U.S. DEPARTMENT OF ENERGY
Division of Coal Conversion

QUARTERLY REPORT

January - March 1977

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COAL GASIFICATION

QUARTERLY REPORT

JANUARY - MARCH 1977

MASTER

U.S. DEPARTMENT OF ENERGY

Division of Coal Conversion 950 6771

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 commercial production of synthetic fuels from 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 converting coal to synthetic liquid and gaseous fuels and for improved direct combustion of coal. These fuels must be storable and suitable for power generation, transportation, and residential and industrial uses.

ERDA's program for the conversion of coal to gaseous fuels was started by two of its predecessor agencies: the Office of Coal Research (OCR) and the Bureau of Mines, U.S. Department of the Interior. Both high- and low-Btu gasification processes are being developed. High-Btu gas can be distributed economically to consumers in the same pipeline systems now used to carry natural gas. Low-Btu gas, the cheapest of the gaseous fuels produced from coal, can be used economically on site, either for electric power generation or by industrial plants.

HIGH-BTU GASIFICATION

High-Btu natural gas has a heating value of 950 to 1,000 Btu per standard cubic foot, is composed essentially of methane, and contains virtually no sulfur, carbon monoxide, or free hydrogen. The conversion of coal to high-Btu gas requires a chemical and physical transformation of solid coal. However, because coal has widely differing chemical and physical properties, depending on where it is mined, it is difficult to process. Therefore, to develop the most suitable techniques for gasifying coal, ERDA, together with the American Gas Association (AGA), is sponsoring the development of several advanced conversion processes.

Although the basic coal-gasification chemical reactions are the same for each process, the processes under development have unique characteristics. There are, for example, important differences in reactor configurations and

methods of supplying heat for gasification. Moreover, because these processes require high temperatures and some require high pressures, temperature-resistant alloys and new pressure vessels must be developed to obtain reliable performance.

A number of the processes for converting coal to high-Btu gas have reached the pilot plant stage. Laboratory research is also continuing in order to develop data for verifying the feasibility of the specific process and for supporting the operation of the plant. Responsibility for designing, constructing, and operating these pilot plants is assigned to Conoco Coal Development Company for the carbon dioxide acceptor pilot plant at Rapid City, South Dakota; Bituminous Coal Research, Inc., for the BI-GAS pilot plant in Homer City, Pennsylvania; Institute of Gas Technology for the HYGAS pilot plant and steam-iron system for the production of hydrogen in Chicago, Illinois; and The Lummus Company for the Synthane pilot plant in Allegheny County, Pennsylvania.

Test runs in the *Carbon Dioxide Acceptor Process* pilot plant during the quarter demonstrated conclusively that air alone could be used to transport spent acceptor from the gasifier to the regenerator. Laboratory research involved tests to determine acceptor activity patterns as well as the long term effect of cycling on reconstituted acceptor.

Plant operations concerning the *BI-GAS Process for the Generation of Pipeline Gas* were restricted during the beginning of the quarter because of the curtailment of natural gas. Operations were permitted in March, but were delayed because of a fire in the carbon dioxide stripper column. The gasifier was operated with coal feed to Stage II for 27.5 hours by the end of the quarter.

The first test conducted during the year at the *HYGAS Process* plant used Peabody No. 10 mine coal previously selected as the next test coal for the plant. Modifications and improvements had been completed in preparation for the initial testing. Steady state conditions were not achieved during the quarter, however.

The second ore circulation test was in progress at the beginning of the year in the pilot plant for the *Steam-Iron System For Production of Hydrogen*. The test was completed during the quarter as was the first producer feed test. Laboratory tests included kinetic studies, char evaluation, attrition studies, and lift-line studies.

The *Synthane Process* pilot plant conducted tests and performed necessary modifications to the plant in an effort to improve gasifier operations and reliability. During the quarter, 250 tons of coal were processed.

Battelle Memorial Institute is responsible for designing, constructing, and operating a process development unit (PDU) in West Jefferson, Ohio, for demonstrating the *Agglomerating Burner Process*. In combustor runs during the quarter, the burner bed was heated autogeneously with the combustion of the Rosebud coal, and the desired temperature was maintained and controlled throughout runs exceeding 130 hours in duration.

A *Liquid Phase Methanation Process* is being developed by Chem Systems, Inc. The pilot plant was prepared for the first experimental run during March. The system was maintained in a ready state anticipating HYGAS gasifier product or hydrogen reformer gas during the last two weeks of the quarter.

C. F. Braun and Company is providing *Technical Evaluation of High-Btu Gasification Processes* and is developing conceptual designs of commercial plants for producing pipeline-quality gas as a basis for evaluating the technical and economic feasibility of each process. Operations at the HYGAS, carbon dioxide acceptor, BI-GAS, and Synthane plants were observed by Braun engineers. Studies continued on the process specifics as well as the conceptual design of commercial plants.

LOW-BTU GASIFICATION

Low-Btu gas, with a heating value of up to 350 Btu per standard cubic foot, is an economical fuel for power generation in combined gas-steam turbine power cycles. On an equivalent Btu basis, conversion of coal to low-Btu gas is less complex than conversion to high-Btu gas and the capital costs are lower. Because different low-Btu gasification processes are optimum for converting different types of coal, and because of the need to provide commercially acceptable processes at the earliest possible date, ERDA is sponsoring the concurrent development of several basic types of gasifiers (fixed-bed, fluidized-bed, and entrained-flow). At the same time, hot-gas cleanup systems are being studied for use with these low-Btu gasifier systems.

Atomic International Division (AI), Rockwell International Corp., has the responsibility for designing, constructing, and operating facilities for a *Molten Salt Gasification Process*. Design and construction of the facility continued throughout the quarter. Groundbreaking for the process development unit occurred in March.

An *Advanced Coal Gasification System For Electric Power Generation* is being developed by Westinghouse Electric Corporation. Two gasifier tests were conducted during the quarter. For the first time, ash was agglomerated at elevated pressures and the carbon losses were extremely low.¹³ Support

studies included the operation of the bench-scale agglomerator for the first time as well as continued coal behavior studies.

An estimated 68 percent of the entire plant construction of the process development unit for the *Low-Btu Gasification of Coal for Electric Power Generation* was completed by Combustion Engineering, Inc. by the end of the quarter. A major milestone was achieved when the hydrostatic tests of gasifier pressure parts were successfully completed in March.

Foster Wheeler Energy Corporation, in conjunction with other industry team members, continued to develop the *Coal Gasification Combined-Cycle System for Electric Power Generation*. Work during the quarter consisted of publishing the Pilot Plant Design Report and drafting the Conceptual Design of a Commercial Plant Report as well as reports on the Cold Flow Model and System Transient Analysis.

Four process development unit (PDU) tests were conducted by Bituminous Coal Research, Inc. during the quarter to evaluate the design and operability of the equipment for the production of *Low-Btu Fuel Gas*. A total of 4 devolatilization/pretreatment tests were completed.

The *Modifications and Operation of an Atmospheric Pressure Ash-Agglomerating Gasifier* by the Institute of Gas Technology continued. The modifications of the ash-agglomerating equipment were nearly completed by the end of the quarter. The shakedown of the cold model was completed in February, and a test program schedule was prepared.

Data continued to be collected for the *Coal Conversion Systems Technical Data Book* being developed by the Institute of Gas Technology to provide a single, comprehensive source of data on coal conversion processes.

Systems, Science, and Software are developing a general *Computer Model of Coal Gasification Reactors*. The formulation of the chemistry for the steam oxygen gasification processes continued during the quarter for the fluidized bed gasification model. Work also continued on the turbulence formulations appropriate to entrained flow.

I. CARBON DIOXIDE ACCEPTOR COAL GASIFICATION PROCESS

CONOCO COAL DEVELOPMENT COMPANY
LIBRARY, PENNSYLVANIA

Plant Site: Rapid City, South Dakota

Contract No.: E(49-18)-415

Contract Funding: \$27,751,622
ERDA: \$18,501,081
AGA: \$ 9,250,541

Contract No.: E(49-18)-1734

Contract Funding: \$3,607,660
ERDA: \$2,405,107
AGA: \$1,202,553

INTRODUCTION

The carbon dioxide acceptor process is being developed by the Conoco Coal Development Company (CCDC) under the joint sponsorship of ERDA and the American Gas Association (AGA). ERDA is providing two-thirds of the funds and AGA, one-third.

The objectives of this contract are to (1) demonstrate the operability of all features of the carbon dioxide acceptor process through operation of a pilot plant and (2) obtain adequate design data to construct a commercial plant capable of producing 250 million standard cubic feet of high-Btu gas per day. Specifically, CCDC is to:

- Test several types of lignite and acceptors
- Design, construct, and operate methanation facilities in conjunction with the gasification pilot plant.
- Use process data derived from pilot plant runs to improve the process.

Figure I-1 shows the development schedule.

Figure I-1. CARBON DIOXIDE ACCEPTOR PROGRAM SCHEDULE

PROCESS DESCRIPTION

A diagram of the carbon dioxide acceptor process is shown in Fig. I-2. In this process, raw coal is crushed to 8 x 100-mesh in hot-gas-swept impact mills, where the moisture content is also reduced from approximately 38

cubic foot. The methanation facilities include a shift converter, carbon dioxide absorber, hydrodesulfurizer, zinc oxide sulfur guard, and a packed-tube methanator. A Dowtherm system is used to remove the heat generated by the strongly exothermic methanation reaction.

Some of the advantages of the carbon dioxide acceptor process are:

- An oxygen plant is not needed because the acceptor is heated and calcined in a separate reactor where air can supply oxygen for combustion without contaminating product gas.
- The circulation rate is lower than that required in other high-Btu gasification processes that circulate solids for heat transfer because the acceptor supplies heat through chemical reaction with carbon dioxide.
- Product gas cleanup requirements are minimized because the acceptor reacts with both hydrogen sulfide and carbon dioxide, the principal impurities in gasifier product gas.
- Raw gasifier product gas may contain enough hydrogen to methanate all of the carbon monoxide and part of the carbon dioxide without requiring water-gas shift conversion prior to methanation.

HISTORY OF THE PROJECT

Bench-scale development of the carbon dioxide process was completed in 1968. Feasibility studies indicated that the process had potential commercial possibilities. Construction of a pilot plant to test the process was completed (except for the methanation facility) in October 1971. Construction of the methanation facilities was completed in late 1974. The pilot plant is designed to use 40 tons of coal and three tons of dolomite per day to produce 500,000 standard cubic feet of high-Btu gas.

Pilot plant shakedown operations began in January 1972 and were completed in April 1972. A series of start-up attempts were initiated followed by the experimental run program. In conjunction with the operation of the pilot plant, CCDC has been continuing its laboratory research to resolve problems and improve the overall process design. Also, the South Dakota School of Mines and Technology has a subcontract with CCDC to (1) conduct studies of dolomite sources, activity, and reconstitution, (2) study sodium removal from lignite, (3) investigate the environmental aspects of the acceptor process, and (4) conduct verification analyses using test samples provided from pilot plant operation.

Two other subcontracts were initiated during 1976.

The Radian Corporation contracted to conduct an intensive analytical program pertinent to an environmental analysis of the carbon dioxide acceptor process. Stearns-Roger Company initiated a detailed economic analysis of the process, completing Phase I of the study by the end of the year.

Recent laboratory research has concentrated on studies of acceptor activity and reconstitution as well as the development of synthetic acceptors.

PROGRESS DURING JANUARY-MARCH 1977

Summary

The year began with the plant in a turnaround condition for the annual plant inspection and the planned reduction of the regenerator internal diameter. Run No. 42 started in January and demonstrated conclusively that air alone could be used to transport spent acceptor from the gasifier to the regenerator.

Run 43A was conducted in March to determine if the regenerator could be operated under neutral and/or oxidizing conditions. The run was terminated because of an electric power outage. Run 43B, a repeat of the previous run, was underway at the end of the quarter.

Laboratory research involved tests to determine acceptor activity patterns as well as the long term effect of cycling on reconstituted acceptor.

Related studies were conducted by the South Dakota School of Mines and Technology (SDSMT) on phase equilibria and melt composition. Radian and SDSMT agreed on a set of analytical methods and cooperated in sampling pilot plant runs. Stearns-Roger Company continued a Commercial Design Study.

Pilot Plant Operations

Following Run 41B in December, the plant was shut down and the entire month of January was devoted to decreasing the regenerator inside diameter to allow operation with 100 percent air. Run 42 demonstrated that the use of air in transporting spent acceptor from the gasifier to the regenerator caused no detrimental effects in the lift line. There was no evidence that the use of air caused hot spots or deposits in the regenerator, as inspection after the run revealed a clean reactor.

