractor studies were conducted by teams led by General Electric, Westinghouse, and United Technologies Corp./Burns and Roe and were supplemented by Lewis Research Center analyses and evaluation. Phase 2 was completed in 1976.

Focus on a relatively small number of advanced conversion concepts in Phase 2 permitted technical and economic evaluations to be made in much greater depth than was possible in the Phase 1 parametric analyses.

PROGRESS DURING JANUARY-MARCH 1977

During the quarter, "Evaluation of Phase 2 Conceptual Design's and Implementation Assessment Resulting From the Energy Conversion Alternatives Study (ECAS)" NASA TM X-73515 was published. A comparative evaluation of Phase I results from ECAS was reported in NASA TM X-71855.

The Phase 2 effort consisted of preparation of conceptual designs, research and development plans, and an implementation assessment of the selected systems. The assumptions used for the conceptual designs concerning component performance parameters, design approaches, and/or configurations were estimated characteristics of a mature-technology power plant. The research and development plans and implementation assessment then addressed the time and funding required to bring each power plant to a state of technology for commercial service, the probability of development success, the technological issues, and other factors that might influence the commercial acceptability, and hence implementation, of each power plant.

Results showed that, relative to the base case of conventional fossil fuel steam plants, a significantly lower cost of electricity and overall efficiency can result in the near term from the use of two technologies: fluidized-bed combustion for power plants using conventional steam conditions, and combined-cycle plants in which an advanced open cycle gas turbine discharging into a steam bottoming plant is fueled by an integrated low-Btu gasifier.

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
Contract Funding: \$3,957,388
(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.

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 1/4-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 particles 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 developed 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.

Figure III-1. COMBUSTOR-GAS TURBINE DEVELOPMENT SCHEDULE

Figure III-2. COMBUSTOR-GAS TURBINE SCHEMATIC

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 cooperation 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 particle exhaust emission standards.

Studies of corrosion problems associated with the hot gas from the combustion chamber continued throughout the year. A special report summarizing the testing of 22 alloys with hot combustion gases was published during September. All of the experimental work under this contract was completed in 1976, and drafting of the final report was initiated.

PROGRESS DURING JANUARY-MARCH 1977

The final report, "Energy Conversion From Coal Utilizing CPU-400 Technology," was published during the quarter. Objectives of the ERDA test program included the demonstration and evaluation of total system and subsystem performance, process controllability, and system effectiveness in the suppression of noxious stack-gas emissions, as well as the identification and solution of process and hardware problems and an

assessment of hot corrosion (sulfidation) and means for its prevention.

Over 3000 hours of coal-combustion testing were carried out in a 2.2-square-foot atmospheric combustor and the four-atmosphere PDU, almost all of it with Illinois No. 6 coal containing about four percent sulfur. In almost 600 hours of coal combustion in the PDU, the computerized process-control system demonstrated a capability for accurate automatic control of the process during startup and normal operating modes as well as transient conditions. Combustion efficiency exceeded 99 percent, with minimal afterburning in the combustor freeboard.

In steady-state operation with 300 percent excess air, the stack emissions of nitrous oxide remained consistently below EPA limits. Tests in the atmospheric unit demonstrated over 90 percent sulfur suppression when a cyclone separator returned unspent dolomite fines to the fluid bed. In the PDU, without fines return, acceptable sulfur suppression was approached using an aged dolomite bed, at a calcium to sulfur mole ratio of 1.75.

Reverse-flow inertial separator tubes proved ineffective for hot-gas cleanup because of the stickiness of the ash, which resulted in plugging of the tubes. Cyclone separators alone did not provide removal of fine particulate adequate either to meet environmental standards, or to assure continuous long-term operation of the turbine. A moving-bed granular filter, designed to remove fine particulate not captured by cyclones, showed operational capability, but structural inadequacy of filter-panel support prevented a full evaluation of the device. Evidence indicated that a granular filter will be a necessary part of a coal-burning system.

Temperature, in terms of both level and constancy, is shown to be the single most important factor in determining whether or not sulfidation will occur in a coal-burning system. At 1600°F, with or without additives, no evidence of sulfidation was found in turbine-blade materials; even brief excursions above 1740°F, however, produced easily detectable sulfidation in the more susceptible alloys. The turbine alloys most resistant to oxidation attack in the coal-combustion atmosphere at 1600°F are those containing high aluminum concentrations, such as IN 713 and IN 738; the most resistant non-turbine materials are those high in chromium.

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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 of 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 sub-bituminous.
- 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 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

Figure IV-1. ANL PRESSURIZED FLUIDIZED-BED COMBUSTOR

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 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.

During 1975 the combustion and regeneration units were modified and additional equipment was installed to physically separate the two units and to provide each unit with its own auxiliary equipment. The units were separated to permit concurrent investigations of both the combustion and regeneration processes, thus increasing research capabilities.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Laboratory and bench-scale studies during the quarter were aimed at providing information on regeneration process development, synthetic sorbent development, limestone characterization, trace elements, and emission controls.

Regeneration Studies

The cyclic sorbent utilization experiment which had begun in November with Greer limestone and Sewickley coal continued during the quarter. This limestone and coal are being used by Pope, Evans, and Robbins (PER)

in the atmospheric pilot plant at Rivesville. Eight combustion/regeneration cycles were completed.

The sulfation (combustion) step for each cycle was performed by adjusting the sorbent feed rate to obtain a constant sulfur retention by the sorbent with no virgin limestone makeup. The retention was selected to yield a sulfur dioxide level in the flue gas which meets the EPA standard (1.2 pounds of sulfur dioxide/million Btu). The reactivity of the limestone with sulfur in the first cycle was equivalent to that experienced in PER's atmospheric combustion. Based on the required sorbent mass feed rate, it was found that the reactivity did not change noticeably in the second cycle. After a reactivity decrease in the third cycle, the reactivity remained fairly constant through the fifth cycle. In the sixth through the eighth cycles, the reactivity appeared to decrease again, based on sorbent mass requirements. The regenerability of the sulfated limestones has ranged from 49 to 71 percent, and it appears to be acceptable. The sulfur dioxide concentrations in the off gas ranged from 6.3 to 8.3 percent.

Synthetic Sorbent Development

The final report, "Sulfur Dioxide Removal from Fluidized-Bed Combustors," of a subcontract with Dow Chemical U.S.A. was completed. In these studies, the reactivity of synthetic sorbents with sulfur dioxide was studied. The ANL findings, that calcium oxide-aluminum oxide is the most practical system among the alkaline-earth systems, was confirmed. The study also concluded that this synthetic sorbent cannot be made at a low enough cost to compete with natural sorbents such as

limestone or dolomite. It was concluded that no further work on synthetic sorbents should be conducted.

Limestone Characterization

The capacity of ten different limestones and dolomites to sorb sulfur dioxide was tested. The sulfur dioxide capacity of these ten precalcined stones varied from a low of 60 grams of sulfur trioxide per kilogram of stone to a high of 390 grams per kilogram. In order to understand the reason for this large variation, measurements were made of the pore volume of the calcined stones as a function of pore diameter. The latter data were used to estimate the internal surface area as a function of pore diameter. It was found that the sulfur dioxide capacity of a stone could be correlated with the surface area of the stone for pores whose diameters were above a minimum pore diameter. The minimum pore diameter differed for different stones being a function of the magnesium carbonate to total carbonate ratio of the stone. The larger this ratio, the smaller the minimum pore diameter which may be utilized for sulfur dioxide sorption.

Trace Elements

Twenty experiments were conducted to test the effect of sodium chloride, sodium sulfate, sodium carbonate, calcium chloride, and potassium chloride on the sulfur dioxide capacity of Greer limestone. All of the substances significantly increased the sulfur dioxide capacity of the limestone. The additives were also found to increase the calcination rate of the limestone. It is believed that the crystal size of the calcium oxide produced was changed, and thereby, the porosity and surface area.

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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 IAA-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 from 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 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 bed in the combustion system is composed of a mixture of coal and limestone, the function of the limestone 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.

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

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 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

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

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

The turbine engine intended to be used in the fluidized-bed coal combustion system is a surplus DOD open cycle turbine of suitable size loaned to the project. It was developed by AiResearch Division of Garrett Corporation, and late in the year AiResearch was awarded a contract for engineering studies of design problems involved in adapting this engine to closed-cycle MIUS utilization. The detailed design work was halted in 1976 due to uncertainties related to furnace design and use of the gas turbine. Coal and limestone feed system and cold model tests continued since they are applicable to any furnace design.

PROGRESS DURING JANUARY-MARCH 1977

The coal feed system was modified during the quarter and successfully placed in automatic operation for a 1000-hour endurance run. Following completion of the run in March, the system was disassembled for inspection.

Results of corrosion tests by FluidDyne were received and used to select the specimens for metallographic examination. Tests were nearly completed on samples cut from the corrosion specimen tubes. Preliminary findings indicated no evidence of corrosion.

A draft report on tests of heat transfer rates from a fluidized bed to air-cooled tubes within the bed was completed. Measured heat transfer coefficients were found to be significantly higher than those predicted by published correlations.

VI. PRESSURIZED FLUIDIZED-BED COMBUSTION RESEARCH

NATIONAL RESEARCH DEVELOPMENT CORPORATION

LONDON, ENGLAND

Plant Site: London, England

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

Contract 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 (1450° 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 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

Figure VI-1. NRDC PRESSURIZED FLUIDIZED-BED COMBUSTOR

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 adding 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 reduced below present EPA emission standards by adjusting the calcium-sulfur ratio.
- 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.