Run 43A was begun in March. The objectives of the run were to operate the regenerator at neutral (almost no oxygen in the offgas and at oxidizing conditions—one to two percent oxygen). Previously, the plant had been operated conservatively at reducing conditions (one to five percent carbon monoxide in the offgas) in order to suppress any formation of low-melting liquids which would lead to formation of deposits. Successful operation without carbon monoxide in the offgas would give a significant increase in overall process thermal efficiency.

After five days at full process pressure and temperature, the plant had stabilized at reducing conditions. The neutral period was begun, but was terminated after two hours at new conditions because of a storm-caused power failure. None of the objectives of the run were met, however, the run did demonstrate for a second time that air alone could be used to both fluidize the regenerator and transfer the recarbonated acceptor from the gasifier.

By the end of the quarter, Run 43B was in the initial stages of startup, with objectives identical with Run 43A.

Laboratory Research

Three runs were made in the automatic cycle tester to determine the effect of carbon dioxide partial pressure on acceptor activity pattern. Dorr-Oliver pelletized lime was used as the acceptor in these runs. Preliminary results suggested that the activity pattern of cycled acceptor is independent of the carbon dioxide concentration in both the gasifier and regenerator.

Two reconstituted acceptor samples, prepared via the Dorr-Oliver lime pelletizing process from spent acceptor

of the Rapid City Plant, were also tested for activity patterns in the automatic cycle tester as well as the thermobalance. Data obtained indicated that this material was as good an acceptor as the previously tested Dorr-Oliver material. Work is currently in progress to test the long term effect of cycling on this reconstituted acceptor. Preliminary work was also begun during the quarter on the determination of the gasification kinetics, via the carbon dioxide acceptor process, of vacuum bottoms from the liquefaction of Western coals.

Related Studies

Work was completed by the South Dakota School of Mines (SDSM) on phase relationships in the calcium carbonate-calcium sulfate-calcium sulfide system in February, and the final report was being prepared. Work also continued on the effects of melt composition on corrosion rates, and monitoring of waste streams from the pilot plant.

Radian Corporation and SDSM also agreed on a set of analytical methods. Samples from Run 42 were analyzed by both labs. Radian also analyzed the samples collected during the first sampling period (Run 39) for major and trace elements.

The design of the high pressure sampling system was completed and purchasing of materials began. Radian's mobile lab was installed at the Rapid City site in January for the sampling of Run No. 42.

Stearns-Roger Company continued with the Carbon Dioxide Acceptor Commercial Design Study. A model was started, and work on flow sheets neared completion.

II. BI-GAS PROCESS FOR THE GENERATION OF PIPELINE GAS

BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

Plant Site: Homer City, Pennsylvania
Contract No.: E(49-18)-1207
Contract Funding: \$66,000,000
ERDA: \$44,000,000
AGA: \$22,000,000

INTRODUCTION

The BI-GAS process is being developed By Bituminous Coal Research, Inc. (BCR), under the auspices of ERDA and the American Gas Association (AGA) as part of the effort to develop a method for producing high-Btu pipeline gas from coal. The pilot plant operational program is being managed by Phillips Petroleum Company.

The principal objective of this program is the development of the BI-GAS process. Specifically, BCR is directed to:

- Conduct laboratory-scale coal gasification experimentation, together with process and equipment development, to verify the technical and economic feasibility of producing high-Btu gas using the BI-GAS process.
- Design, construct, and operate a multi-purpose research pilot plant with the aid of engineering subcontractors.

Figure II-1 shows the overall program plan.

PROCESS DESCRIPTION

The BI-GAS process is a two-stage, high-pressure,

oxygen-blown system using pulverized coal and steam in an entrained flow. A diagram of the BI-GAS process is provided in Figure II-2.

Raw coal is first pulverized so that approximately 70 percent will pass through 200-mesh. The coal, mixed with water, is fed to a cyclone, where the solids are concentrated into a slurry. Coarse underflow from the cyclone is sent to a wet grinding mill for further crushing. The slurry is further concentrated in a thickener and centrifuge, repulped and mixed with flux to generate the desired concentration, and fed to the downstream high pressure feed system.

A high pressure slurry pump picks up the blended slurry and transports it under pressure to a steam preheater. The hot slurry is then contacted with hot recycle gas in a spray dryer for nearly instantaneous vaporization of the surface moisture. The coal is conveyed to a cyclone at the top of the gasifier vessel by the stream of water vapor and inert recycle gas, as well as additional recycled gas from the methanator. The coal is separated from the hot recycle gas in the cyclone and the coal flows by gravity to the gasifier.

The coal enters the gasifier through injector nozzles near the throat separating the stages. Steam is introduced through a separate annulus in the injector. The two streams combine at the tip and join the hot synthesis gas rising from Stage 1. A mixing temperature of about

Figure II-1. BI-GAS PROGRAM SCHEDULE

Figure II-2. BI-GAS PROCESS SCHEMATIC

2200°F is attained rapidly and the coal is converted to methane, synthesis gas, and char. The raw gas and char rise through Stage 2, leave the gasifier at about 1700°F, and are quenched to 800°F by atomized water prior to separation in a cyclone. The synthesis gas (containing carbon monoxide, carbon dioxide, hydrogen, water,

hydrogen sulfide, and methane) passes through a scrubber for additional cooling and cleaning. The clean gas, along with the desired amount of moisture, is sent to a carbon monoxide shift converter to establish the proper ratio of carbon monoxide and hydrogen required in the methanation process.

Three process steps follow shift conversion: hydrogen sulfide removal, carbon dioxide removal, and methanation. Three process alternatives are planned for investigation. In Alternative 1, the hydrogen sulfide and carbon dioxide are removed in a Selexol unit and the sulfur is subsequently recovered in a Claus plant. The gas stream passes through a fluidized-bed, catalytic methanation system for conversion to high-Btu gas. In Alternative 2, hydrogen sulfide is removed in the Selexol unit, sulfur is recovered, and the gas stream (still containing carbon dioxide) goes to the methanator. Carbon dioxide is then removed following methanation. Alternative 3 allows the gas stream to pass directly from the shift converter through the methanator. The hydrogen sulfide and carbon dioxide are removed in a later step. Of the three options, Alternative 1 is the process that is currently being used in the pilot plant.

The BI-GAS process has several advantages:

- A high yield of methane is obtained directly from coal, minimizing subsequent processing of the product gas.
- All types of coal can be gasified without prior treatment, since the process uses an entrained rather than a fixed- or fluidized-bed system.
- The reaction conditions in the upper stage of the gasifier are such that no tar and oils are formed in the gasification process.
- All the coal charged into the process is consumed; the principal by-products are slag for disposal and sulfur for sale.
- Gas generated at high pressures is adequate for transport in existing gas distribution systems without further compression.

Potential operating problems are:

- The slagging section of the gasifier has never been tested under operating conditions similar to those of the BI-GAS reactor. Slagging has been conducted at low pressures in cyclone boilers but slagging at high pressures without a proved reliable method of temperature control may be troublesome. Proper control of slag removal will be necessary to prevent the slag tap hole from plugging.
- The coal feed system for the pilot plant has not been tested.
- Char particles may strike the wall of the reactor, adhere to the wall, or cause erosion of the refractory material.

HISTORY OF THE PROJECT

This project was started in December 1963. BCR's first experiments confirmed the basic assumption that a high yield of methane could be obtained directly from coal by reaction with steam at elevated temperatures and pressures. BCR next conducted continuous flow experiments in an externally heated reactor processing five pounds of coal per hour. The experimental data were extrapolated to design a process development unit that would simulate the conditions of Stage 2 of the BI-GAS process. The unit was internally fired and could process 100 pounds of coal per hour. Experiments were designed to determine the optimum residence time, coal rank, and processing conditions (pressure, temperature, and hydrogen partial pressure) that would produce the greatest yield of methane. North Dakota lignite, Wyoming subbituminous C coal, and Pennsylvania high volatile A bituminous coal were used in the experiments. During these experiments, BCR found that the physical design of the Stage 2 process development unit influenced methane yield. Therefore, a cold flow model of Stage 1 and the bottom of Stage 2 was developed to investigate methods for improving the flow patterns in Stage 2 and to establish design criteria for the slagging section of the gasifier.

BCR developed the basic design criteria for a fully-integrated pilot plant capable of processing five tons of coal per hour and producing 100,000 standard cubic feet of clean pipeline-quality gas per hour. Stearns-Roger was awarded the contract for constructing the \$34 million facility on July 11, 1972. The pilot plant management contract was subsequently awarded to Phillips Petroleum Company in November 1974. The gasification vessel to be used in the pilot plant was designed and built by Babcock and Wilcox, a Stearns-Roger subcontractor. The pilot plant was completed in 1976 and start up operations began. Formal acceptance of the plant from Stearns-Roger Construction Co. was made by Phillips Petroleum Company on September 15. By the end of the year the flash drying system and gasifier system were operated successfully. Baseline conditions were established and maintained until the objectives had been achieved.

BCR continued to supply laboratory support as needed to pilot plant operations. On the basis of the laboratory research, Harshaw Chemical Company's type M-647A-3-18-6P catalyst was selected as the first charge of the pilot plant methanator. Optimum operating conditions were determined by testing the catalysts in a process development unit operating in both continuous and semi-continuous modes.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Plant operations were restricted during the beginning of the quarter because of the curtailment of natural gas. The curtailment was reduced during March to a level that permitted operations. The first test run was interrupted before operations had reached a coal feed stage because of a fire in the carbon dioxide stripper column. Operations were re-established and the gasifier was operated with coal feed to Stage II for 27.5 hour.

BCR continued laboratory tests in support of the overall program throughout the quarter. Slag viscometer tests were begun and one PEDU test was completed.

Pilot Plant Operations

During January and February, operations of the plant were in areas that did not require natural gas usage because of a 65 percent curtailment in January and a 100 percent curtailment effective February 1. This curtailment was reduced to 25 percent and finally to a level in March that permitted operations. Plant maintenance, repairs, instrument calibration, system checks, and operating programs were emphasized in preparation for

gasifier operation when natural gas became available. Upon notification of a reduction in natural gas curtailment to 25 percent on March 14, repairs and modifications that were underway were completed or halted and preparation for startup began.

The plant was approaching operating conditions required for coal feed to the gasifier when a fire was detected in the insulation of the carbon dioxide stripper column. The test run was interrupted for safety reasons. When operating conditions were again established, the gasifier was operated with coal feed to Stage II for 27.5 hours and with intermittent char feed to Stage I until another shutdown was caused by a fire at the outlet of the recycle gas heater.

Laboratory Research

A series of tests by BCR with the slag viscometer were begun in January. Rosebud coal ash was mixed with crushed Allegheny River gravel to determine the effect of that material as a flux. BCR continued its work with viscosity altering additives as they might be applicable to pilot plant operation.

One PEDU test was conducted during March, using the second batch of the Homer City catalyst (BCR Lot No. 3737).

III. PIPELINE GAS BY HYDROGASIFICATION (HYGAS PROCESS)

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois
Contract No.: E(49-18)-2434
Contract Funding: \$8,230,179
ERDA: \$5,486,786
AGA: \$2,743,393

INTRODUCTION

The HYGAS process is being developed by the Institute of Gas Technology (IGT) as part of the joint program of ERDA and the American Gas Association (AGA). ERDA is providing two-thirds of the funds and AGA, one-third.

The objective of this contract is to operate the HYGAS pilot plant facility to continue and expand research and development efforts directed toward completion of a commercial concept suitable for producing pipeline quality gas from coal. IGT's specific objectives include:

- Development of a high-pressure hydrogasification process that uses all ranks of coal.
- Determination of the technical and economic feasibility of the HYGAS process using the steam-oxygen hydrogen-generating system.
- Demonstration of the feasibility of ash agglomeration as a technique to increase carbon utilization.
- Determination of steady-state conditions and acquisition of scaleup data.

The overall program plan is shown in Figure III-1.

PROCESS PILOT PLANT DESCRIPTION

Several processing steps are required to convert coal to high-Btu gas with the HYGAS process. A key feature is the use of hydrogen and steam in hydrogasification. A diagram of the process is provided in Figure III-2. Coal preparation involves crushing the coal to -8 mesh. Caking coal is pretreated in a fluidized bed at temperatures between 750°F and 850°F at atmospheric pressure to destroy caking tendencies and produce a free-flowing coal. Noncaking coal is fed directly to the slurry tank. The coal is slurried in this tank with an aromatic recycle oil to form a thick slurry. This slurry is then pumped to 1000 psig and injected into the top section of the gasifier (slurry dryer) which contains a fluidized bed of hot coal particles. Oil is vaporized and removed, together with the hot gases passing upward from the first stage of the gasifier.* Vaporized oil is recovered for reuse by quenching the effluent of the gasifier.