The 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. Test 5, completed in 1975, was a 57-hour test using Illinois No. 6 coal at a bed temperature of 1595°F and an excess air rate of about 90 percent. The combustion and sulfur retention efficiencies of the acceptor achieved in Test 5 were similar to those achieved in earlier tests. Emission of nitrogen oxides was lower than expected, given the high excess air rate, and sulfur emission was somewhat higher than expected, possibly because of experimental scatter, the high excess air rate, or feeding dolomite separately from the coal. The equipment showed no hard deposits in the primary cyclone, but some erosion of the refractory in the cyclone. Whether the lack of deposits resulted from operating conditions different from those in previous tests (mainly more excess air) or the modifications of the design could not be determined.

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

Modifications to the combustor in preparation for Test 6 were completed in September 1976. The test was

delayed when an equipment fault was discovered during commissioning of the sub-assemblies. After repair, the combustor was pressure tested and commissioned during the quarter and Test 6 began in mid-November. Coal-burning continued for 70 hours before the unit was shut down due to a complete hold up in the coal feed hopper. Adequate data were obtained, however, to achieve the objectives of Part I of the test. Repairs on the secondary cyclone which interrupted the test were completed and preparation for Part II began.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Test No. 6 was completed during the quarter and modifications of the combustor in preparation for Test No. 7 were also completed. One test at higher fluidizing velocity was completed in March.

Discussion of Activities

Test No. 6/2 was completed in January with a total test time of 78 hours. Apart from intermittent coal feeding irregularities, no particular difficulties were encountered. Operating conditions for Test No. 6 were:

<i>Test</i>	<i>6/1A</i>	<i>6/1B</i>	<i>6/2A</i>	<i>6/2B</i>
Fluidizing velocity, ft/sec	2.75	2.75	2.45	2.45
Bed temperature, °F	1590	1610	1585	1593
Pressure, psig	70	73	73.5	74.0
Excess air, %	25	30	100*	119*
Coal feed rate, lb/hr	573	529	330*	316*
Dolomite feed rate, lb/hr	92	146	80	63

*Approximate values

The object of the tests was to operate the pilot-scale combustor with a deep bed (eight feet) and tall tube bank to determine the effects on combustion efficiency, sulfur dioxide and nitrous oxides emissions and circulation. Results of Test No. 6 indicated that a deep tube bank was not detrimental to operation at fluidizing velocities of approximately 2.5 feet per second.

Modifications to the combustor were completed in March in preparation of Test No. 7. The objective of the test was to operate the pilot-scale combustor for a total run time of 100 hours at a high fluidizing velocity (seven feet per second) and high excess air (100 percent) to determine the effects on combustion efficiency, sulfur dioxide, and nitrous oxide emission and circulation.

One test at the higher fluidizing velocity was successfully carried out. Test duration was 100 hours and data were obtained at approximately 90 and 60 percent excess air. Combustion efficiency was high, temperature distribution throughout the bed was substantially uniform, and there were no signs of sintering or accumulations in the tube bank.

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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 technical 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 boiler applications.

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.

The facility bid package specification was completed by PERC during the first quarter of 1976. Holley, Kenney, Schott, Inc. was selected to do the detailed design of the CTF and act as construction manager. As of the end of 1976, the project was 29 percent complete.

A 1000-hour combustion test was completed in August in the 100 HP firetube boiler. The test identified areas where improved controls and measurements were needed. Consequently, a number of modifications were made to the 100 HP boiler during the last quarter of 1976. A surfactant test program was also begun.

PROGRESS DURING JANUARY-MARCH 1977

Combustion tests were conducted firing No. 6 fuel oil and coal-oil slurries during the quarter to establish a configuration for the fuel circulating system which would permit stable operation. Improved operability resulted from better control of fuel delivery to the burner nozzle. Impingement of the flame on the combustor walls was eliminated by modifications to the diffuser. Combustion tests were conducted firing 20 and 30 percent slurries.

During the next quarter an experimental program will begin, aimed at characterizing the combustion of slurry at various boiler operating conditions and fuel concentrations. Measurements will be made to define combustor temperatures and pressures, gas composition, and ash characteristics.

The equipment to be used in the surfactant testing program was received and assembly was nearing completion. Some preliminary data was obtained, establishing the relationships between coal concentration and specific gravity and coal concentration and viscosity. A test program was defined and some potential stabilizers were obtained from industry for testing.

Based on the projected 18-month architectural and engineering management schedule, the overall project design and construction of the 700 HP CTF is approximately thirty percent complete.

VIII. SOLVENT-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 multiburner, 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 JANUARY-MARCH 1977

Curtailment of natural gas usage, due to extreme weather conditions, prohibited combustion tests for a period of about eight weeks. Natural gas is required to preheat the 500-pound-per-hour steam furnace prior to testing. An alternate fuel system, using bottled liquid propane, was installed and used to complete the agricultural waste pyrolysis char program. Propane also became difficult to obtain.

Since combustion test work was limited, the pulverizer to the 500-pound-per-hour furnace was used to prepare coal for the coal-oil slurry combustion test program (Section VII). The need for fine material, greater than 90 percent minus 200-mesh, along with sieving to guarantee the product size, has resulted in a reduction in the throughput of the pulverizer. Approximately 800 pounds of coal can be processed in an eight-hour day. The 100 HP boiler, firing 20 percent slurry, consumes 600 pounds of coal in an eight-hour day. A separate coal drying and

pulverizing system was purchased to eliminate the dependence of the slurry program on the pulverizer supporting the 500-pound-per-hour combustion system.

When the natural gas situation eases, the SRC combustion program will determine the effect of firing rate upon furnace operability and emissions of nitrous oxides

and hydrocarbons. Additional tests will be conducted to determine the effect of several of these emissions.

Low volatile char, obtained by pyrolysis of agricultural waste, was blended with an equal weight of Pittsburgh seam coal, duplicating an earlier combustion test. This test completed the agricultural waste pyrolysis char combustion program.

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 entire 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 1/4-inch 310 stainless steel pipe with individual water flow controls were installed.

Fuel is pneumatically injected into the base of the combustor with 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 exchanger 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 JANUARY-MARCH 1977

The No. 1 18-inch fluidized-bed combustor was modified to meet the requirements of the EPA/Westinghouse tests. A new plenum and flat plate distributor were designed and fabricated. The run was completed and 500 pounds of bed material were generated for use by Westinghouse in leaching tests for environmental assessment. Pittsburgh seam coal mixed with limestone at a calcium-to-sulfur ratio of 3.5-to-1 was used during the tests. The coal feed rate was 35 pounds per hour and the limestone feed rate was 13 pounds per hour. Sulfur dioxide emissions amounted to 23 ppm, nitrous oxide approximately 400 ppm, and total hydrocarbons were 4.5 to 4.6 ppm.

Basic planning, drawings, and flow sheets are complete and contractors were installing foundations for the six foot by six foot cold model combustor. Overall construction of the No. 2 fluidized-bed combustor was 80 percent complete by the end of the quarter. Both of the units are to be used for the study and improvement of hardware and ancillary equipment. The No. 2 18-inch hot model will be used for sorbent and heat transfer studies also. The overall objective is to improve the reliability and efficiency of fluidized-bed combustors.

Test plans were also formulated to check the validity of using temperature sensitive infra red camera equipment to track hot particles in a closed vessel. The No. 2 18-inch fluidized-bed combustor will also be used as a cold model for this test which will be the first run for the unit once it is completed.

Test plans and run schedules were completed for the Montana subbituminous Rosebud coal. Run periods were in progress at the end of the quarter. Twenty run periods at various percentages of excess oxygen, various fluidizing velocities, and various bed temperatures were scheduled. A test plan was started for the assessment of Texas Big Brown lignite which will follow.

X. HIGH TEMPERATURE DUST CONTROL

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

Contract No.: E(49-18)-1782
Contract 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 used in the project is operated for ERDA by Pope, Evans, and Robbins, Inc. (PER) at a government-owned test facility in Alexandria, Virginia.

- Development of procedures and 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 JANUARY-MARCH 1977

The final report of the project was written during the quarter. The document, prepared by the U.S. Army Construction Engineering Research Laboratory (CERL), evaluated the dust-extraction properties of an array of Particle-Precipitating Heat Transfer Surfaces (PPHTS).

The PPHTS consisted of a set of combustion system heat-exchanger tubes with external fluting on the upstream faces and elliptic curvatures on the downstream faces. These curves create aerodynamic forces which remove dust particles from the gas stream. This study evaluated the efficiency of the PPHTS array in removing dust particles from the exhaust stream of the Energy Research and Development Administration (ERDA) fluidized-bed combustor at Alexandria, Virginia. Total and fractional particle collection efficiencies were determined for three test sections, having two different rod cross sections and two different duct cross sections, subjected to various operating conditions.

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

For these test sections and conditions, maximum total particle collection efficiency was found to be 8.2 percent. Maximum fractional efficiency was 36 percent for particles less than 0.4 microns in diameter. Total and fractional collection efficiencies were found to decrease with increasing flow rate. For the conditions tested, rods with deeper, narrower cavities had greater collection efficiencies than those with shallower, wider cavities, probably due to larger surface area for diffusional

capture of particles.

The study indicated that PPHTS arrays show potential for collection of submicron particles. In addition, the basic operating characteristics of the PPHTS were established. Further testing could establish the rod configurations and suction and flow rates which would yield maximum fractional collection efficiencies.

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

EXXON RESEARCH AND ENGINEERING
COMPANY

LINDEN, NEW JERSEY

Contract No.: E(49-18)-1798

Contract 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 economic, 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 was 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 specifications for boilers, boiler age distribution, and boiler replacement data.

- Assessment of the demand for fluidized-bed combustion technology, including consideration of the cost of fluidized-bed combustion systems, 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 JANUARY-MARCH 1977

The final project report, "Application of Fluidized-Bed Technology to Industrial Boilers," was published in January. The document (NTIS No. PB264528) is available through the National Technical Information Service, Springfield, Virginia 22161.

XII. ON-LINE PARTICULATE ANALYSIS INSTRUMENTATION

LEEDS & NORTHRUP COMPANY
NORTH WALES, PENNSYLVANIA

Contract No.: E(49-18)-2412
Contract Funding: \$106,095
(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 particles 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 equation:

$$\sin \theta = (1.22/d)\lambda$$

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 particle 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 .325 micron.

HISTORY OF THE PROJECT

Leeds and Northrup Company (L&N) was awarded a contract in May 1976 to develop a particle analysis instrument for fluidized-bed combustion systems.

Prior to specifying the particulate instrument configuration, the range of gas duct dimensions and typical particulate loadings that would be accommodated by the resultant instrument was determined. The loading information was acquired at a meeting in July where measurement and interface requirements were discussed.

Following completion of tests at Argonne National Laboratory (ANL), the instrument will be installed for subsequent testing on Curtiss-Wright Corporation's small gas turbine unit. Tests will be performed initially on the four-inch diameter inlet to the turbine, followed by testing on the ten-inch duct after the final filter.

The instrument assembly was completed and checked out during December 1976. Functional tests on background noise, particle size calibration, and sensitivity were performed. Problems with the laser performance, optical prism, and background noise were identified and solutions initiated. After these problems are resolved, the instrument will be shipped to ANL.

PROGRESS DURING JANUARY-MARCH 1977

The final stability tests were conducted in March in preparation for delivery of the particle analyzer to ANL. During the tests, the laser performance deteriorated to an unacceptable condition. The laser was returned to the vendor for replacement of the laser tube and its mechanical support structure. Upon return the unit showed considerable improvements, but still did not perform to specifications. After meeting with the vendor, the original unit was returned for diagnostic study and a new unit placed on loan.

Before shipping the instrument to ANL, two problems need to be resolved:

1. Develop assurance that acceptable laser stability can be maintained.
2. Modify the calibration procedure for volumetric loading since this cannot be accomplished automatically in the prototype instrument.

XIII. PARTICLE MEASUREMENT IN FLUIDIZED-BED COMBUSTION SYSTEMS

SPECTRON DEVELOPMENT LABORATORIES,
INC.

COSTA MESA, CALIFORNIA

Contract No.: E(49-18)-2413

Contract 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 distribution 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 Morphokinometer (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 particulates from airborne platforms, cloud chambers, furnaces, and erosion test facilities.

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 JANUARY-MARCH 1977

Spectron Development Laboratories, Inc. compiled a report, "Laser Interferometer Analysis of Flue Gas Particles From a Fluidized-Bed Combustor." The report described the series of tests performed at the ANL to accomplish the following objectives:

- Demonstrate that laser interferometer measurements could be made through windows exposed to temperatures and pressures present in the fluidized-bed combustor (FBC) regime.
- Compare laser interferometer measurements with mechanical sample measurements.

- Demonstrate that the instrument could be operated efficiently by personnel who had little or no prior experience with it.

The laser interferometer system obtained data at three different sample points in the combustor and was operated for a period extending over three months by ANL personnel.

The system used at ANL was a laboratory prototype used for various applications including wind tunnel, airborne particle monitoring, and combustion diagnostics. It was not optimally designed for the ANL combustor application. Windows and window flange designs were shown to be adequate for the ranges of temperatures and pressures covered. The tests indicated that the flange design could be improved to reduce the nitrogen flow rate required to maintain window cleanliness. Window position creep as the flue gas line temperature reached equilibrium was not a problem at ANL, but could be significant in other installations. It was suggested that the laser interferometer optical system be designed to move with the window. It was also recommended that equipment be designed specifically for coal processing facility installations.

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 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

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

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 the 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 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. Funds from ERDA-FE finally became available 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 tests with water that were begun in July 1976. 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.

By the end of 1976, all of the tasks planned for the water test, with the exception of the vapor separator test, were completed. These included measurement of the argon distribution, heat load of individual boiler tubes,

boiler temperature distribution, combustion gas temperature distribution, and combustion air pressure drop.

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 deposi-

tion 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.

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 operating tubes, header drums, and manifolds at high temperature and under a large external pressure. This was a major factor in the large estimated boiler weight and cost in the study cited above.

Nearly all the mechanical design work for the potassium system was completed by the end of 1976, and fabrication of modifications and new components for the system proceeded very well, with the piping and welding fabrication on the condenser nearly completed.

A 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 also prepared during the year.

PROGRESS DURING JANUARY-MARCH 1977

Summary

The scope of the program was redefined during March. The primary effort was concentrated on a parametric analysis of various plant arrangements with both cesium and potassium as the working fluid, and the design and analysis of a vertical tube natural circulation boiler for a pressurized furnace.

Discussion of Activities

The scope of the program was changed during the quarter. It is now limited to a study of an atmospheric

fluidized-bed system using either cesium or potassium as the working fluid. The work on the atmospheric system will be covered in a single report to be completed by September 30, 1977.

The scope of work for the revised program includes the following major tasks:

- Parametric cycle analysis for cesium and potassium power systems.
- Conceptual designs for an atmospheric pressure fluidized-bed furnace.
- Condenser-steam generator conceptual designs for cesium and potassium at several condenser temperatures.
- Metal vapor turbine design and analysis.
- Conceptual layouts of overall system.
- Preliminary design of an atmospheric pressure fluidized-bed furnace for either a cesium or potassium power system.

The primary effort during the quarter included the compilation of physical and thermodynamic properties of potassium and cesium, the analysis of a series of potassium and cesium turbine designs, and the determination of the cycle efficiency for both fluids for a variety of operating conditions.

As the basic thermodynamic data used did not cover the lower temperatures needed for the current work, computer codes were prepared for the temperature range of 583°K to 1278°K for cesium and from 667°K to 1278°K for potassium. The wet regions for both diagrams extends down to 28 percent moisture. Tables of the specific heat, viscosity, and thermal conductivity for both the liquid and vapor, and a table of the sonic velocity were prepared for both working fluids.

The metal vapor turbine design work was limited to analyses to determine the number of stages, blade height and stress, and the turbine efficiency. The comparison of the turbine designs and efficiencies for cesium and potassium was based on the decision to make the units nearly identical in size and number of stages. It is possible to take advantage of the smaller enthalpy change across the turbine for cesium to reduce the number of stages. Although this would result in a somewhat less expensive cesium unit, it would also reduce the efficiency of the unit by several points. Consequently, the speed of the cesium unit was made one-half that of the potassium unit which gives machines of nearly the same size and number of stages. This lower speed has a very significant effect on the materials requirements for the blades and disks.

The first stage blade height for a cesium turbine operating at 1800 rpm is about the same as for a

potassium unit operating at 3600 rpm. This means that the centrifugal stress on the first stage rotor blades, which is proportional to the square of the speed, is four times as great for the potassium turbine as for the cesium unit. At a rotor temperature of 1028°K, this factor of four increase in stress would result in a factor of about 400 in the creep rate of the material. Furthermore, the required flow area, and thus the blade height, increases much more

rapidly for the potassium unit, with the last stage requiring about 1.5 times the area of the cesium unit. As the centrifugal stress is directly proportional to the rotor annulus area, the centrifugal blade stress in the last stage will be about six times greater with the potassium unit. Thus, for the turbine, there are significant advantages in using cesium rather than potassium.

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XV. INDUSTRIAL APPLICATION OF FLUIDIZED-BED COMBUSTION PROCESSES

INDUSTRIAL SUPERHEATED STEAM BOILERS

COMBUSTION ENGINEERING, INC.

Sub-scale Unit Site: Windsor, Connecticut
Demonstration Unit

Site: Great Lakes, Illinois
Contract No.: No. E(49-18)-2473
Contract Funding: \$7,679,340
ERDA: \$5,868,400
Industry: \$1,810,940
Projected Start-up: February 1980

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
Contract Funding: \$4,008,375
ERDA: \$3,274,757
Industry: \$ 733,618
Projected Start-up: June 1979

INDUSTRIAL BOILERS

GEORGETOWN UNIVERSITY

WASHINGTON, D.C.

Project Site: Washington, D.C.
Contract No.: No. E(49-18)-2461
Contract Funding: \$14,181,312
ERDA: \$9,569,350
Industry: \$4,611,962
Projected Start-up: April 1979

FLUIDYNE ENGINEERING CORPORATION

Sub-scale Unit Site: Minneapolis, Minnesota
Demonstration Unit

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

BATTELLE MEMORIAL INSTITUTE, COLUMBUS LABORATORIES

COLUMBUS, OHIO

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

SUPPORT STUDIES

ARTHUR G. MCKEE AND COMPANY

Contract No.: EX-76-C-01-2418

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 eliminating the flue gas desulfurization requirements.

Industrial Superheated Steam Boilers

Combustion Engineering, Inc.

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 Engineering, Inc. will develop a commercial atmospheric, natural circulation, fluidized-bed steam generator designed essentially as a package boiler; i.e., shop assembled and capable of shipment by rail. It must be capable of firing coal while meeting all environmental standards without the use of auxiliary sulfur dioxide removal equipment and be competitive with other methods of coal firing for industrial practice.

The program is divided into two phases. Phase I consists of designing the constructing a sub-scale test unit. The unit will contain a three square foot fluidized-bed module designed to deliver 2,300 pounds per hours of steam at 365 psig and 560°F while burning 284 pounds per hour of coal and limestone.

Phase II consists of the detail design, construction, and testing of a full-size, fluidized-bed (10' x 12') package boiler as a demonstration plant with a capacity of 50,000 pounds per hour steam flow at 365 psig and 560°F while burning 5,000 pounds of coal in a limestone bed.