Dry coal particles, at approximately 600°F from the slurry drying section, flow by gravity through a dipleg into a lift pipe. This lift pipe serves as the first stage of hydrogasification. In this stage, the heated coal comes in

*Gas, passing through the bed of coal particles, fluidizes or agitates it, thus facilitating heat exchange and gas-solids contact.

PROJECT	FY 75	FY 76	TR. QR.	FY 77	FY 78	FY 79
ASH AGGLOMERATION UNIT	CONSTRUCTION ↓ △ SHUTDOWN ↓ △ CONSTRUCTION ↑ △ OPERATION	OPERATION ↓ △ EVALUATE MECHANICAL RELIABILITY ↓ △ OPERATION				
STEAM-OXYGEN UNIT	CONSTRUCTION ↓ △ SHUTDOWN ↓ △ CONSTRUCTION ↑ △ OPERATION	OPERATION ↓ △ EVALUATE MECHANICAL RELIABILITY ↓ △ OPERATION				
INTEGRATED PILOT PLANT OPERATION INPUT: 75 TONS/DAY COAL OUTPUT: 1.5×10^6 SCFD HIGH BTU GAS	OPERATION ↓ △ SHUTDOWN ↓ △ CONSTRUCTION ↑ △ OPERATION	OPERATION ↓ △ EVALUATE MECHANICAL RELIABILITY ↓ △ OPERATION		OPERATION ↓ △ SHUTDOWN ↓ △ CONSTRUCTION ↑ △ OPERATION		
				PROCESS EVALUATION		

LEGEND: △ BEGIN MILESTONE ▽ COMPLETE MILESTONE
 ○ DECISION MILESTONE

Figure III-1. HYGAS PROGRAM SCHEDULE

Figure III-2. HYGAS PROCESS SCHEMATIC

contact with a hot gas from the lower sections of the reactor. This gas contains methane, carbon oxides, hydrogen, and steam. The hydrogen chemically reacts with the more reactive part of the incoming coal, forming additional methane. Approximately one-third of the methane in the final product gas is produced in this step.

In the second stage hydrogasification section, the partially converted coal from the first stage mixes with the rising hydrogen-rich gas at about 1400-1700°F. Part of the hydrogen and steam react chemically with the coal, forming methane and carbon oxides. Approximately one-third of the methane in the final product gas is produced in this step. Hot residual char is then transferred to the third stage. Here the steam and oxygen react with the char in a fluidized bed to produce a mixture of gases rich in hydrogen. This mixture is passed upward into the hydrogasification sections. Ash is removed from the bottom of the steam-oxygen zone.

The raw product gas leaving the top of the reactor at about 600°F is cooled and rinsed in a water quench, purified, and passed to a methanator. The ratio of hydrogen to carbon monoxide in the purified gas entering the methanator is adjusted to about three to one. The purified gas passes through a nickel catalyst at 800-900°F and is transformed to pipeline quality gas with an average heating value of 1,000 Btu per standard cubic foot.

HISTORY OF THE PROJECT

Development of the HYGAS process by IGT under the sponsorship of AGA began in 1946, and continued under joint sponsorship with the Office of Coal Research (OCR), now a part of ERDA, in 1964. The pilot plant was designed and built to convert 75 tons of coal per day to 1.5 million cubic feet of clean high-Btu gas. During 1973, the plant produced pipeline-quality gas from coal in sustained test operations. Since then, the duration of the test runs has increased, and longer, more stable operating periods have been achieved.

During 1975, eleven test runs were made in the HYGAS pilot plant. The longest run was made in July, demonstrating the technical feasibility of using lignite. Fifteen days of self-sustained operation were achieved with over 1000 tons of lignite processed. The entire plant was on stream for 92 percent of the time, or 333 hours. Steady-state conditions were achieved for 160 hours. The heat and material balances were within ± 5 percent of closure. Subsequent to Test 37 with lignite, IGT was authorized to start testing with Illinois No. 6 bituminous coal.

Twenty-six runs were made with the ash-agglomerating gasifier during 1975, also. Process parameters were varied to determine the optimum operating conditions. Using coke breeze, agglomerates were successfully produced for a 200-hour steady state period and full dust recycle was maintained.

All sections of the HYGAS plant, including methanation, were brought on stream for the first time during 1976. This was a milestone achievement, making the first time that a steam-oxygen integrated HYGAS gasification process had produced a high Btu pipeline gas from a bituminous coal feed material.

Concurrent laboratory research was directed toward the study of the penetration of slurry liquid into coal pores, effects of acidic condensing atmospheres on castable insulations, and methanation catalyst evaluation.

Of major technical and economic importance to this process is the production of the hydrogen-rich gas required for hydrogasification. Two techniques for producing this gas are being investigated: steam-oxygen and steam-iron. A steam-oxygen unit, which gasifies char, was constructed and installed in the base of the HYGAS pilot plant hydrogasification reactor during 1974 and has been operated successfully. The steam-iron technique is being developed by IGT under separate contract (see Section IV). Currently, a pilot plant for demonstrating this technique has been constructed adjacent to the HYGAS pilot plant site. Shakedown runs and batch tests of the two-megawatt electrothermal gasifier for producing hydrogen-rich gas were completed in early 1974. Although this technique has been demonstrated to be technically feasible, it was found to be too costly due to the large quantity of electrical power required. No further investigations of this unit will be made.

Data obtained during integrated operations of the entire HYGAS pilot plant continue to be used to formulate engineering design bases and to establish reliability trends in operating equipment.

PROGRESS DURING JANUARY-MARCH 1977

Based on laboratory evaluations performed on candidate Illinois Basin bituminous coals in December, Peabody No. 10 mine coal was selected as the next test coal for the HYGAS pilot plant. All of the coal had been delivered by February and coal-crushing tests were performed. Modifications and improvements had been made to the plant in preparation for the first test with this coal, Test 59.

Problems in the pretreater coal feeding system as well as leaky seals in the reactor delayed start up. Subsequently conducted in March, Test 59 did not achieve steady state conditions. A total of 52 tons of pretreated coal was fed to the reactor before leaks forced the termination of this test.

Results of process development unit tests with Peabody No. 10 mine coal yielded carbon conversions of 88 percent in the steam/oxygen gasifier at 1820° F.

IV. STEAM-IRON SYSTEM FOR PRODUCTION OF HYDROGEN

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois
Contract No.: E(49-18)-2435
Contract Funding: \$9,282,647
ERDA: \$6,188,431
AGA: \$3,094,216

INTRODUCTION

The steam-iron process is being developed by the Institute of Gas Technology (IGT) as a possible alternative for producing hydrogen for use in the HYGAS pilot plant (Section III) and as a means of producing hydrogen for industrial or other coal conversion processes. The process is being developed under the auspices of ERDA and the American Gas Association (AGA). ERDA is providing two-thirds of the funds and AGA, one-third.

The objectives of this contract are to design, construct, and operate a steam-iron pilot plant facility for the production of hydrogen. The system will provide process and design data for a commercial-size facility. The development schedule for the process is shown in Figure IV-1.

PROCESS DESCRIPTION

The steam-iron process is a system for producing hydrogen for the hydrogasification of coal, and it is also hoped that it may be an attractive source of hydrogen for the petrochemical and other industries requiring hydrogen. A flow diagram of the steam-iron pilot plant is shown in Figure IV-2.

In the pilot plant, a char-water slurry containing from 35 to 50 percent char is heated in a direct fired furnace to produce a lean-phase mixture of char and steam. The steam lifts the char to the preheater bed at the top of the producer vessel. There it is fluidized with air and steam, thereby combusting approximately ten percent of the feed char and raising the temperature from 600°F to approximately 1750°F.

The preheated char then enters the producer bed where it is gasified at approximately 2000°F with air and steam to yield a reducing gas. Spent char is cooled with additional steam and discharged from the producer vessel at about 1000°F. The 2000°F reducing gas is then fed to the reducer bed of the steam-iron reactor.

The producer gas enters the reducer/oxidizer reactor vessel in the lower part of the reducer section, where it reacts with a recirculating stream of iron oxides, converting FeO to Fe. The producer gas reaches a conversion level of about 20 percent in the lower stage before entering the upper stage. The bulk of the conversion (65 percent) is attained by the conversion of Fe₃O₄ in the upper stage. Steam fed to the lower oxidizer section converts FeO to Fe₃O₄ and conversion of up to 30 percent of the feed occurs in this stage. Further conversion of steam occurs in the upper oxidizer, where Fe is oxidized to FeO. The system is designed for a final steam conversion of up to 60 percent.

PROJECT	FY 75	FY 76	TR. QR.	FY 77	FY 78	FY 79
STEAM IRON UNIT	CONSTRUCTION		▽			
		△	▽	OPERATION		ENGINEERING EVALUATION ▽ ↓ ○

LEGEND : △ BEGIN MILESTONE ○ DECISION MILESTONE
 ▽ COMPLETE MILESTONE

Figure IV-1. STEAM-IRON SYSTEM PROJECT SCHEDULE

Figure IV-2. STEAM-IRON PILOT PLANT SCHEMATIC

Four fluidized beds are used in the steam-iron process to obtain full countercurrent operation. The reducing stages are located above the oxidizing stages with external recirculation of the Fe_3O_4 -rich solids from the bottom to the top of the vessel. This configuration avoids dual, vertical solids transport systems that would be required if the oxidizing and reducing stages were located side by side. The advantages of the steam-iron system include:

- Elimination of the need for a large oxygen plant.
- Reduction in the amount of carbon dioxide scrubbing required since most of the carbon dioxide produced in the system is vented in the spent reducing gas, which by-passes the purification system.
- Elimination of the downstream shift reactors.
- Energy recovery and sale of by-product electricity may lead to an overall coal-to-energy conversion of greater than 70 percent.

It is believed that these benefits may lead to a more economical overall process which more than compensates for the additional costs of the auxiliary steam-iron reaction system.

HISTORY OF THE PROJECT

Steam-iron process research has been conducted periodically for many years. The earliest use of the steam-iron process featured a fixed, packed bed of iron ore that was reduced to iron with gases containing carbon monoxide and hydrogen. The iron was then oxidized with steam to produce iron oxide plus a mixture of hydrogen and unreacted steam. Continuous hydrogen production was provided by using two beds that were cyclically reduced and oxidized. This process was neither economic nor compatible with high pressure operations and was dropped in favor of steam reforming of natural gas as a method for producing hydrogen. The process was revised in the late 1950's by the U.S. Bureau of Mines for use in producing hydrogen for coal gasification. In 1961, IGT began working on the process and continued until 1971. This work was performed under the sponsorship of Fuel Gas Associates. In 1973, IGT resumed work on the project and has been developing the process under the joint sponsorship of the Office of Coal Research (OCR, now a part of ERDA) and AGA.

The pilot plant was completed in 1976, concluding the tasks under contract E(49-18)-1518. Subsequent operations were continued under a new contract. The first iron ore solids circulation tests were made late in 1976.

PROGRESS DURING JANUARY-MARCH 1977

Summary

The second ore circulation test was in progress at the beginning of the year. It was completed during the quarter as was the first producer feed test. Laboratory tests included kinetic studies, char evaluation, attrition studies, and lift line studies.

Pilot Plant Operations

The second ore circulation test was completed in January. Pressures in the steam-iron vessel were maintained at 300 psig, and temperatures in the fluidized beds were held above 500°F during circulation periods. The test was terminated, as scheduled, toward the end of the month to replace the liner in the ore lift line.

While modifications were made to the lift line, preparations were started to conduct char feed testing in the producer reactor, with the first producer feed test successfully completed in March. A total of 7.5 tons of char was fed to the producer reactor over a period of 36 hours. Slurry concentrations of up to 30 weight percent solids were pumped through the slurry heater and vaporized without difficulty. A bed level was established in the producer zone, and steady operation was achieved over a period of four hours. Reactor temperatures were limited between 500° and 1000°F because of mechanical problems with the process air to compressor. The test was terminated after a startup burner flame failed. All solids were discharged easily. The reactor internals were in excellent condition following the test.

Laboratory Tests

Kinetic Studies

Ten reactivity and ten attrition tests were performed in March on solids prepared by several coprecipitation procedures. The results showed that four materials tested had higher reactivities than siderite and that the reactivity of IGT Iron-Chromia 5, containing 62.6 weight percent iron, six weight percent chromium, and one weight percent magnesium (the balance of the weight is oxygen), was the best of the lot. However, the attrition resistance of the material was significantly lower than that of siderite. Attrition test results show that only one material, IGT Iron-Alumina 13, containing 60 weight percent iron, 12.6 weight percent aluminum oxide, and one weight percent magnesium, had better attrition resistance than

siderite. Attempts will be made to improve the attrition resistance of IGT Iron-Chromia 5 by incorporating various concentrations of silica and calcium oxide in this material.