Industrial Boilers

Georgetown University

Georgetown University was awarded ERDA contract E(49-18)-2461 on June 30, 1976. The contract provides for the engineering, design, construction, testing, operation, and evaluation of an atmospheric fluidized-bed boiler functioning as a source of steam and using high-sulfur coal. The boiler, located on the campus of Georgetown University, will have the capacity of generating 100,000 pounds per hour of saturated steam. It will supply the University's 250 psig steam distribution

system and be able to meet the changing load conditions of a university complex.

Work under this contract is being accomplished through a teaming arrangement with Georgetown University as the prime contractor and the Fluidized Combustion Company (FCC) as a subcontractor. FCC is a joint venture of wholly-owned subsidiaries of Pope, Evans, and Robbins, Inc. and Foster Wheeler Corporation.

A program plan was developed and accepted by ERDA in September 1976. Thirty percent design documents were also completed and submitted for ERDA approval. Joint design review conferences were held at the 30 percent and 50 percent stage of completion. A new concept for the boiler was introduced at the 50 percent conference and approved by ERDA.

The development of the new concept was the result of evaluations intended to optimize the steam generator design. All natural circulation boiler circuitry was incorporated in the new design instead of the forced circulation circuitry of the original design.

Performance engineering continued on the original design until November. At that time, ERDA approved the new concept and the preliminary engineering was initiated.

Battelle Memorial Institute, Columbus Laboratories

In addition to the general objectives as expressed in the PON, Battelle Memorial Institute, Columbus Laboratories, Contract No. (49-13)-2472 has the specific objective to demonstrate the application of an advanced fluidized-bed combustion process called Multi-Solids Fluidized Bed Combustion (MS-FBC) to an industrial steam generator.

The project consists of two phases. Phase I, Development, Engineering, and Design is concerned with design information for development of the MS-FBC process, and design of a 25,000 pound per hour industrial steam generator. Phase II involves the actual construction of the steam generator and demonstration operation as a lead steam generator. The 30 percent design of the sub-scale unit and related facilities was completed and reviewed by ERDA by the end of 1976. The detailed design of the combustor/boiler was completed. A bid package prepared, bids solicited, and a fabrication contract issued.

A boiler capacity of 150,000 pounds per hour of saturated steam at 250 psig was selected for the con-

ceptual boiler design. A preliminary process flow diagram was developed and reviewed in-house.

Indirect-Fired Heaters

Exxon Research and Engineering Company

Between four and twelve percent of the crude oil processed in oil refineries is consumed to maintain the refinery operations. Under contract No. E(49-13)-2471, Exxon Research and Engineering Company 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.

Two principal areas of technology which have been identified as being peculiar to process heater application and which are not being addressed in any on-going boiler program concern the effects of tube size and hydrocarbon coking. These two areas will be investigated in this program.

Indirect-fired process heater tubes are conventionally two to five times larger than boiler tubes. A typical crude oil heater may have a multitude of four- to eight-inch diameter tubes in the heat pick-up zones as contrasted to the one- to two-inch diameter tubes normally used in steam boilers.

Similarly, the parameters affecting hydrocarbon coking must be investigated. When heating a hydrocarbon to 600°F+ (as required for separation by distillation or other typical processes) some degradation of the oil and coke laydown on the inside tube wall is unavoidable. The rate of coke laydown is affected primarily by the temperature of the hydrocarbon film on the inside wall of the tubes. This film temperature, in turn, is a function of several parameters relating inside film coefficient and heat transfer rate. Both overall average and localized conditions within the heat transfer zone must be examined.

Phase I of the program will consist of three laboratory experiments designed to generate data on the following:

- Effect of tube size and arrangement on bed fluidization.

- Relationships between heat flux and tube coking rate.
- Tube peripheral flux maldistribution in a fluidized bed.

Based on these data, a technical and economic evaluation of the commercial potential for this technology will be made.

Program effort during 1976 was assigned to the planning and design of the first two laboratory units that are to be a part of the Phase I program. The first unit, a two-dimensional flow visualization unit consists of an atmospheric pressure, transparent test chamber wherein the fluidization and mixing characteristics of a fluidized bed containing immersed tubes can be observed and quantitatively measured. The unit design was completed and construction initiated.

The second laboratory unit, the process steam coking unit, consists of four single-tube heat exchangers, an electric heat source, and a gas-fired crude preheater. The process design for the unit was completed and approved. The objective of studies conducted on the unit will be to determine what effect the high flux levels available in fluidized-bed combustor will have on the coking rate of a hydrocarbon process stream and to determine if these coking rates can be controlled within an acceptable range of operations. Comparative rates of coking at different flux levels, fluid mass velocities, and bulk temperatures will be determined.

FluiDyne Engineering Corporation

Supplementing the general objectives of the PON, the specific objective of FluiDyne Engineering Corporation's contract E(49-18)-2463, is to demonstrate that an atmospheric-pressure fluidized-bed air heater and distribution system using high sulfur coal and secondary fuels may be applied economically and efficiently to serve both the space heating and process needs of metal manufacturing plants.

The demonstration facility will be located at the Owatonna Tool Company in Owatonna, Minnesota, and will be designed to efficiently handle the various load fluctuations that occur at the facility. The plant provides a unique opportunity to demonstrate and study the operation and interfacing of a fluidized-bed combustor (FBC) into existing systems and equipment in a variety of typical manufacturing operations. Preliminary effort during 1976 concentrated on the technology support and preliminary design of the demonstration unit.

Fluidized-bed combustion performance and equipment operation tests with Iowa coal, designated as the primary fuel for the demonstration program, were completed. These tests were followed by additional performance tests with petroleum coke and Tennessee coal, both secondary fuels.

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.

PROGRESS DURING JANUARY-MARCH 1977

Industrial Superheated Steam Boilers

Combustion Engineering, Inc.

Work on development activities within Phase I of the program continued throughout the quarter. Initial testing of the two-dimensional model was completed. Some additional tests still are to be run. The full scale cold flow model was tested intermittently during February and March. A Test Program write-up was completed. It details the information needed from the sub-scale unit operation and includes a test matrix to obtain this data. Design of the sub-scale unit included first issue of the general arrangement drawings and preparation of the fluidized-bed boiler pressure part drawings. Subcontracts were issued for vendor's equipment requiring long lead times. Preliminary engineering activities continued on the demonstration plant.

Industrial Boilers

Georgetown University

Fluidized Combustion Company and its subcontractors continued to concentrate major effort during the quarter on the final design. Joint design review conferences were held at the 80 percent stage of completion for the general construction, steel fabrication and erection, and mechanical contracts.

Plant design proceeded at a reduced rate from the original schedule in order to coordinate effectively with the new boiler design approved by ERDA following the 50 percent review.

Drawings were submitted to the D. C. Building Department in January. Initial comments were reviewed and acted upon. Approval of the Board of Zoning Adjustment, which must precede award of a building permit, was delayed until April at least.

Battelle Memorial Institute, Columbus Laboratories

Design of the subscale experimental unit system was completed. Bids for construction were received and the contract awarded to Sauer, Incorporated. Construction began in February. Fabrication of the combustor/boiler was also underway during the quarter.

Indirect-Fired Heaters

Exxon Research and Engineering Company

Construction of the two-dimensional flow visualization unit continued during the quarter. All materials and equipment components needed for the assembly of the unit were on site except for the air blower, motor and associated control valves and silencers. All civil, structural, and piping subcontracts were completed.

The design of the coking unit test facility was completed, and all equipment components were ordered. Assembly of the unit began during March.

Planning and design of a third unit had just begun at the end of the quarter. This will be a high temperature heat flux unit in which maldistribution of heat input to

a bundle immersed in a hot fluidized bed will be examined. Both peripheral and tube-to-tube flux patterns will be studied. Some complimentary tests will also be carried out in an ambient temperature fluidized bed where only the conductive/convective component of the heat transfer mechanism will be measured. A Task Plan was prepared for these studies and submitted to ERDA for review and approval.

Fluidyne Engineering Corporation

During the quarter, fluidized-bed combustor (FBC) performance and equipment operations tests with petroleum coke and Tennessee coal were completed. Additional tests with in-plant waste paper, cardboard, and wood as a fuel were planned. Fabrication and installation activities on the vertical slice FBC and ancillary equipment continued during the reporting period. Cold flow shakedown tests were completed. The Vertical Slice Combustor Test Plan and the written response to ERDA comments and concerns regarding the Vertical Slice 80 percent Design Package and Test Plan were submitted to ERDA for approval.

The conceptual design of the atmospheric pressure fluidized-bed combustion system was also completed. The system consists of two FBC units, each with a bed area of 49.3 square feet, that can be operated separately or together to provide a total heat output of 28.5×10^6 Btu per hour. The system is sized to use Illinois No. 6 coal as a primary fuel. Tennessee coal, Iowa coal, and petroleum coke can also be used. Owatonna dolomite will be the primary sorbent.

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XVI. MODELING OF FLUIDIZED-BED COMBUSTION PROCESSES

MASSACHUSETTS INSTITUTE OF
TECHNOLOGY

Contract No.: E(49-18)-2295

Contract 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 five 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.

PROGRESS DURING JANUARY-MARCH 1977

During the quarter, the study of gas-solid reaction kinetics continued. The effect of attrition, elutriation, and overflow on bed combustion efficiency and bed particle size distribution was considered. A desulfurization program was developed, designed to predict the sulfur dioxide effluent gas concentration and sulfur acceptor stone utilization in a continuously operated fluidized-bed combustor. Results of calculation showed that the sulfur dioxide removal efficiency approached an upper limit as the calcium to sulfur molar feed ratio was increased.

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XVII. FLUIDIZED-BED WASTE MATERIAL UTILIZATION

VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

Contract Funding: \$1,500

TENNESSEE VALLEY AUTHORITY

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

Contract Funding: \$29,000

UNITED STATES DEPARTMENT OF AGRICULTURE

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

Contract Funding: \$1,766,548

UNITED STATES DEPARTMENT OF TRANSPORTATION

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

Contract Funding: \$42,750

L. JOHN MINNICK

Contract No.: EF-77-C-01-2549

Contract Funding: \$259,530

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 various studies to demonstrate the effectiveness of using this fluidized-bed combustion (FBC) waste for agricultural purposes, and for non-agricultural utilizations.

PROGRAM DESCRIPTION

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

The Tennessee Valley Authority will conclude a 2-year program to 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 Agricultural Research Service, United States Department of Agriculture, will evaluate, over a 5-year period, 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 fly ash, lime, and waste cement kiln dust will also be tested.

The 27-month program with Dr. L. John Minnick will evaluate possible non-agricultural utilization of FBC wastes. Laboratory, pilot and field testing will be performed in such applications as pozzolans, waste stream treatment, pH modification and ceramics.

PROGRESS DURING JANUARY-MARCH 1977

Virginia Polytechnic Institute and State University

The three-year study of the application of fluidized-bed combustion (FBC) material to farm acreage planted with peanuts was completed in March. The FCB material appeared to be equivalent to anhydrite; however, only a limited number of production situations were researched.

No phytotoxicity was detected from application of the FBC material on peanuts during any of the three years. An especially high rate of 2,400 pounds per acre, included in the 1976 tests, did not appear to affect the peanuts adversely. Possible toxicity problems with repeated usage should be researched more extensively if concentrated usage is planned.

Tennessee Valley Authority

A pot experiment initiated August 1976 to measure liming effects of fluidized-bed waste (FBW) on acid coal strip mine spoil was in progress during the quarter. A pot experiment with soybeans was initiated in February.

Results from a greenhouse pot experiment with peanuts and corn showed that FBW applied at relatively low rates was a satisfactory liming material and source of sulfur and micronutrients other than boron. At high disposal rates FBW was toxic for peanuts, apparently because of the extremely high soil pH. It is likely that this toxicity would soon be dispelled by rainfall under field conditions.

Agricultural Research Service

Studies continued throughout the quarter to determine chemical and physical characteristics of fluidized-bed waste (FBW) material from several sources. Chemical characterization of various batches of FBW material indicated tremendous variation in the concentration of most elements. Elemental composition of the material also varied considerably between different size fractions.

Leaching studies were conducted to determine rate of elemental release under controlled environmental conditions. Incubation studies under controlled environmental conditions were also underway.

Studies continued comparing fluidized-bed material with agricultural lime plus equivalent sulfur and with fly ash. In other greenhouse and growth chamber studies,

growth and nutrient uptake of soybeans, oats, tall fescue, swiss chard, red clover, and buckwheat were compared on an acid soil after treatment with FBW material and lime and sulfur sources. A study was initiated to compare FBW material with lime and sulfur sources on an acid soil and an acid strip mine spoil, using buckwheat and tall fescue as test crops.

Field studies continued with alfalfa and corn at four locations with widely different climate and soil types. Field studies were initiated during the quarter to determine effects of rates of FBW and lime, with and without composted garbage waste, on yield and nutritive value of potatoes.

Federal Highway Administration

Chemical composition of the fluidized-bed waste (FBW) material was determined. The three principal

components of FBW are silica, lime, and calcium sulfate. Silica and lime are present to about the same degree (30 percent), while calcium sulfate is about half of the lime content (15 percent).

Unconfined compressive strength testing of soil/FBW FBW specimens was completed during the quarter. Results of the test showed that, in general, the inclusion of FBW with soil causes substantial increases in unconfined compressive strength. This increase was expected as both lime and calcium sulfate promote strength development.

Soil/FBW specimens were evaluated with respect to freeze-thaw durability using vacuum saturation techniques. A series of specimens were subjected to vacuum saturation after a seven-day cure. Three of the four systems, Manor, Summit, and Wharton, indicate that freeze-thaw durabilities are enhanced with FBW treatment. Additional testing needs to be completed on the Upshur specimen for confirmation of results.

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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

Contract 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, build-up, and installation of the pilot plant. The final phase is a 24-month effort to operate the pilot plant and to evaluate 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 combustion 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 particles and alkali salts in the combustion gas stream.

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

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 standard of 0.7 pounds of NO_2 per million Btu. In addition, the use of the sulfur sorbent material in the bed allows emissions of sulfur oxides to be below the current standards 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 of 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 turbine 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 JANUARY-MARCH 1977

Preliminary design of the pressurized fluidized-bed (PFB) pilot plant continued during the quarter. Preparation of the environmental analysis report covering the construction and operation of the plant was in progress.

Technology support continued in several areas. Fabrication and instrumentation of the heat exchanger for tests at National Research Development Corporation in Leatherhead, England, continued. Investigation into alternate manufacturing methods for heat exchanger tubes also continued. Tests were also new in the 12-inch diameter fluosolids reactor at the Dorr-Oliver Test Laboratory.

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XIX. EVALUATION OF A PRESSURIZED FLUIDIZED-BED COMBUSTION (PFBC) COMBINED CYCLE POWER PLANT CONCEPTUAL DESIGN

BURNS AND ROE INDUSTRIAL SERVICE
PARAMUS, NEW JERSEY

Contract No.: E(29-18)-2371

Contract Funding: \$1,385,052
(100% ERDA)

INTRODUCTION

Under the terms of this contract, Burns and Roe Industrial Service will provide an evaluation of a coal-fired combined-cycle power plant conceptual design. The design will use a pressurized fluidized-bed (PFB) combustor air heater cycle with a unique supplemental fuel-fired atmospheric fluidized-bed (AFB) heat recovery boiler for obtaining high efficiency. Improvement in the cycle will be achieved by reheating the gas turbine effluent in the PFB or by additional heating of the gas turbine effluent in the AFB.

PROGRAM DESCRIPTION

The contractor will perform administrative services in the following areas:

- Commercial plant design definition
- Commercial plant requirements definition
- Design trade-off studies
- Reliability and maintainability evaluation
- Environmental analysis
- Economic analysis
- Alternate plant approaches evaluation and comparisons

Four viable system configurations utilizing gas turbines, a waste heat steam bottoming system, and pressurized fluidized-bed combustion will be studied to determine which system exhibits the highest overall efficiency. The four systems to be studied are:

- Case 1—Basic combined cycle (no reheat or exhaust firing).
- Case 2—Exhaust-fired combined cycle.
- Case 3—Reheat at power turbine inlet.
- Case 4—Reheat at low-turbine inlet plus exhaust firing.

HISTORY OF THE PROJECT

Work under this contract began in July 1976. During the year, performance data on the four basic configurations of pressurized fluidized-bed (PFB) power plant arrangements were compiled into a set of tables entitled "PFB Combined Cycle Comparison." Preliminary cost data of major equipment for the different schemes were also compiled during the quarter. Preliminary design for a PFB with a pressure ratio of ten and a 2.5-atm reheat PFB were completed.

PROGRESS DURING JANUARY-MARCH 1977

During the quarter it was decided to concentrate all future work on the cycle containing pressurized fluidized-bed (PFB) combustors exhausting to gas turbines followed by a steam-cooled atmospheric fluidized-bed (AFB) fired boiler. This cycle offers greater power output and efficiency than one using a simple waste heat boiler and assumes that the AFB combustors will be available in the same time period as the PFB combustors.

Design of the PFB and AFB combustors continued with efforts concentrated on the development of layout and equipment arrangements. Heat transfer and stress analyses were initiated on the high temperature gas

transport lines from the PFB combustors to the inlet to the gas turbine. Data on the mechanical equipment for the steam system was being compiled.

Work also continued in the areas of civil/structural engineering, instrumentation and control, and electrical engineering to define and layout the plant.

Trade-off studies continued to identify the range of parameters for a 600 Mw combined cycle power plant. Parameters included pressure rates, engine configurations, and operating temperature.

Efforts were resumed on the development of an order of magnitude capital and operating cost estimate for a spent sorbent regeneration system sized for a 600 Mw plant.

XX. COAL-FIRED COMBINED-CYCLE DEVELOPMENT PROGRAM

GENERAL ELECTRIC ENERGY SYSTEMS —
TECHNOLOGY DIVISION
SCHENECTADY, NEW YORK

Contract No.: E(49-18)-2357
Contract Funding: \$4,382,396
(100% ERDA)

INTRODUCTION

A Coal-Fired Combined-Cycle (CFCC) power concept is being developed under this contract with General Electric Company. The combined steam and gas power cycle utilizes a pressurized fluidized-bed (PFB) combustor burning coal.

The Energy Systems Program Department (ESPD) of General Electric leads the program, performing the required program management, system engineering, reliability, and environmental effort. Foster-Wheeler, under subcontract to GE, is responsible for the combustor/steam generator design activity and technology support. Exxon is supplying experimental support, using their miniplant facility and integrating the testing with ongoing Environmental Protection Agency-sponsored work. Within General Electric, ESPD will be supported by Corporate Research and Development for hot-gas cleanup technology, by the Gas Turbine Division for gas turbine design/technology, and by the Projects Engineering Operation of the Installation and Service Engineering Business Division for commercial power plant balance-of-plant design and costing.

PROGRAM DESCRIPTION

The CFCC approach provides cooling of the fluidized-bed combustor through the use of steam tubes in the bed,

which supply a steam turbine-generator. The partially cooled combustion gases exiting from the combustor drive a gas turbine generator after passing through a hot-gas cleanup train.