Char Evaluation

Char evaluation tests were conducted to determine operational characteristics of high-ash beds. Operating performance of chars containing five and eight weight percent volatile matter were also compared.

Attrition Studies

Seventeen attrition tests were conducted with -60 + 80 U.S.S. size fraction of siderite. The effect of cyclone-inlet velocity on the attrition characteristics of this size fraction in the cyclone was determined. The effect of gas density and bed weight on attrition characteristics of

siderite at the gas distributor was also determined, as was the effect of gas density on the attrition characteristics of siderite in the cyclone.

A mathematical model for attrition was developed that can predict the rate of fines generation and size distribution of the attrited material to within a ± 10 percent.

Lift-Line Studies

Lift-line studies included a total of 16 tests. Eight tests were run to determine the effect of lean-phase lift-gas velocity on the operation of the transition zone between the lean- and dense-phase lifts. The remaining tests were performed to determine the reproducibility of the data. Results showed that, at constant operating conditions, the reproducibility of the data was excellent. However, it is very difficult to achieve identical conditions as well as smooth operation of the system.

V. SYNTHANE PROCESS

THE LUMMUS COMPANY
BLOOMFIELD, NEW JERSEY

Plant Site: Allegheny County,
Pennsylvania

Contract No.: E(49-18)-0003

Contract Funding: \$24,000,000
(100% ERDA)

INTRODUCTION

The Synthane process was developed by the Bureau of Mines and is now the responsibility of ERDA. The government-owned Synthane pilot plant is being operated by the Lummus Company. The objective of this contract is to obtain definitive process information, sufficient for commercial design purposes, on the conversion of coal to gas of pipeline quality. The overall program plan for the development of the Synthane process is shown in Figure V-1.

PROCESS DESCRIPTION

A key feature of the Synthane process is that pretreatment of caking coals is integrated with gasification. Another feature is that gas with a relatively high methane content is produced directly. A schematic of the Synthane process is provided in Figure V-2. There are four major steps in the process: coal pretreatment, coal gasification, shift conversion and purification, and methanation.

Coal, crushed to -20-mesh, is dried, pressurized to approximately 70 atm, and is transferred into the fluidized-bed pretreater by means of high pressure steam and oxygen. Pretreatment provides a mild oxidation of the

coal particle surface so that caking coals will not agglomerate in the gasifier. The coal overflows from the pretreater into the top of the fluidized-bed gasifier about ten feet above the bed level, falls through hot gases rising from the fluidized bed, and is devolatilized. This devolatilization contributes significantly to the methane yield. Steam and oxygen enter the gasifier just below the fluidizing gas distributor. The gasification reaction occurs within the fluidized bed. Unreacted char flows downward into a bed fluidized and cooled with steam, and is removed through lock hoppers. This char can then be burned to produce process steam. The product gas, containing methane, hydrogen, carbon monoxide, carbon dioxide, ethane, and impurities, is passed through a venturi scrubber and a water scrubber to remove carry-over ash, char, and tars. The concentration of hydrogen and carbon monoxide in the gas is adjusted to a three-to-one ratio in a shift converter. The acid gases are absorbed in a hot-potassium carbonate scrubber. Carbon dioxide is reduced to two volume percent and sulfur is reduced to 40 parts per million. Regeneration of the potassium carbonate solution produced a hydrogen sulfide-rich gas, which is converted to elemental sulfur by the Stretford process. The remaining traces of sulfur in the product gas are removed by passing the gas through activated charcoal. The purified gas must be reacted catalytically to convert the hydrogen and carbon monoxide to methane.

Two alternative methanation systems are being investigated: the hot gas recycle (HGR) system and the tube wall

- More than half of the methane is produced directly in the gasifier. By maximizing methane production in the gasifier, oxygen requirements are reduced. Therefore, the investment for an oxygen plant is lower and the sizes of all process vessels downstream from the gasifier are reduced by 30 to 50 percent, compared to processes in which the raw gas from the gasifier contains little or no methane.
- The process flow system and equipment are relatively simple.

Some of the disadvantages of the process are:

- Char is produced which must be utilized for steam production in an environmentally acceptable manner.
- Some tars and oils are produced which must be disposed of or utilized.
- More economical coal feeding methods than the currently used lock hopper system must be developed.

HISTORY OF THE PROJECT

The Synthane process was developed by the Bureau of Mines at the Pittsburgh Energy Research Center, Bruce-ton, Pennsylvania. Development work started with scattered research in several areas. In 1961, work was started on methods of pretreating caking coals in fluidized beds. A preliminary design contract was awarded to M. W. Kellogg Company in August 1970 to determine if the data were sufficiently complete to proceed with design of the pilot plant. The contract was extended for additional gasifier tests and further evaluation of the Synthane project. Based on the results of the gasifier tests and the evaluation, the Bureau of Mines concluded that the process was feasible and the design could begin.

In June 1971, a contract was awarded to Lummus for obtaining process information and designing the pilot plant. The contract was modified several times to increase its scope to include rating and sizing heat exchangers, purchasing equipment, preparing a bid package, preparing a final report, additional engineering, inspecting and control monitoring, etc. Rust Engineering was awarded a contract to construct a pilot plant from the design information obtained by Lummus.

Construction of the Synthane pilot plant was completed in March 1975 and all areas and systems were transferred from the construction contractor to ERDA. Through 1975 work concentrated on installation of auxiliary equipment and the repair and modification of

the plant due to faulty equipment and design changes. During the first quarter of 1976 these repairs and changes were made and initial testing began. Gas was first produced from Rosebud Coal on July 7, 1976. The efforts for the remainder of the year were directed toward making the gasifier operational and reliable.

PROGRESS DURING JANUARY-MARCH 1977

Summary

After completion of modifications at the beginning of the year, the Synthane plant remained down until February 23 due to the energy crisis. The plant was then operated for six days, processing 250 tons of coal. Continuous run lengths of 13, 23, 25, and 42 hours were achieved. Feed rates were at design, and carbon conversion of 65 percent were achieved for a 24-hour period. The run was terminated because of plugging of the outlet cone of the gasifier.

After cleanup, inspection, and revisions, the plant operated again from March 15 through 17. The run was terminated because of low bed density and poor conversion. Another start up on March 22 lasted only 10 hours. The plant remained down from March 23 through 30 for cleanup and modifications. A run was in progress at the end of the quarter.

Pilot Plant Operations

The Synthane plant was shut down December 20, 1976 for modifications and repairs. Inspection and modifications were completed by January 21, but the unavailability of carbon dioxide and fuel oil due to the energy crisis delayed startup until February 23.

During the extended outage, modifications made to the gasifier were designed to resolve the major problem of fouling of the scrubbing systems. Changes were made to the gasifier internals to provide a deep bed injection of coal feed rather than a free fall, representing a major change in process conditions for the February run. This was expected to minimize tar production and minimize the elutriation of fines from the free fall into the cyclone. Additionally, the trickle valve was removed from the cyclone dip leg and a steam eductor was installed. The steam eductor is designed to provide a motivating force to help remove the fines from the cyclone dip leg into the fluidized bed.

Plant start up began again February 23 and ran for six days to March 1. Oxygen and feed remained in the gasifier for 113 hours. Periods of continuous operation of 13, 23, 25, and 42 hours were achieved. During this period, 250 tons of dried coal was fed to the gasifier. Data evaluation showed improved higher overhead temperatures, no tar formation, 65 to 70 percent conversion, but continued heavy fines carryover.

After the run, vessel inspection showed the eductor under the cyclone to be plugged with fines, but the cyclone dip leg was clear. It was decided to remove the eductor, and the cyclone dip leg purges were reinstalled in the hope that the deep bed injection procedure and no tar generation would allow the cyclone to function without plugging.

The plant was started up on March 15 and operated through March 17. It was believed the cyclone began functioning during this run for the first time because the

fines return to the bed caused the bed density to drop from 22 pounds per cubic foot to eight pounds per cubic foot. With the low bed density, very poor carbon conversions were achieved. It was proposed that poor conversions were due to the bypassing of fresh coal feed from the deep bed piping directly into the cone and out with the char.

The plant was restarted on March 22 after shortening the deep bed injection piping and removing the eight plugs that had been installed in the bottom row of cone nozzles in an attempt to achieve better gas distribution. After a short run of 10 hours, which was aborted because of the inability to remove char, it was determined that unplugging the nozzles caused the clinker formation. They were consequently replugged.

Plant start up commenced March 31. Coal feed rate was established at three tons per hour, gasifier bed height at 15 feet, and bed temperatures were maintained at 1500°F.

VI. AGGLOMERATING BURNER PROCESS

BATTELLE MEMORIAL INSTITUTE
COLUMBUS LABORATORIES

COLUMBUS, OHIO

Plant Site: West Jefferson, Ohio

Contract No.: EF-77-C-01-1513

Contract Funding: \$12,944,484
ERDA: \$12,271,370
AGA: \$ 673,114

INTRODUCTION

The agglomerating burner gasification process is being developed by Battelle Memorial Institute, under the sponsorship of ERDA. The objective of the current contract is to develop a two-stage process using a self-agglomerating fluidized-bed combustor as part of a practical and economical means for producing synthesis gas by steam gasification of coal. A process development unit is to be designed, constructed, and operated, and the following aspects of the process are to be explored:

- Operability of a self-agglomerating fluidized-bed coal combustor that operates on eastern bituminous coal under pressure and uses air for combustion.
- Mechanical feasibility of continuous circulation of hot ash agglomerates between fluidized-bed combustor and gasifier vessels at seven atm pressure and at flow rates and temperatures required for effective heat transfer.
- Operability of integrated fluidized-bed burner and gasifier vessels both fed by eastern bituminous coal (or char in the case of the combustor) and operating at seven atm pressure.

Concurrent with the operation of the process development unit, Battelle will perform process engineering studies which will result in a conceptual design of a scaled-up version of the agglomerating burner process. Also, Battelle will perform the necessary engineering,

design, and related technical effort to enable the procurement of a small gas turbine (which can be installed in the system for more efficient utilization of process energy), but will not include the actual purchase of the unit. Figure VI-1 shows a revised schedule for the development of the agglomerating burner process for the latest contract modification.

PROCESS DESCRIPTION

Conversion of coal to pipeline-quality gas using the agglomerating burner process requires completion of five steps: coal preparation, coal pretreatment, coal gasification, gas cleanup, and methanation. Figure VI-2 shows a diagram of the process.

In the coal preparation section, coal is crushed and separated into two sizes: -100 mesh and -8 +100-mesh. Caking coal in the -8 +100-mesh range is fed to a fluidized-bed pretreater where it is mixed with gas and air at atmospheric pressure and 750°F. It is cooled, fed to the gasifier, and reacted with steam in a fluidized bed. The -100-mesh coal is burned with air in a fluidized-bed combustor in a manner allowing agglomeration of the ash at a temperature approaching the ash fusion point (2100°F). Combustion of coal in this self-agglomerating mode yields hot flue gases that, because they are sufficiently

PROJECT	FY 75	FY 76	TR. Q.	FY 77	FY 78	FY 79
PROCESS DEVELOPMENT UNIT INPUT: 25 TONS/DAY COAL OUTPUT: 0.8×10^6 SCFD HIGH-BTU GAS	CONSTRUCTION			FEASIBILITY DEMONSTRATION PHASE		
		SHAKEDOWN				

LEGEND:
 ▲ BEGIN MILESTONE
 ▼ COMPLETE MILESTONE
 ○ DECISION MILESTONE

Figure VI-1. AGGLOMERATING BURNER PROGRAM SCHEDULE

Figure VI-2. AGGLOMERATING BURNER PROCESS SCHEMATIC

free of fly ash, can be expanded in a gas turbine for energy recovery. Hot ash agglomerates are transferred continuously from burner to gasifier by means of a steam lift. Superheated steam enters the gasifier below the distributor plate. Coal is fed through lock hoppers and is conveyed by inert gas to the gasifier. Hot agglomerated ash

flows downward and transfers a portion of its sensible heat to support the coal gasification reactions. The temperature of the hot ash agglomerates decreases to 1600° F or 1500° F. Product gas from the gasifier is sent to the gas cleanup section. Most of the agglomerated ash is recycled to the burner for reheating. Ash equivalent to

the ash content of the coal fed to the burner is removed from the system continuously to maintain a constant quantity of ash agglomerates in the cycle.