The objective of this program is to evaluate the CCFC design and to conduct a supporting development program. The program is necessary to evaluate the pressurized fluidized-bed combustor concept, for developing engineering correlations to be used in optimizing the commercial plant concept, and for evaluating the combustor/steam generator, the hot-gas cleanup, and advanced gas turbine materials for this application. The results of this program will provide for PFBC technology advancement and also provide a backup concept and program for commercialization of pressurized fluidized-bed combustion.

The work is organized into six major tasks:

- Commercial plant evaluation
- Combustor/steam generator development
- Gas turbine technology
- Hot gas cleanup technology
- Experimental support
- Project management

Several component and system design options over a range of system parameters will be studied at a conceptual level for the purpose of tradeoff evaluation. After a formal commercial plant design review, a single system

and component design approach will be defined in detail, and a design evaluation report prepared.

The supporting technology tasks will be conducted in parallel with the commercial plant definition activity. Certain key technology uncertainties have been previously identified and will be studied. These include combustor effluent characterization, cyclone and granular bed filter performance, combustor hot-gas ducting evaluation, gas turbine materials and bucket cladding development for increased corrosion resistance, advanced particulate cleanup equipment development, and combustion chemistry modifications.

Performance data will be acquired from Curtiss-Wright for commercially available cyclone separator equipment, from Exxon for currently available granular bed filter performance, from the Fireside Corrosion Task 2 Program for turbine materials performance, and from Combustion Systems Limited for tube bundle performance. Integration of the technology work with the commercial plant evaluation activity will be achieved by guiding the testing plans on the basis of the system requirements as established, and by determining test parameter ranges by the system tradeoff studies. The system tradeoff studies will also be employed to establish recommended extensions/modifications for related government technology programs in support of CFCC needs.

HISTORY OF THE PROJECT

Beginning in January 1974, a study team representing General Electric, Foster-Wheeler Energy Corporation, Exxon Research and Engineering Company, and Combustion Systems Limited evaluated the CFCC approach. On the basis of these studies, it appeared that the CFCC approach offered the following advantages over alternative approaches:

- Higher power plant efficiency in the range of interest
- Reduced corrosion potential, due to low fluidized-bed tube temperature (air in tube cycle)
- Reduced hot-gas cleanup flow rate (uncooled combustor cycle)

Engineering activity in the present program was initiated with a review of alternate basic assumptions for conduct of the Commercial Plant Design Study, including site, power level, codes and standards approach. Recommendations in this area were presented to ERDA in the first program review in July 1976. The Commercial

Plant Design Requirements Report was submitted to ERDA in October.

PROGRESS DURING JANUARY-MARCH 1977

Summary

The commercial plant design study continued with primary emphasis on trade-off studies not dependent on tube bundle testing. Preliminary system analysis studies of seven alternate pressurized fluidized-bed coal-fired combined-cycle power plants were completed. A scoping study report was completed by Foster Wheeler, and auxiliary equipment design continued.

Discussion of Activities

The commercial plant design actively was replanned during the quarter to accommodate the revised schedule for testing of the model coal fired combined cycle (CFCC) tube bundle at Combustion Systems Limited (CSL) in Leatherhead, England. Series #6 experiments, conducted with 2-1/2 feet per second pressurized fluidized-bed (PFB) velocity at 20 and 100 percent excess air were completed in January. Results indicated that the Foster Wheeler tube bundle performed very satisfactorily with no evidence of hot spots or stratification in the bed.

In the interim period the commercial plant design study continued with primary emphasis on the trade-off studies not directly dependent upon the test data. Plant layout drawings were prepared for the two design options as the trade-off studies continue to assess the two major concepts as well as optimizing other aspects of the design.

Preliminary system analysis studies of seven alternate PFB coal fired combined cycle power plant were completed. These continued to demonstrate that the basic design has the best thermal efficiency at achievable temperatures. It also demonstrated that the CFCC has the least penalty if gas turbine inlet temperature has to be reduced because of clean-up or materials limitations.

Foster Wheeler documented its design efforts to date in a scoping study report that was distributed for review. Auxiliary equipment design continued in areas not dependent upon the tube bundle tests. Hot Gas Ducting design of the test section was completed with material selection and detail design showing adequacy of the approach.

Procurement of materials and fabrication of gas turbine bucket cladding test specimens continued throughout the quarter. Seven of the cladding alloys were applied to the discs. Four others demonstrated fabrication feasibility and will be completed in the next quarter. The remainder will probably be deleted from the program due to fabrication difficulties.

Efflux characterization efforts continued. Development and evaluation of the Aerodyne and Advance Cyclone equipment continued with prime emphasis upon

procurement and installation of models and test set up in preparation for testing during the next quarter.

Detailed planning for the tests in the Exxon mini-plant was started. Before an acceptable test can be defined, however, the performance of the mini-plant without recirculation must be measured and determined to be equivalent to that expected in a commercial plant, and the Ducon granular bed filter checkout must have progressed to a stage to provide a representative environment to the materials in the test section.

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XXI. DIAGNOSTIC ASSESSMENT FOR ADVANCED POWER SYSTEMS

SANDIA LABORATORIES
LIVERMORE, CALIFORNIA

INTRODUCTION

The objective of the first phase of the program is a review and assessment of diagnostic techniques which are needed to characterize the flow at the combustor exit and turbine inlet in advanced, open-cycle gas turbine systems which will be used for stationary power generation. These systems will be designed for firing with pulverized coal, coal-derived liquid and gaseous fuels, and heavy residual fuels.

PROGRAM DESCRIPTION

For the purpose of initially defining diagnostics requirements, two different advanced turbine systems were assumed. System I is a low turbine inlet temperature system (LTTS) with high ash carry-over into the turbine, and System II is a high turbine inlet temperature system (HTTS) fired with a clean liquid or gaseous coal-derived fuel or incorporating an efficient interstage gas cleanup system.

It is assumed that the combustors will be fired directly with crushed or pulverized coal or with coal-derived liquid or gaseous fuels. Efficient and reliable operation of such systems over sustained periods will require combustor performance to standards which are in accordance with advanced gas turbine design specifications. Specifications of all critical properties of the combustor product flow at the inlet to the turbine nozzle will include the pressure, gas static temperature and velocity, particulate

loading density, and mean particle size and size distribution. The requirement of continuous operation, and, hence, long blade lifetimes will most likely place constraints on both the average values of these properties and their profiles across the radius of the turbine inlet annulus. Similar constraints will be imposed due to the necessity of minimizing combustion-generated pollutants. It is also likely that maximum permissible concentrations of corrosive trace species, in both the solid and vapor phase, will be specified.

Conventional diagnostic techniques which utilize physical probes for temperature measurement, velocity measurement, and gas sample analysis will be severely limited in the turbine inlet environments of advanced stationary power systems. New diagnostic methods will be necessary to obtain the required spatial property distributions in some cases.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Diagnostic techniques for the determination of particle size distribution, particle mass loading density, gas velocity, gas temperature, and species concentrations were investigated. The techniques which seemed the most potentially useful were identified. It appeared likely that a combination of advanced laser-based optical techniques and conventional probe sampling methods are necessary to fulfill the diagnostic requirements of the advanced combustor/turbine systems.

Particle Size Distribution

There are no commercially available instruments for reliable measurement of particle sizes in flows containing a hot, polydisperse system of particles of unknown shape, index of refraction and composition. Several nonperturbing, optical techniques are potentially applicable, though no single technique can accurately measure particle sizes through the entire range of interest. An experimental program will be initiated to investigate the application of new and existing techniques to hot, dirty flows.

Particle Mass Loading Density

A probe for the determination of spatial distribution of mass loading density must be developed and proven. There is currently no reliable method for converting optically-determined number density and size distribution measurement into mass loading density values as some of the particles in the combustor exit flow are porous or hollow and agglomerates may contain voids. Physical probes will undoubtedly be required as complements to optical techniques for unambiguous determination of mass loading density.

Velocity

Laser Doppler velocimetry has been developed as a nonperturbing optical technique and used to characterize velocity fields, both laminar and turbulent, in a number of applications, including combustion flows. With

proper design, the laser Doppler velocimeter concept should be successful when applied to the expected flows.

Temperature

It was determined that two advanced laser-based optical techniques, Raman scattering and two-line atomic fluorescence should be developed for application to particulate-laden combustor exhausts. The development should include comparative measurements, in simulated and actual gas turbine combustor flows, obtained with state-of-the-art physical probes and with the advanced optical systems.

Species Concentrations

Stable species concentrations in the combustor exhaust flow need to be determined so that combustor performance can be related to concentrations of carbon monoxide, hydrocarbons, and soot. Emission requirements will limit the allowable concentrations of oxides of sulfur and nitrogen. For temperatures below 1500° K, gas and solids sampling using conventional water-cooled isokinetic probes would be adequate if probe clogging could be avoided. At higher temperatures, uncertainties due to inadequate probe quenching could be large. For species concentration measurements throughout the expected ranges of temperatures and pressure, a competitive alternative technique is vibrational Raman scattering. Development of the technique for application to a particulate-laden combustor exhaust is required, however.

XXII. COMBINED CYCLE RESEARCH PROGRAM

MASSACHUSETTS INSTITUTE OF
TECHNOLOGY

CAMBRIDGE, MASSACHUSETTS

Contract No.: E(49-18)-2295

INTRODUCTION

Massachusetts Institute of Technology was commissioned by the Energy Research and Development Administration to provide essential data for the future development of combined cycle power plants. Gas turbine — steam turbine combined cycle power plants, operating on coal or coal-derived fuels, are thought by many experts to be the most practical and efficient choice for the next generation electric power production. The major benefits of this combined cycle system are the potential attainment, at relatively low risk and development cost, of high efficiencies while maintaining pollutant emissions within environmental specifications.