Burner flue gas, after passing through a cyclone, is scrubbed in a venturi and sent to the stack. There is also a provision for sending the flue gas through a heat exchanger and a gas turbine for energy recovery. The product gas, after leaving a cyclone at the gasifier, also passes through a venturi scrubber system. Gas purification, shift conversion, and methanation system for the treatment of the product gas are not part of the present program and no facilities are being provided for these operations. There is, however, ample space at the plant site for future incorporation of these functions.

Three advantages of the agglomerating burner process are:

- Recirculation of hot ash to supply heat in the gasifier eliminates the need for partial oxidation and, thus, the need for an oxygen plant.
- Hot flue gas (free of fly ash) can be expanded through a turbine, thus increasing the overall thermal efficiency of the process.
- Self-agglomerating coals such as eastern bituminous may be converted to synthesis gas by this process.

HISTORY OF THE PROJECT

The initial research on the gasification process was sponsored by Union Carbide Corporation at Battelle in the early 1960's. That work included the study of agglomerating ash burner performance in bench scale reactors a few inches in diameter using a bituminous coal (Pittsburgh No. 8) and a subbituminous western coal from Lake DeSmet, Wyoming. Gasifier performance was studied in a three-inch diameter bench-scale reactor in which the hot circulating agglomerated ash was simulated by circulating heated sand. Lake DeSmet subbituminous coal was used in these experiments. Other experiments were conducted to estimate turbine-blade erosion by fly ash in the gaseous products of combustion from powdered Lake DeSmet coal burned under ash agglomerating conditions. All the experimental work sponsored by Union Carbide was done at atmospheric pressure. A U.S. patent covering the work at Battelle was issued in March 1965 and assigned to Union Carbide. The Government has a royalty-free license under this patent.

After several attempts, beginning in 1965 by Union Carbide and later by Battelle, to interest the Office of Coal Research (OCR) in the process, OCR and the American Gas Association agreed in 1972 to sponsor further development jointly. Under this agreement, the development work was supervised by an operating committee drawn from AGA and OCR and financed one-third by AGA and two-thirds by OCR. AGA withdrew its support in August 1974 and the work has since been supervised and financed entirely by OCR and, more recently, by ERDA.

The preparation of a bid package for the engineering design and construction of a process development unit for operation under pressure began in the fall of 1972 through an interim authorization of AGA. A contract was awarded to Battelle by the Office of Coal Research (OCR) in January 1973 to install and operate the unit. Chemical Construction Corporation (Chemico) was selected as the engineering contractor to prepare the detailed engineering design and to construct the process development unit at Battelle's Engineering Station in West Jefferson, Ohio. Design work began in February 1973, and was essentially completed in January 1975. Field construction began in June of 1974 and was successfully completed by a local subcontractor in mid-August 1976.

Commissioning of the available sections of the PDU continued concurrently with the completion of construction and all scheduled commissioning was completed by the end of August. Heat up of the burner/gasifier system to condition the refractories was initiated late in that month and completed early in September 1976.

Controlled circulation of solids, with stable bed conditions, was achieved at relatively low temperatures and pressure over several periods of continuous operation, each in excess of 100 hours. The effect of primary process control points on solids circulation was established. Preliminary calculations indicated that design circulation rates of up to 20 tons per hour were achieved.

Work to date demonstrated that Rosebud subbituminous coal can be fed to, ignited, and burned in the fluidized bed of the burner. Coal ignition took place smoothly and dependably at bed temperatures as low as 1000°F. The burner bed was heated autogeneously with the combustion of the Rosebud coal and the desired temperature was maintained and controlled throughout runs exceeding 100 hours in duration.

Research activities have included evaluation of alternatives for the use of natural gas, analysis of sulfur dioxide emission levels (the concentration was well below

governmental limits), and studies dealing with alternative designs for the power recovery turbine.

PROGRESS DURING JANUARY-MARCH 1977

Summary

In combustor runs during the quarter, the burner bed was heated autogeneously with the combustion of the Rosebud coal and the desired temperature was maintained and controlled throughout runs exceeding 130 hours in duration.

Although the temperatures of the fluidized burner bed in these preliminary runs have been held at conservative levels below about 2100°F, ash from the Rosebud coal was captured and accumulated as an agglomerated coating on the fluidized, inert, starter-bed material. Bench-scale tests indicated that operation of the PDU burner at temperatures around 2200°F would result in efficient agglomeration, consequently, these higher bed temperatures will be used in future operations.

Process Development Unit

Two extended PDU combustor runs were completed in January. In the first combustor run, coal was burned autogeneously in the burner at a rate of about 80 pounds an hour for 90 hours. Rosebud coal of a 50 percent plus 100-mesh size consist was used. The average temperature in the combustor bed was about 1900°F and the operating pressure for most of the run was 30 psig.

A finer Rosebud coal was used for the next run. More than 55 percent of the Rosebud coal was ultrafine minus 325-mesh coal. It was fed to the burner at the rate of 112 pounds per hour for over 130 hours. The average temperature in the combustor for most of the run was between

2000° and 2100°F. The operating pressure for the run ranged from 30 psig in the early part of the run to about 50 psig at the end. The run was terminated by the failure of an elbow in the gas scrubber caused by corrosion.

In both runs the ash from the Rosebud coal was captured in the bed as an agglomerated coating on the inert starter bed material. As Rosebud coal had not been worked with before, conservatively low temperatures were used. The overall efficiency of ash capture (ash agglomeration) was significant but not high. These runs completed the experimental work under Task 4.

Work under Task 5 was delayed while essential systems were converted from firing with natural gas to firing with oil which was completed in February. During conversion, the Williams mill system was extensively modified in attempts to reduce the amount of air introduced into the system through leaks.

The experimental program for the first gasification run was started in March. It was necessary to interrupt the run twice because of mechanical difficulties before coal could be fed to the system. One interruption was caused by blockage in the flue-gas exit system, and the other by difficulties with the oil-fired bed heaters. Work was performed to clear the difficulties and the run will be resumed during the next quarter.

Related Studies

A number of small-scale tests were made with the Rosebud coal in a bench-scale agglomerating combustor. The results of those tests indicated that operation of the PDU combustor at temperatures around 2200°F resulted in efficient agglomeration and ash capture.

Preliminary process flowsheets for a 250 billion Btu-per-day high-Btu conceptual process based on the agglomerating burner gasification process were completed. The initial design of an erosion test rig was 85 percent completed by the end of the quarter. The turbine proposals were reviewed and a tentative selection was made.

VII. LIQUID PHASE METHANATION PROCESS

CHEM SYSTEMS, INC.

HACKENSACK, NEW JERSEY

Plant Site: Hackensack, New Jersey

Contract No.: E(49-18)-1505

Contract Funding: \$2,170,000
ERDA: \$ 723,333
AGA: \$1,446,667

Contract No.: E(49-18)-2036

Contract Funding: \$539,244
ERDA: \$359,496
Industry: \$179,748

INTRODUCTION

The liquid phase methanation process is being developed by Chem Systems, Inc., under the auspices of ERDA and the American Gas Association (AGA). ERDA is providing two-thirds of the funds and AGA, one-third.

The overall objective of this contract is to develop a practical and useful process for converting coal-derived synthesis gases to methane as the major constituent of synthetic natural gas, using liquid fluidized beds.

The work is divided into three phases. The first phase is a laboratory investigation to establish the technical feasibility of methanation of synthesis gases by passing them through a liquid containing solid catalyst particles. The specific objectives are to:

- Develop an acceptable process liquid (to suspend catalytic particles) and investigate the use of aromatic and paraffinic hydrocarbons as possibilities.
- Investigate various catalytic materials that can be used in the methanation process.
- Determine the catalyst particle size that will pro-

duce the optimum process reaction.

- Develop a reaction correlation model for investigating the mass transfer from gas to liquid, the mass transfer from liquid to catalyst, and the catalytic surface reaction.

The second phase includes the design, procurement, construction, and operation of a process development unit having a design feed gas rate of 1,500 standard cubic feet per hour. The specific operational objectives were to determine:

- Catalyst life, recovery, and regeneration methods
- Liquid life and effectiveness
- The effect of all process variables on performance
- The correlation between the laboratory reaction models and process development unit performance data
- Data needed for engineering designs and cost estimates of large plants

The third phase includes the design, procurement, technical supervision, and construction of a pilot plant methanation unit. The unit will be used to (1) demonstrate the liquid phase methanation process on a synthesis gas actually produced in a coal gasification process

and (2) obtain data for detailed design and engineering of a methanation unit for a coal gasification plant having a capacity of about 250 million standard cubic feet per day.

The schedule for the development of the liquid phase methanation process is shown in Figure VII-1.

PROCESS DESCRIPTION

The key feature of the liquid phase methanation process is the use of a liquid phase that removes the heat generated by the highly exothermic methanation reaction and also serves as the fluidizing medium for the reaction catalyst. A schematic of the process is shown in Figure VII-2.

Liquid phase methanation is a three-phase process: gas (primarily carbon monoxide and hydrogen), liquid (aromatic hydrocarbon or paraffinic oil), and solid (nickel catalyst). The process consists of five steps:

- Absorption of reactants from the gaseous phase
- Diffusion of reactants through the liquid phase
- Chemical reaction on the solid surface
- Diffusion of products through the liquid phase
- Desorption of products to the gaseous phase

In this process, inert liquid is pumped upward through the reactor (which operates at 20 to 68 atm and 570°

–650° F at a velocity sufficient to both fluidize the catalyst and remove the reaction heat. At the same time, the low-Btu feed gas (carbon monoxide and hydrogen) is passed upward through the reactor where it is converted to methane in the presence of the fluidized catalyst. The heat of the exothermic reaction is absorbed by the inert liquid as sensible heat. The liquid is then circulated through a heat exchanger to maintain the desired temperature, and the cooled inert liquid stream is recycled to the reactor.

Conversion of a carbon monoxide and hydrogen to methane is on the order of 95 to 99 percent complete, depending on the pressure, temperature, and space velocity of the inlet gas. Other components of the product gas are water vapor and vaporized inert liquid, hydrogen, and carbon dioxide. There may be minute quantities of ethane and propane also. Most of the inert liquid condenses in the primary cooler and the remainder condenses in the secondary cooler along with the water.

The reactor effluent gases are cooled. Any water produced in the reaction is condensed along with the process liquid that was vaporized in the reactor. The liquids are phase separated. The process liquid is recycled back to the reactor. Part of the water can also be recycled back to the reactor as required with the remainder being sent to the plant's condensate system. The cooled gases can then be sent to a small trim methanator for final conversion of carbon monoxide and hydrogen to methane. Carbon dioxide may be removed either prior to or after the final methanation step. The final methanator is a

LEGEND:
 ▲ BEGIN MILESTONE
 ▼ COMPLETE MILESTONE

Figure VII-1. LIQUID PHASE METHANATION PROGRAM SCHEDULE

Figure VII-2. LIQUID PHASE METHANATION PROCESS SCHEMATIC

fixed bed unit where complete reaction occurs adiabatically in a single pass through the reactor. The effluent gases from this polishing reactor are cooled by preheating feed gas and then against cooling water or air. The product SNG (HHV > 950 Btu/SCF) is dried and compressed (if required) to pipeline gas pressure.

There are several advantages to the liquid phase methanation process:

- Inert liquid circulation provides excellent temperature control in the system.
- The uniform temperature of the system permits optimum reaction conditions.
- Small particles of catalyst contained by the liquid make it possible to achieve a higher rate of reaction than is possible with gas-solid methanation, using larger catalyst particles.
- Catalyst attrition is usually much lower than it is for gas fluidized beds due to the cushioning effect of the liquid.
- Catalyst activity is maintained and the necessity of overdesigning the reactor to accommodate declining catalyst activity levels is eliminated.

- The methanation reaction is nearly complete in a single pass, eliminating the need for recycle or multiple reactors.
- Higher conversion per pass is achieved because the axial diffusivity of the reactants is relatively low compared to a gas-solid fluidized bed.

HISTORY OF THE PROJECT

In addition to an extensive literature search of both the methanation reaction and the fluidization of solids, Chem Systems initially conducted studies on the thermal stability of liquids and selected a number of potentially suitable liquids for further experimentation. A small reactor was constructed and put on stream in July 1972. The initial feasibility studies demonstrated that (1) there are commercially available liquids capable of withstanding the reaction temperatures and pressures (480°F to 660°F, 35 to 70 atm) without being degraded, and (2) the rate of methane formation in the presence of the

liquid phase was well above the original estimates of the rate required to make this process commercially attractive.

In screening studies designed to narrow the choice of liquids and catalysts, Chem Systems determined that aromatic and paraffinic hydrocarbon liquids can be used without being subjected to noticeable degradation and that commercially available catalysts are equally flexible. However, to maintain catalyst activity, it is necessary to maintain a hydrogen atmosphere when the system is not in operation.

Development of the liquid phase methanation process has continued on three levels; bench-scale unit, process development unit, and pilot plant. The bench-scale unit has been used for experiments with process liquids and catalysts and for the development of a reaction model correlating the physical and chemical aspects of the liquid phase methanation reaction process. The model was also used for developing data for designing the larger units. The process development unit was used to:

- Measure density differences in the fluidized catalyst bed height under various reaction conditions
- Determine optimum process performance values
- Determine criteria for reliable design of larger plants
- Determine catalyst life and effectiveness
- Determine catalyst regeneration techniques
- Determine liquid life and effectiveness
- Assess correlations between laboratory and performance data

Work with the process development unit was completed in early 1975.

Davy Powergas, Inc., Houston, Texas, was the subcontractor selected for constructing the pilot plant methanation unit. The reactor for the unit has a diameter of two feet, is 15 feet high, and has a capacity of approximately two million standard cubic feet per day of feed gas. The unit is skid-mounted so that it can be shipped to and operated at any site that can provide a supply of synthesis gas.

All tasks under contract E(49-18)-1505 were completed during 1976 and work under contract E(49-18)-2306 was initiated. The Liquid Phase Methanation (LPM) pilot plant was completed and shipped to the IGT HYGAS plant in Chicago, Illinois. It was reassembled and shakedown operations begun. By the end of the year all systems had been checked out.

PROGRESS DURING JANUARY-MARCH 1977

Winterization of the Liquid Phase Methanation (LPM) pilot plant was the main focus of mechanical work completed during the beginning of the quarter.

During the first week in March, the pilot plant was prepared for the first experimental run. The system was maintained in a ready state anticipating HYGAS gasifier product or hydrogen reformer gas during the last two weeks of the quarter. While waiting for the gas, liquid only catalyst fluidization studies were performed.

VIII. EVALUATION OF HIGH-BTU GASIFICATION PROJECTS

C. F. BRAUN AND COMPANY
ALHAMBRA, CALIFORNIA

Project Site: Alhambra, California
Contract No.: E(49-18)-2240
Contract Funding: \$4,631,043
ERDA: \$3,087,362
AGA: \$1,543,681

INTRODUCTION

High-Btu gasification projects are being evaluated by the engineering firm of C. F. Braun and Company. The project, initiated in September 1972, is being sponsored by ERDA and the American Gas Association (AGA). ERDA is providing two-thirds of the funds and AGA, one-third.

The overall objectives of this contract are to provide technical evaluations of gasification processes currently being investigated and develop conceptual designs for commercial plants to produce pipeline-quality gas using each of the candidate processes. These evaluations and concept designs will permit early identification of problem areas so as to develop solutions through pilot plant accelerated mechanical development programs. They will provide bases for recommending the process that should be demonstrated with commercial-size equipment. The process will be selected based on criteria such as successful demonstration in pilot plant operations, reliability, suitability for handling a variety of coals, economic viability, thermal efficiency, and significance of potential environmental impacts.

PROGRAM DESCRIPTION

Braun's tasks fall into two categories: technical evaluations and development of conceptual designs for com-

mercial plants for each of the candidate high-Btu processes.

Technical evaluations involve a variety of activities to support ERDA and AGA. Specifically, Braun is concerned with:

- Proposed changes to existing research programs. These changes usually result from knowledge gained during research and generally are designed to solve problems in obtaining and evaluating research data and in determining ways to overcome technical problems.
- Design and construction of pilot plants. This includes reviews of bid packages, assistance in selection of contractors, and review and approval of engineering design work.
- Proposed changes to existing pilot plants. This would involve, for example, the addition of unit operations such as gas cleanup or methanation to pilot plants that do not have such facilities, or changes to the design of existing equipment to improve operation or eliminate causes of equipment failure.
- Review of all contractor activities to ensure that work is proceeding according to plan. This review covers research programs in progress, pilot plant operations, pilot plant modifications, pilot plant design, reported progress in research, and reported pilot plant accomplishments.

Other technical support activities include investigating all major equipment problems and recommending

changes or redesign, conducting practicability and feasibility studies necessary to prevent unproductive research, monitoring construction activities and operations, consulting on pilot plant problems, reviewing performance data, and analyzing process operation difficulties.

Conceptual designs of commercial-scale plants are being developed for six processes: carbon dioxide acceptor, BI-GAS, HYGAS, Synthane, agglomerating burner, and Lurgi. Although the gasification unit of each process is unique to that process, the coal handling, gas cleanup, shift conversion, methanation, and effluent treatment sections are quite similar. Therefore, for each of the processing sections, Braun has been evaluating and developing optimum methods for use in the conceptual designs. In some cases, the method selected is being designed by Braun; in other cases, the method is a licensed process.

For uniformity and comparability, several basic criteria for the designs were established:

Coal types:	Western-Montana subbituminous Eastern-Pittsburgh seam Lignite
Plant capacity:	250 million cubic feet per day of pipeline-quality gas
Heating value:	900 BTU per standard cubic foot minimum; HHV at 30-60°F (sat- urated) or start HHV on new line
Carbon monoxide:	0.1 volume percent maximum
Sulfur compounds:	Less than 0.2 ppmv (methanation requirement)
Inert gases:	5 volume percent with no more than 3 volume percent carbon dioxide included
Water content:	7 pounds per million standard cubic feet of gas
Specific gravity:	0.59 to 0.62 (compared to air as 1.0)
Hydrocarbon dewpoint:	-40°F at 68 atm
Effluents:	Water with high concentration of dissolved solids, which will be re- turned to the mine Stack gas with 250 ppmv sulfur compounds reported as sulfur di- oxide of which not more than 10 ppmv may be hydrogen sulfide (dry basis); below current federal regulations

Initially, Braun has been concentrating on development of designs for commercial plants using Montana subbituminous coal. The designs for Pittsburgh seam coal will be prepared when the conceptual designs for subbituminous coal are finished. The designs will be modified continuously as more information becomes available from (1) actual performance data generated in the pilot plants, (2) continuing evaluation work on the accessory sections required in the overall plants, and (3) technological developments.

Ultimately, the conceptual designs will be used to establish an estimate of the overall capital and operating cost of each plant and to compare the economics of the processes. Based on an April 1973 report by the Synthetic Gas-Coal Task Force for the Supply-Technical Advisory Committee National Gas Survey of the Federal Power Commission, a procedure has been developed for calculating the average cost of gas over 20 years (estimated plant lifetime) and covers the estimation of investment and operating costs. The estimates will be based on a uniform set of ground rules covering all cost-related factors such as interest charges, utilities, construction, taxes, etc.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Braun engineers followed the operations of the HYGAS, carbon dioxide acceptor, BI-GAS, and Synthane pilot plants. Studies also continued on the process specifics as well as the conceptual design of commercial plants.

Technical Evaluations

High-Btu Gasification Processes

In support of the technical evaluation effort Braun engineers visited the HYGAS, carbon dioxide acceptor, BI-GAS, and Synthane pilot plants during the quarter. Operations were observed and input data for the conceptual design of commercial size plants was obtained.

A summary of carbon and coal conversions on previous pilot plant runs of the HYGAS plant was prepared. A computer program was also developed and tested for calculating material balances from plant data.

Braun made extensive revisions to the heat and material balance computer program of the carbon dioxide acceptor plant in order to bring it in line with recent plant modifications. Heat and material balances were calculated for Runs 40B and 42.

Evaluations of the char feed eductor system of the BIGAS pilot plant continued. Work began on the preparation of a char eductor data sheet.

Process Specifics

It was decided to include a sixth process comparison in the Gas Purification Report which also includes the Seloxol versus Hot Carbonate Studies. The Benfield hot potassium carbonate process will be compared with the Seloxol process based on the IGT Steam-Iron HYGAS process for Eastern coal.

The capital cost estimates to update the Shift Conversion Study were completed and a draft outline prepared.

The report "Wet Methanation Evaluation," FE 2240-18 was published by ERDA. A capital cost estimate of the liquid phase methanation process was completed. A rough draft of an interim report on fixed bed methanation process arrangements was also written.

In the area of effluent evaluations, work continued on proposal evaluations. Work also continued on the Materials of Construction Report. The Single versus Two Stage Absorption Report, the Phenol Recovery Report, and the interim Plant Size Study Report were submitted to ERDA by the end of the quarter. The Methanation Catalyst Evaluation, Methanation Carbon Dioxide Level Report, and the Process Alternatives for Sulfur Management Report were also completed.

Eighteen problem areas were studied under the mechanical development program in order to formulate development programs for subcontract awards to qualified vendors. Work also continued on the Lurgi Factored Estimate Design for Eastern Coal as well as lignite.

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IX. MOLTEN SALT GASIFICATION PROCESS

ATOMICS INTERNATIONAL DIVISION
ROCKWELL INTERNATIONAL CORPORATION
CANOGA PARK, CALIFORNIA

Plant Site: Santa Susana, California
Contract No.: EF-77-C-03-1429
Contract Funding: \$9,729,990
(100% ERDA)

INTRODUCTION

The molten salt coal gasification process is being developed by the Atomics International Division of Rockwell International Corporation. This 45-month project, initiated in March 1976, is sponsored by ERDA. Figure IX-1 shows the program schedule.

The objective of this project is to demonstrate the feasibility of the molten salt coal gasification process for use in environmentally-acceptable generation of electric power. Atomics International is to design and construct a process development unit (PDU) which will convert one ton of coal per hour to a non-polluting low-Btu fuel gas. The PDU will be located at the Santa Susana Test Site of Atomics International. In addition, Atomics International is to operate the plant to obtain data for evaluating the process and designing a full-scale commercial plant.

As part of the PDU development, Atomics International is also conducting experimental and analytical development work on an older reactor with a capacity of 470 pounds per hour operating to a maximum of three atm. Among the key areas being studied in this program are:

- Air and solids feed system design and operating parameters
- Melt withdrawal and quench system design requirements

- Entrainment of particulates in the product gas and purification requirements
- Optimum sodium carbonate regeneration process flow scheme

PROCESS DESCRIPTION

In the molten salt gasification process, coal is gasified to produce electricity through gas and steam turbines. Three major steps are required: (1) molten salt coal gasification, (2) electric power generation, and (3) sodium carbonate regeneration. Figure IX-2 provides a schematic of the process.

In the gasification section, coal and sodium carbonate are transported by compressed air (10-20 atm) into the bottom of the melt bed in the molten salt furnace. The molten pool is composed of sodium carbonate along with sodium sulfide, and sodium sulfate formed during the process. Gasification reactions (partial oxidation and pyrolysis) take place at 1800°F and 20 atm. The fuel gas produced has a heating value of approximately 150 Btu per standard cubic foot and is predominately carbon monoxide, hydrogen, and nitrogen. Because the melt retains the ash and sulfur from the coal, the melt must be continuously withdrawn from the furnace so that fresh sodium carbonate can be added. The melt stream is subsequently regenerated.

PROJECT	FY 76	TR. Q.R.	FY 77	FY 78	FY 79	FY 80
PHASE I - PRELIMINARY ENGINEERING		△				
PHASE II - DETAILED ENGINEERING AND DESIGN		△				
PHASE III - PROCUREMENT		△				
PHASE IV - PLANT ERECTION			△			
PHASE V - STARTUP				△		
PHASE VI - OPERATION AND EVALUATION					△	

LEGEND : △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure IX-1. MOLTEN SALT GASIFICATION PROGRAM SCHEDULE

Figure IX-2. MOLTEN SALT GASIFICATION PROCESS SCHEMATIC

The hot fuel gas from the molten salt furnace is combusted in a gas turbine which converts the energy of the fuel gas to electric energy. After passing through the turbine, the exhaust gas is used to produce steam for operating a steam turbine, thereby producing additional electricity. Flue gas (primarily carbon dioxide) leaving the boiler heats incoming combustion air and is then used for sodium carbonate regeneration.

In the regeneration section, the melt withdrawn from the molten salt furnace is transported to a quench tank where the salt is dissolved in water. The resulting slurry is then passed through a filter for removal of ash. The filtrate, containing dissolved sodium sulfide, is carried to the stripper where sulfur is stripped off as hydrogen sulfide and subsequently converted to elemental sulfur in a Claus plant. The remaining solution is carbonated, crystallized, centrifuged, dried in a rotary kiln, and recycled to the molten salt furnace as regenerated sodium carbonate.