PROGRAM DESCRIPTION

The objective of the Combined Cycle Research Program is to provide essential data for the future development of advanced gas turbine — steam turbine combined cycle power plants with overall efficiency and operating cost advantages over conventional power plants. The research deals with critical, highly coupled problems related to combined cycles, turbine cooling with air and water, materials corrosion, and high temperature fuel gas desulfurization. The composite result of research in these areas will provide needed data for gas turbine component design and thus serve as a necessary complement to the ERDA High Temperature Turbine Technology Program. This effort will also supply corrosion data for other metal and ceramic components and necessary informa-

tion concerning high temperature desulfurization, as well as providing accurate experimental data for input into, and verification of, the various computer simulator models under development.

Cascade testing will include both measuring the heat transfer rate to an uncooled airfoil and the testing of a cooled design, representative of the first stage nozzle of a large (100 Mw), high performance gas turbine at correct gas/metal temperature ratios. Experiments will be conducted in the MIT Blowdown Linear Cascade.

The water cooling test facility was designed to study the relevant parameters affecting heat transfer on the coolant side of a liquid-cooled, high-temperature gas turbine airfoil. An electrically heated tube is used to simulate conditions in an airfoil coolant channel. The test program will measure the heat transfer coefficient and pressure drop under varying conditions of coolant pressure, inlet temperature, flow rate, and degree of evaporation for both stationary and rapidly rotating tubes. The stability of flow will also be investigated. Studies will be concentrated on the closed coolant loop type system in which coolant circulates through the airfoil and is directly returned for reuse instead of being injected into the gas stream after cooling.

HISTORY OF THE PROJECT

The project began in July 1976. Most of the major facility construction and modifications were completed

by the end of the year, including the initial construction of the water cooling facility and the pressurized Thermogravimetric Analyzer (TGA).

PROGRESS DURING JANUARY-MARCH 1977

Summary

Research during the quarter established cascade operating parameters and airfoil instrumentation locations. The water cooling facility circuit was successfully operated under pressure. Work also continued on the study of the behavior of tungsten oxide, kinetic corrosion studies of alumina, and measurements of surface tension of sodium sulfate.

Discussion of Activities

During the quarter, the cascade operating parameters and airfoil instrumentation locations were established. An eight blade cascade will be tested. The two center blades each have 20 instrumentation taps: one blade for pressure measurement, the other for heat transfer.

The tube water cooling facility was successfully flow

tested through a range of pressures and flow rates. The analytical work to determine fluid properties in water cooled passages began.

Work was also in progress during the quarter on the corrosion of metal and ceramic parts of turbine systems. The work was directed to obtain a better understanding of the basic aspects of the mechanism of corrosion resulting from the presence of liquid sodium sulfate on the surface of the parts. Studies were conducted of the thermodynamics properties and behavior of sodium and potassium sulfates. An apparatus was constructed to study the kinetics of the dissolution of ceramic materials in molten salts under controlled conditions of temperature, pressure, and activities of the constituent species of the salts.

The initial part of a longer term study of the possible role that wetting of the protective oxide and/or alloy by liquid sodium sulfate may play in the corrosion process was begun by the measurement of the surface tension of liquid sodium sulfate for a variety of conditions.

The auxiliary equipment installation to provide reaction gases to the thermogravimetric analyzer was installed and checkout nearly completed. Synthetic dolomite was prepared and analyzed and found to have properties approaching natural dolomite.

XXIII. ATMOSPHERIC FLUIDIZED-BED COMPONENT TEST AND INTEGRATION UNIT (AFB/CTIU)

MORGANTOWN ENERGY RESEARCH CENTER
MORGANTOWN, WEST VIRGINIA

INTRODUCTION

A stacked-bed Atmospheric Fluidized-Bed Combustor/Component Test and Integration Unit (AFBC/CTIU) will be built and operated by the Energy Research and Development Administration (ERDA) at Morgantown Energy Research Center (MERC). MERC will serve as ERDA Project Manager and conduct in-house cold model test programs as well as provide technical support during design and construction of the CTIU. The six-Mw CTIU will address and resolve a number of key fluidized-bed combustor/boiler development technical issues which will arise in the Rivesville 30 Mw system (Chapter I). It will also provide design data for stacked-bed applications and steam generation scale-up to a commercial 200 Mw plant. The CTIU will test improved solids-handling systems, develop technology for vertical stacking of multiple beds, and serve as a boiler development laboratory to test tube bundle geometries and materials in operating fluidized-bed combustors.

PROCESS DESCRIPTION

The AFBC/CTIU is a coal-fired boiler which consists of a three-cell fluidized-bed combustor with the beds stacked one above the other. The bottom two cells burn coal and the third (or top) cell, the carbon burnup cell (CBC), burns the residual carbon in the ash. Ash removal from flue gases will be in cyclone separators with reinjection for carbon burnup in the separate carbon

burnup cell or within either coal burning cell. Final gas cleaning will be effected by bag filter collectors.

AFBC/CTIU will be designed with the provision to handle two of each of the coals, sorbents, and additives. With two coal-burning cells, each cell may be operated with a different coal/sorbent/additive. Combination or blends of coals may be burned in individual or both cells. The capabilities greatly increase the operating flexibility of the unit. Development work will examine uniformity of coal feed, plugging of coal feeders by fines, and caking of coals.

Spent bed material is removed, purified by size classification and magnetic separation, and stored hot for reinjection into any of the combustor cells. Air for fluidization and injection is provided by primary and auxiliary forced-draft fans. An induced-draft fan moves the flue gases through the dust removal system and vents into the stack. The complete system is designed with sophisticated analytical instrumentation, computerized data acquisition, and electronic control systems so that the maximum amount of useful data can be obtained. A schematic of the process is shown in Figure XXIII-1.

HISTORY OF THE PROJECT

Reynolds, Smith, and Hills of Jacksonville, Florida were selected as the Architect/Engineer for the project. Engineering work was started in June 1976. Work to date

Figure XXIII-1. MORGANTOWN AFB/CTIU SCHEMATIC

has included project scheduling, specification of major equipment, and the site and building layouts.

PROGRESS DURING JANUARY-MARCH 1977

Work during the quarter included the engineering required to specify the steam generator and related

system components as well as the definition of the site and building requirements. The procurement package for the steam generator was completed and was ready for bidding.

A project review at the completion of Title I engineering was conducted for FE/ERDA at the end of March. The schedule and funding requirements were finalized and about 40 percent of the engineering design work was completed.

XXIV. PRESSURIZED FLUIDIZED-BED COMPONENT TEST AND INTEGRATION UNIT (PFB/CTIU)

ARGONNE NATIONAL LABORATORY
ARGONNE, ILLINOIS

INTRODUCTION

A conceptual design of a three-Mw Component Test and Integration Unit was completed by Argonne National Laboratory. The unit is intended to support the pressurized fluidized-bed (PFB) combustor development program by providing the flexibility to investigate alternative and advanced concepts of fluidized-bed combustion. It will allow testing of components, instrumentation, and materials on a scale that is large enough to utilize commercial-scale equipment yet small enough to allow rapid modification of equipment and operating conditions.

PROGRAM DESCRIPTION

The PFB/CTIU is to provide the capability for research in the following areas:

- Evaluation of the technical feasibility of the proposed operating conditions for the larger scaled pilot plants.
- Investigation of the ability of gas-cleaning devices to reduce particulate and corrosive-impurity load-

ings in the combustor off-gas levels that are consistent with requirements for satisfactory gas turbine operation and sufficient to meet EPA particulate emission standards.

- Assessment of potential erosion, corrosion, and fouling problems of gas turbine components caused by constituents in the off-gas of a PFBC unit.
- Demonstration of the reliability of the pilot plant PFBC concept by long-term operation of the system.
- Evaluation of an additive regeneration scheme that will be incorporated into the PFBC/PDF if the results of smaller scale experiments indicate that this process step is ready for scaleup.
- Investigation of alternative PFBC pilot plant concepts.

HISTORY OF THE PROJECT

ERDA granted ANL approval to proceed with the CTIU conceptual design which will serve to test components and support the pilot plant in April of 1976. Stearns-Roger Corporation of Denver, Colorado is currently working on the final plant definition.

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XXV. HIGH TEMPERATURE TURBINE TECHNOLOGY (HTTT) PROGRAM

**CURTISS-WRIGHT CORPORATION
WOOD-RIDGE, NEW JERSEY**

Contract No.: E(49-18)-2291

Contract Funding:
\$1,503,000

**GENERAL ELECTRIC COMPANY
SCHENECTADY, NEW YORK**

Contract No.: E(49-18)-1806

Contract Funding: \$3,079,571

**UNITED TECHNOLOGIES CORPORATION
FARMINGTON, CONNECTICUT**

Contract No.: E(49-18)-2292

Contract Funding: \$2,055,000

**WESTINGHOUSE ELECTRIC CORPORATION
LESTER, PENNSYLVANIA**

Contract No.: E(49-18)-2290

Contract Funding: \$2,809,235

INTRODUCTION

Present base load electric generating plants, which can consume coal directly in combination with conventional steam turbine systems, achieve efficiencies of between 35 and 38 percent depending upon the fuel sulfur content and energy required for stack gas scrubbing. Therefore, if clean, coal-derived fuels are to be used for baseload

power generation at hundreds of megawatts power level, energy conversion systems of higher efficiency or lower overall cost must be developed to compensate for the process energy losses, and possibly other additional costs, incurred in coal gasification or liquefaction.