The key advantages of the molten salt coal gasification process include the following:

- The process allows the use of a complete range of coal particle sizes, from $\sim 1/4$ in. down to fines. There is no requirement for close sizing of the coal, removal of fines, or coal pulverization. Only crushing is required to a size small enough to allow pneumatic transport of the coal ($< 1/4$ in.).
- The process is well suited to the gasification of all types of coals, from anthracite through lignite. Pretreatment is not required for caking coals, and, therefore, there is no associated loss of heating value.
- The gasification is carried out in a thoroughly mixed, three-phase turbulent bed environment, allowing excellent temperature control and precluding the occurrence of hot spots.
- Practically all the sulfur and ash of the coal are retained in the melt, minimizing the requirements for product gas cleanup.
- The sulfur of the coal is recovered in elemental form, minimizing storage, handling, and marketing problems.
- The molten salt gasifier operates in a stable manner over a wide range of air and coal feed rates, indicating the potential for good load following capability.
- The overall process has a high thermodynamic efficiency.
- The process shows a good potential for the economic generation of electric power.

HISTORY OF THE PROJECT

Before December 1974 (when ERDA and industry began co-sponsoring the previous project), Atomics International did extensive experimental work to develop the molten salt combustion and gasification process. Tests were initially conducted in a laboratory-scale unit and then in a bench-scale combustor. The purpose of the experimentation was to determine combustion rates, conditions for obtaining different ratios of carbon monoxide to carbon dioxide, ash-melt interaction, ash capacity of melt, chemical reaction of sodium carbonate with ash, and suitable metal to withstand corrosion. The tests revealed that the combustion rates achieved for various feedstocks such as char, coal, coke, etc., with wide ranges of fixed carbon, volatile matter, sulfur, and ash contents were much greater than with conventional burning. In addition, the tests showed that the process was environmentally acceptable as well. Atomics International concluded that the molten salt process was sound and that a pilot plant should be constructed and operated to further explore and demonstrate its potential for commercialization.

To obtain the necessary design data for a pilot plant, Atomics International constructed a molten salt test reactor capable of processing 250 pounds of coal per hour. This reactor is eight feet high and has an inside diameter of three feet. Experimental and analytical development work was also conducted to provide design data and confirm key assumptions. Some of the areas investigated are:

- Effects of pressure on gasifier operation and performance.
- Air and solids feed system design and operating parameters.
- Melt withdrawal and quench system design requirement.
- Optimum sodium carbonate regeneration process flow scheme.

In the previous project the preliminary design of a pilot plant was completed during the third quarter of 1975 and the plant cost estimated. Because these new costs were considerably higher than the original estimates, alternative approaches were evaluated in order to select a program which would enable the objectives to be met at a lower cost. Based on these studies, it was decided to move the pilot plant from Norwalk Harbor, Connecticut, to the Atomics International (AI) field laboratory in Santa Susana, California. It was further decided that a one-ton-per-hour plant would be constructed rather than the original five-ton-per-hour facility. During the first quarter of 1976, the proposal to construct the one-

ton-per-hour plant was reviewed by ERDA and the development contract for the five-ton-per-hour facility was terminated.

Phase I, preliminary engineering, was completed in August 1976. It was decided that AI would be for the entire detailed design and this work began in November.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Groundbreaking for the Process Development Unit (PDU) occurred on March 8. Design and construction continued throughout the quarter. The ERDA contract number for the project was changed to EF-77-C-03 1429.

Process Development Unit

Authority to construct the PDU was granted by the Ventura County Air Pollution Control District on March 7, 1977. ERDA approved the selected subcontractor for the first construction package (civil work). Groundbreaking for construction occurred on March 8, 1977. At the end of the quarter, approximately 80 percent of the PDU site rough grading had been completed.

Evaluation of solicited bids for the second construction package, which consisted of initial structural steel work and erection of the gasifier vessel, was completed and ERDA approval requested.

The fabrication of the gasifier vessel skirt and anchor bolt chain was completed. All of the gasifier/quench detail drawings were completed and a final design review held.

X. ADVANCED COAL GASIFICATION SYSTEM FOR ELECTRIC POWER GENERATION

WESTINGHOUSE ELECTRIC CORPORATION
LESTER, PENNSYLVANIA

PDU Site: Waltz Mill, Pennsylvania
Contract No.: EF-77-C-01-1514
Contract Funding: \$26,000,000
(through calendar year 1976)
ERDA: \$22,000,000
Industry: \$ 4,000,000

INTRODUCTION

The advanced coal gasification system for electric power generation is being developed by Westinghouse Electric Corporation. ERDA is providing the major portion of the funds through the pilot development unit. Industrial contributions to data include expenditures of \$4 million as well as various related test facilities. The industry team is composed of the following firms:

Public Service Company of Indiana
Westinghouse Electric Corporation
Amax Coal Company
Bechtel, Incorporated
Peabody Coal Company / Kennecott
Copper Corporation

The primary objective of this contract is to develop a fluidized-bed system for producing low-Btu gas from coal and apply the system to a combined-cycle electric generation system. Westinghouse is to:

- Conduct laboratory research to refine the advanced gasification process.
- Design and construct a process development unit with a capacity of 12 tons of coal per day.
- Operate the process development unit to establish the operating characteristics of the gasification system. This will provide data for develop-

ing scale-up factors for the design and construction of a future 120-ton-per-day pilot plant.

The successful operation of the pilot plant will demonstrate the technical and economic feasibility of generating electric power from coal while meeting anticipated environmental emission regulations. The overall program is directed toward the operation of a combined-cycle power plant integrating a gasifier with a 130 Mw-range state-of-the-art turbine. The schedule for development of the advanced coal gasification system is provided in Figure X-1.

PROCESS DESCRIPTION

A schematic of the advanced coal gasification system for electric power generation is provided in Figure X-2. Production of low-Btu gas by this process requires completion of three operations: coal preparation, devolatilization-desulfurization, and gasification-combustion. In the coal preparation section, the coal is crushed to -6+100-mesh, dried, and transported to a reactor vessel for devolatilization-desulfurization and partial hydrogasification. A central draft tube is used primarily for recirculating solids. Recycled solids required to dilute the feed coal and temper the hot inlet gases flow downward in the fluidized bed surrounding the draft tube. The fluidizing

LEGEND: $\triangle$ BEGIN MILESTONE
 ∇ COMPLETE MILESTONE

Figure X-1. ADVANCED COAL GASIFICATION PROGRAM SCHEDULE

Figure X-2. SCHEMATIC OF THE GASIFICATION PROCESS DEVELOPMENT UNIT

agent is a portion of the gases entering the unit. Recirculating solids have flow rates up to 100 times the coal feed rate to prevent the agglomeration of the feed coal as it devolatilizes and passes through the plastic or sticky phase. Dense, dry char collects in the fluidized-bed at the top of the draft tube and is withdrawn at this point. Dolomite or calcium oxide (sorbent) is added to the

fluidized-bed to absorb the sulfur present as hydrogen sulfide in the fuel gas. Spent sorbent is withdrawn from the bottom of the reactor and regenerated. Heat for devolatilization is supplied primarily by the high-temperature fuel gas produced in the gasifier-combustor. After separation of fines and ash, product gas is cooled and scrubbed with water for final purification.

Final gasification occurs in a fluidized-bed gasifier-combustor. Char from the devolatilizer-desulfurizer is burned with air in the lower leg of the gasifier at 1900-2000°F to provide the heat for gasification. Heat is transported from the combustor to the gasifier by combustion gases flowing upward and by fines that escape upward and are trapped and recycled to the space between the combustor and gasifier. Ash from combustion of fines agglomerates on the ash from the char and segregates in the lower bed leg for removal.

There are several advantages to the advanced coal gasification system for electric power generation. For example, the system:

- Uses a variety of coals, including caking and high-ash coals, without costly pretreatment.
- Utilizes a wide range of coal particle sizes without extraction of fines.
- Operates at high thermal efficiency.
- Reduces heat losses by conducting desulfurization at an elevated temperature.
- Produces a clean fuel that meets present and future environmental emission control standards.
- Reduces gaseous and particulate emissions from electric power plants.
- Eliminates the need for utility stack gas cleaning processes.

The potential economic advantages of the system include reduction of the rate of consumption of natural gas, environmental costs normally associated with cheap fuels, and the operating cost of an electric power generating plant by 20 to 30 percent.

HISTORY OF THE PROJECT

Initial development of the advanced coal gasification system involved laboratory research, including the design and construction of a process development unit. The process development unit was completed in 1974 and a test program was initiated to establish the operating characteristics of the system and provide data for developing scale-up factors for a pilot plant. Other laboratory research has involved:

- Fluidized bed desulfurization with dolomite
- Development of scale-up design correlations for fluidized beds
- Combustion of coal-derived fuel in diffusion-flame gas turbine combustors
- Identification and testing of apparatus for high-temperature gas stream particulate control.
- Development of a specification for the tolerance of

a modern utility gas turbine to particulates, vaporized alkali metals, and other gaseous contaminants.

In addition to laboratory research, work on developing conceptual designs of the combined-cycle generating plant was initiated in 1974. These designs will be used to estimate costs, system control requirements, mass balances, site requirements, etc., for a commercial-sized facility.

During 1975, the process development unit was modified and repaired. The modifications included the installation of a computer control and data monitoring system. Corrective designs were completed and modifications were made to various process and utility subsystems including the cooling water and waste handling subsystems. A number of design modifications were also made on the gas generator system.

Laboratory research in 1975 focused on providing design data for the process development unit, and on providing data and predicting operating conditions for the conceptual design of a commercial sized plant.

Studies of the gas turbine combustor system were performed to determine the operational conditions necessary to ensure efficient, stable, durable, and environmentally acceptable performance. Tests were conducted on two dual-fuel coal gas/distillate oil combustors. Combustion stability was studied by measuring carbon monoxide emissions. It was determined that moisture content affected combustion stability and consequently required regulation. A new second-generation combustor was designed on the basis of these tests.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Two gasifier tests were conducted during the quarter. For the first time, ash was agglomerated at elevated pressures and the carbon losses were extremely low.

Support studies included the operation of the bench-scale agglomerator for the first time and continued coal behavior studies. The experimental series in the semi-circular unit performed to simulate the gasifier-combustor operation were completed and the unit modified to the devolatilizer configuration.

Process Development Unit

Efforts to start-up the gasifier at the beginning of the year were hindered by the effects of cold weather: freezing

of process lines and lack of fuel supply. When the weather modified, a number of changes were made in the test plant as well as with certain plant equipment to conserve propane and carbon dioxide.

Test TP-011-3 was completed after numerous problems, mechanical as well as a result of weather, had been encountered during start-up. For the first time, ash was agglomerated at elevated pressures and the carbon losses were extremely low. Results of the tests indicated that recycle gas flow rates into the annular region around the air tube should be increased to provide a more violent fluidized region near the top of the air tube to prevent any stagnation of ash or coke breeze particles in that region.

Results also suggested that future tests study the ash agglomerate formation with a close control on ash contents in the bed and ash collection annulus rather than strictly on ash-to-char interface control.

Test TP-011-4 was completed, establishing a number of operational techniques. Additional data were obtained on fluidized-bed operation and on heat and material balances. The test was prematurely terminated without accomplishing all of the goals. Important conclusions drawn from the results included:

- Ash agglomeration occurred at 1900°F when bed ash concentration was between 20 and 35 percent.
- Ash particle size for a minus 6-mesh feedstock at 1900°F bed temperature was 1500 microns and bed particle size was 600 microns when ash content in the agglomerates was held in the range of 50 to 80 percent.
- Bulk density of agglomerates was 44-54 pounds per cubic foot while bulk density of the bed was 29-40 pounds per cubic foot.
- Efficient mixing in the ash annulus near the top of the air tube appears to be important in preventing sintering of the agglomerates.
- Ash withdrawal and continuous char feed need to be maintained in order to control ash concentrations locally in the combustion zone.
- Slugging in the annulus due to high gas velocities caused excessive solids mixing which resulted in a skin temperature excursion.
- Adjusting inlet air temperature and both air and

steam flow rates controls reactor start-up and steady-state bed temperature.

Support Studies

Plans for characterization of PDU product streams were formulated in January. Product gas streams will be analyzed for gaseous composition, particulates, alkali metals, ammonia and trace elements. Solids streams will be checked, with the proximate and ultimate analyses as well as composition and particle size distribution reported.

The experimental series performed to simulate the gasifier-combustor operation in the PDU, using a 3.8 centimeter diameter air nozzle in the semi-circular unit was completed. Four locations of the air nozzle were tested. The experiments were also performed with the air nozzle flow alone; with a combination of air nozzle flow and flow in the char-ash separation zone; and with a combination of air nozzle flow, flow in the char-ash separation zone and flow through the conical section between the gasifier and the combustor. In all cases, smoother operations were observed with all three flow inlets operational.