One promising method for increasing baseload plant efficiency using coal-derived fuels is through use of an advanced design, combined gas turbine-steam turbine

system, versions of which are already in use in utility intermediate and peaking applications with petroleum fuels. Studies indicate that potential coal to bus-bar efficiencies of 44 percent and above are possible in integrated, advanced, low-Btu gasifier-combined cycle generating systems. Reaching this level of efficiency while fulfilling the other demanding baseload operating requirements, however, is predicated on achieving two difficult technological objectives. First, the turbine inlet temperatures must be increased to values of 2600°F and above while limiting the concomitant energy losses; component cooling, for example. In addition, the gas turbine must be adapted to the coal-fuel combustion environment.

PROGRAM DESCRIPTION

The Energy Research and Development Administration's High Temperature Turbine Technology (HTTT) Program addresses many of the critical problems concerning the "hot end" components of a large, coal-fired, high temperature high efficiency gas turbine engine. The objective of the program is to advance in a ten-year period, the technology of a high temperature (multi-stage) power turbine subsystem to a point where minimal risks would be involved for an agency or manufacturer to develop the turbine subsystem for use in a full scale, open cycle gas turbine system.

The program is divided into three phases, which proceed from definition of plant and power system requirements, definition of technology needs, system and subsystem reference designs, through bench-scale technology testing to the Turbine Subsystem Technology Readiness Verification Test Program. The three phases consist of:

- I. Program and System Definition
- II. Technology Testing and Test Support Studies
- III. Technology Readiness Verification Test Program.

Only Phase I will be contracted initially.

In May 1976, ERDA signed contracts with four companies: Curtiss-Wright Corporation, General Electric Company, United Technologies Corporation, and Westinghouse Electric Corporation. Because of the scope of the engineering experience required for performance of Phase I Tasks, each of the gas turbine oriented companies assembled an industrial team that complemented the effort for engineering the entire combined cycle power plant including the gasification and coal handling operations. Phase I is to be completed by March 1977.

Curtiss-Wright Corporation

The bases of the overall plant design description for Phase I of the contract by Curtiss-Wright Corporation was an air-blown Lurgi fixed-bed gasifier.

Combined cycle efficiency was calculated for a representative group of fuel gas clean-up systems with the result that hot gas clean-up had the highest thermal efficiency. The hot iron oxide desulfurization process being developed by the United States Bureau of Mines at Morgantown, West Virginia, with a back-up commercial cold-gas clean-up system was selected as the best fit for the program requirements. Within this framework several alternate schemes for particulate and tar removal prior to hot gas desulfurization were generated and efficiencies calculated.

A two-spool gas generator was selected as the basis of the turbine design within the requirement that it operate at 2600°F and above on a variety of gaseous and liquid fuel. Transpiration air cooling was to be applied to the hot turbine vanes and blades.

A reference combined cycle design was generated for the low-Btu gas primary turbine send out power level of 131,000 Kw with the result that a 700 Mw power plant was selected as the basis of the overall plant design description. A double-ended 230 Mw electric generator driven from both ends was selected as the basis of the turbine module design to take advantage of economy of size. Inlet filtration systems, secondary cooling air, and silencing was specified based on the Middletown site condition.

General Electric Company

The scope of the work conducted by General Electric Company for the whole three phase program will encompass the design development, manufacture, and test of a full-size turbine subsystem adapted to a General Electric MS-7001 gas turbine. The system will be tested in a National Low Btu Gasification Test Facility, or alternatively, in the General Electric load test facility in Greenville, South Carolina. Only Phase I has been contracted.

Two gasification systems, the advanced fixed bed and the entrained bed, were evaluated and compared in order to select a single system for an overall plant design description. Comparisons favored the fixed bed system due to more favorable control characteristics, more experience, and a significantly higher overall plant thermal efficiency. The Benfield Acid Gas Removal System was selected for gas cleanup.

United Technologies Corporation

United Technologies Corporation directed Phase I design definition studies primarily at achieving the critical objectives of high performance, durability, low risk, and acceptable emissions for the turbine and combustor subsystem. In addition, the program addressed investigation of engine turbine cooling schemes as well as the application of advanced materials since turbine operating temperatures of growth generations will approach near stoichiometric proportions.

Westinghouse Electric Corporation

In conducting Phase I of the contract, the Westinghouse Generation Systems Division teamed with Detroit Diesel Allison (DDA) Division of General Motors as a major subcontractor. The team combined the experience of DDA in high temperature aircraft engines with the extensive background of Westinghouse in industrial combined cycle plants for electric utilities.

During Phase I, Westinghouse conducted extensive preliminary design studies and an assessment of the state-of-the-art to identify the advanced technology developments required to achieve the overall HTTT Program goals. Throughout the effort, special consideration was given to the ultimate use of the high temperature turbine technology to be developed.

The main thrust of the program was the preliminary design of a 2600°F inlet temperature combustion turbine element with growth potential to 3000°F. Other areas of investigation included: combined cycles using coal gasification and coal liquid fuels, the definition of the associated compressor; the combustor configured in an engine; and the fuels clean-up (both gaseous and liquid) required for long life turbine operation for electric utility applications.

PROGRESS DURING JANUARY-MARCH 1977

United Technologies Corporation

Phase I was completed during the quarter. Two turbine subsystem designs which supplement each other and offer maximum performance potential at low risk were selected. The low-Btu combustor design selected offers maximum potential at low risk. Combined cycle plant concepts were developed during Phase I to assure the applicability of the subsystem designs.

The primary turbine subsystem design included an air-cooled rotating structure and a water-cooled static structure. Conventional convection and film air cooling techniques were employed for the rotating structure similar to those successfully used in the FT50 and other industrial engines. Cooling air extracted at the compression exit is cooled prior to injecting it into the turbine rotor. Good performance at high firing temperature is assured by the introduction of water cooling in the static structure, thereby adapting an advanced technique in a low risk application. The coolant is subcooled boiling water, which avoids complex problems associated with two-phase heat transfer. The water cooling system is designed in a closed loop and rejects heat to the steam bottoming system. The combined cycle plant in operation with the primary design turbine should attain 44 percent efficiency.

The alternate turbine design employs the same static structure cooling techniques as the primary approach, but incorporates water cooling of the rotating structure. The rotating blades are cooled by circulation of supercritical water. The required pressure is achieved by centrifugal force in the turbine rotor and circulation is the result of buoyant forces due to thermally induced density changes in the fluid. This circulation technique is known as the thermosyphon process. One important aspect of this design is that cooling, as in the static structure, is accomplished with a closed loop system which rejects heat to the steam bottoming system and does not add to the plant water consumption.

Both turbine subsystems designs are suitable for continuous 2600°F operation with potential growth to 3000°F. The alternate design may be regarded as a technology building block which can be added to the primary design to assure high performance even if significant reduction of a metal temperature becomes a durability requirement. The two design approaches impart a proper balance among the factors of technology advancement, minimum technical risk, and high performance. The turbine cooling schemes allow the use of conventional materials and provide acceptable durability in the not yet fully defined corrosive environment produced from contaminants in coal-derived fuels.

Westinghouse Electric Corporation

Phase I of the Program was completed during the quarter. The following preliminary design and analysis tasks were reported in the topical technical reports:

- Combined cycle studies to examine the effects of properly integrating the advanced concept gas turbine with the coal gasifier/gas cleanup system.

- The thermal and mechanical definition of the critical high temperature components and general assembly arrangement of a four-stage air-cooled Reference Turbine subsystem, using Lamilloy in the first three rows of blading.
- Definition of the approximately one-third scale model of the Reference Turbine that is intended for use in Phase III.
- Definition of the configuration and performance of the full-scale gas turbine engine and subscale test engine incorporating the high temperature turbines. The size of the test engine will permit Phase III testing on coal gasifiers that will be operational in the required time-frame.
- Design definition for a backup turbine design concept which uses water and steam to cool the first two stages with the remaining stages essentially the same as in the air-cooled design.
- A study of available data on coal gasification and gas cleanup systems to identify a comprehensive

sive program for firmly establishing the characteristics of coal derived fuels and related system requirements.

- Preliminary design of the advanced low-Btu gas combustor required for the high temperature gas turbine engine. Three concepts, each utilizing Lamilloy for wall cooling, were studied for the application. The selection of an advanced can-type design was approved by ERDA for further development under a separate program that would parallel the Phase II and III activities. A program plan to bring the combustor to the point of technology readiness was prepared as part of the Phase I effort.

A Phase II detailed "Technology Testing and Test Support Studies" Program Plan and the Phase III "Technology Readiness Verification Program" Preliminary Plan were prepared with DDA.

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; ° API = $\frac{141.5}{\text{Specific gravity, } 60^{\circ}\text{F}/60^{\circ}\text{F}} - 131.5$

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.

calcination — the process of heating a solid to a high temperature to 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 from crushed coke usually passing a 1/2 inch or 3/4 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.

deminerallization — 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 $\text{CaMg}(\text{CO}_3)_2$.

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 oil 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 suspended solids from a flowing liquid by means of the centrifugal forces set up when the liquid is made to flow through a tight conical vortex.

hydrocoking—coking of tars, SRC, etc., under hydrogenating conditions 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 hydro-

gen 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 calcite 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.

methanation—the production of methane (CH_4) from carbon monoxide 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—particled 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 compounds, 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-stream 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) containing about 0.1 percent ash and about 10 percent of the sulfur in the original coal feedstock; calorific value is about 16,000 Btu per pound; may be used as a clean fuel for power generation by combustion; utilized for the production of high-grade metallurgical coke, anode carbon, and activated carbon by coking, or hydrogenated to produce synthetic crude oil.

space velocity—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 moist 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, mineral-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 a 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: $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2$.

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