The semi-circular unit was converted to accept a larger air tube to study the effects of air tube size on gasifier-combustor performance. Following these tests the model was modified to the devolatilizer configuration to study the performance of the conical distributor plate for the integrated operation in the PDU.

The carbon-steam and carbon-carbon dioxide reactions with coke breeze continued to be studied. Results showed that coke breeze is far less reactive than Minnehaha char.

The mechanical problems encountered in the initial operation of the bench-scale ash agglomerator were corrected and five tests performed during the quarter in the effort to determine the correct combination of bed temperature and bed circulation pattern needed to build up discrete ash agglomerate particles.

XI. LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT

Plant Site: Windsor, Connecticut
Contract No.: E(49-18)-1545
Contract Funding: \$22,109,084
ERDA: \$14,739,389
Industry: \$ 7,369,695

INTRODUCTION

A method for the production of low-Btu gas from coal for electricity generation is being developed by Combustion Engineering, Inc., under the sponsorship of ERDA and an industry team composed of Combustion Engineering and the Electric Power Research Institute. ERDA is providing two-thirds of the funds and the team, one-third. The overall objective of this contract is to generate electricity economically from a low-Btu coal gas in an environmentally acceptable manner, with a minimum of process development. Combustion Engineering is conducting a three-phase program involving the design, construction, and operation of a coal gasification process development unit. The objectives of this program are to:

- Demonstrate the capability and suitability of the process and equipment to produce low-Btu gas of the predicted composition, heating value, and cleanliness from the design coal.
- Provide data to be used as the design basis for commercial-scale equipment that would process about 110 tons of coal per hour and result in an electrical generating capacity of 300 Mw.

Combustion Engineering also has a continuing research program to refine the process and verify its technical and economic feasibility. The schedule for development of this low-Btu gasification process is

provided in Figure XI-1.

The Combustion Engineering gasification process is based on an air-blown, atmospheric-pressure, entrained-bed gasifier. A schematic of the process is provided in Figure XI-2. In the process, a portion of the pulverized coal and recycled char are fed to the combustion section of the gasifier and burned to supply the heat necessary for the endothermal gasification reaction. In the combustion section, nearly all of the ash in the system is converted to molten slag, which is then drawn off the bottom of the gasifier. The remainder of the pulverized coal is fed to the reduction portion of the gasifier where it is contacted with hot gases entering the reduction zone from the combustor. The gasification process takes place in the entrainment portion of the reactor where the coal is devolatilized and reacts with the hot gases to produce the desired product gas. This 1700°F product gas is then cooled to 300°F. At this point, the gas contains solid particles and hydrogen sulfide that must be removed. Solids are removed and recycled by means of a spray drier, cyclone separators, and venturi scrubbers. Hydrogen sulfide is removed and elemental sulfur produced by the Stretford process. The clean low-Btu gas (127 Btu per standard cubic foot) can then be delivered to the burners of power boilers, gas turbines, or combinations of the two in a combined-cycle power generator.

Operating conditions will have a variety of effects on the cost and quality of the gas produced in this system. For example, oxygen could be substituted for air in the

Figure XI-1. LOW-BTU GASIFICATION PROGRAM SCHEDULE

Figure XI-2. SCHEMATIC OF LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

gasifier combustor, thereby increasing the heating value of the product gas from 127 to 285 Btu per standard cubic foot. Conversely, this change will also increase the cost of producing the gas, depending on the price of oxygen and the quantity used.

The value of the atmospheric gasification system is that development work is only necessary on the operation and control of the gasifier. All other components are commercially available items with predictable operating characteristics.

HISTORY OF THE PROJECT

Initial work on the development of a system for the low-Btu gasification of coal for electricity generation involved the economic evaluation of various coal gasification and energy conversion systems for the production of electricity. The primary criterion for the systems selected was the maximum use of proved processes. Of the systems selected for use in this process, the only unproved component was the gasification process. All other components were of established and proved design.

Two gasification processes, differing only in operating pressure, were considered: one at atmospheric pressure and the other at ten atm. It was determined that if the gasification pressure were increased from one to ten atm the total plant cost would be reduced by eight percent. This savings results from the ten-fold reduction of gas volume and, hence, equipment size. Conversely, much of the process simplicity would be lost and additional development would be required for:

- Lock hoppers for feeding solids into pressure vessels.
- A more complex gasifier to withstand more severe operating conditions.
- Heat exchangers to withstand greater erosion due to higher solids concentration in the gas stream.
- Techniques for char recovery at elevated pressures.
- Processes for removal of liquid slag from the pressurized gasifier.

Because of these complications, entrainment gasification of coal at atmospheric pressure was the process selected for development. The gasifier may be air blown or oxygen blown, depending on the particular requirements of the plant in which it would be installed. It was determined that the air-blown version would be developed initially because it appeared to be the most economical for application to the majority of electric power plants.

Design of the process development unit began in 1974. The unit, to be located at Windsor, Connecticut, will have a capacity of five tons of coal per hour. The objectives of this phase include (1) development of component and process concepts and details necessary for the design and operation of gasification systems of this type and (2) completion of the engineering required for construction of the unit.

By the end of 1975, the designs of many of the subsystems were nearly completed, and request for quotations were issued for various components. About 30 percent of the major equipment for the process

development unit had either been approved for purchase or released for fabrication by the end of 1975. Plot plans and general equipment arrangements were completed, and preparation of the construction site for excavation and foundation installations was started. Some work had been done on establishing operating procedures and developing a test plan for evaluating the performance of the steady-state gasifier. Construction is scheduled to be completed in Summer 1977 and operations are expected to continue until mid-1978.

Laboratory research during 1975 included the investigation of various refractories with slag and gas and the development of a one-third scale plastic model for studying stream flow patterns. A mathematical analysis of the gasifier was carried out through the use of computer modeling of the unit. Plant metallurgical requirement studies and environmental studies were also conducted. Supporting studies consisted mainly of an analysis comparing the costs of producing electricity by various integrated gasification power plant systems. Two alternatives were selected for further study: a conventional steam plant with an atmospheric gasifier and a combined-cycle plant with a supplementary-fired boiler and atmospheric gasifier. In addition, specifications for an automated data-acquisition and reduction system were completed.

PROGRESS DURING JANUARY-MARCH 1977

The computerized PDU construction and start-up schedule became operational in January. Key items are being expedited in order to maintain the target start-up date.

The entire plant was 68 percent complete as of the end of the quarter. A major milestone was achieved during the period when the hydrostatic test of gasifier pressure parts was successfully completed in March.

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XII. COAL GASIFICATION COMBINED-CYCLE SYSTEM FOR ELECTRIC POWER GENERATION

FOSTER WHEELER ENERGY CORPORATION
LIVINGSTON, NEW JERSEY

Plant Site: Sioux Falls, South Dakota
Contract No.: E(49-18)-1521
Contract Funding: \$8,685,000
ERDA: \$5,790,000
Industry: \$2,895,000

INTRODUCTION

The objective of this project is to design a pilot plant capable of producing low-BTU gas from many types of coal and to integrate the coal gasification system with a combined-cycle electric power generating unit. The project is divided into four phases: Phase I—Technical feasibility studies, Phase II—Detailed design and engineering of the pilot plant, Phase III—Pilot plant construction, and Phase IV—Pilot plant start-up and operation. The current contract covers Phase II. The program schedule is shown in Figure XII-1.

PROCESS DESCRIPTION

A schematic of the projected coal gasification combined-cycle system is provided in Figure XII-2. In this process, coal is dried, pulverized so that 70 percent will pass through 200-mesh, and fed to the upper section (Zone II) of the gasifier via lock hoppers. The coal is gasified by steam and the hot gases rising from the lower section of the gasifier (Zone I). The low-Btu product gas leaving the gasifier passes through a refractory-lined cyclone separator to remove char. The char is cooled to approximately 800°F and injected into Zone I by superheated steam. The char reacts with the steam and air at 2800°F and is completely gasified. The ash becomes

Figure XII-1. COAL GASIFICATION COMBINED-CYCLE SYSTEM PROGRAM SCHEDULE

molten slag and flows from the bottom of the gasifier where it is quenched in water and withdrawn. A fluxing agent (limestone) is used to maintain proper viscosity of the slag. The hot reaction gases and carry-over char from Zone I rise into Zone II of the gasifier, thus completing the cycle.

After the char is removed from the gas in the cyclone separator, the raw gas is passed through several heat recovery systems and the steam produced is recycled to the gasifier. The gases leaving the waste heat recovery system flow through a water scrubber where carry-over particles and ammonia are removed. The sour water stream flows to a sour water stripper and sludge removal system where ammonia is recovered and dust particles are removed. Raw gas from the gas scrubber goes to a Selexol gas cleanup system for removal of hydrogen sulfide and carbon dioxide. The hydrogen sulfide-rich gas is sent to the Claus plant for sulfur recovery.

Figure XII-2. COAL GASIFICATION COMBINED-CYCLE SYSTEM SCHEMATIC

The clean product gas, which has a heating value of 146 Btu per standard cubic foot, goes to a combustor to fuel a gas turbine generator. Exhaust gases from this generator go to a waste heat boiler which generates steam for a steam turbine generator. Some of the clean product gas is also used as a fuel in the gasifier.

One of the advantages of the system is that the entrained gasifier used has an inherent capability to handle agglomerating coals at high throughput. In addition, the reaction temperatures in the gasifier are high enough so that no tars or heavy hydrocarbons are produced. The environmental performance of the total system is expected to be excellent. Station heat rates for the system, employing gas turbines currently being developed by U.S. manufacturers, are expected to be better than those obtainable from conventional power generation systems.

HISTORY OF THE PROJECT

Initial studies of the process, started in August 1972 and completed in March 1974, confirmed the technical

feasibility of the process and established the process design basis. Under the current contract, signed on January 14, 1975, Foster Wheeler is responsible for the detailed design and engineering of a pilot plant with a capacity of 20 tons of coal per hour. General Electric Company, a subcontractor to Foster Wheeler, is providing assistance with the design of the gas turbine and waste heat boiler. The design philosophy for the pilot plant is to concentrate the technology development efforts on the gasifier and its related equipment. Commercially proved equipment and processes will be used, where possible, throughout the remainder of the system to minimize overall development problems. The draft of the Pilot Plant Design Report was submitted to ERDA during 1976.

In addition to the design and engineering work on the pilot plant, Foster Wheeler has a continuing laboratory research program. Much of this effort involves conducting tests in a one-third scale, cold flow model. This unit was fabricated from clear plastic material to permit viewing the internal flow patterns. Tests to be conducted with the model will aid in developing the coal and char injectors, determining the position and orientation of the injectors in the gasifier shell, and mapping gas and slag distribution patterns.

PROGRESS DURING JANUARY-MARCH 1977

All technical work was completed for the design of the pilot plant at Sioux Falls, South Dakota during 1976. The final results of this work are contained in 11 volumes of technical information. During the quarter, Foster Wheeler Energy Corporation (FWEC) was in the process of printing the final copy of this report.

The basic process design of the commercial plant was also completed. FWEC was defining the ancillary facilities during the quarter and drafting the report of the results.

The draft copy of the final report of work completed on the cold flow model was in the process of being assembled. The final report of the system transient analysis work was being edited.

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XIII. LOW-BTU FUEL GAS (TRI-GAS PROCESS)

**BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA**

Plant Site: Monroeville, Pennsylvania
Contract No.: EF-77-C-01-1527
Contract Funding: \$2,690,000
(100% ERDA)

INTRODUCTION

Bituminous Coal Research (BCR) is developing a multiple fluidized bed coal gasification process for producing low-Btu fuel gas from caking and noncaking coals. The project is being sponsored by ERDA. The low-Btu fuel gas product will be suitable primarily as boiler fuel gas for electricity generation, although alteration of operating conditions could yield medium-Btu gas suitable for other uses. The research task includes the design, construction, and testing of a process development unit, and laboratory investigations. The schedule for development of the low-Btu fuel gas system is shown in Figure XIII-1.

PROCESS DESCRIPTION

The BCR low-Btu research effort is based on a three-stage fluidized-bed gasification process. Stage 1 of the three-stage system receives the raw coal and functions as the pretreatment step in which the coal is devolatilized. Stage 3 flue gas is used as the fluidizing medium for Stage 1. The coal then flows by gravity to Stage 2, where devolatilized coal is gasified with air and either steam or carbon dioxide to generate the desired product gas. Stage 1 flue gas is fed to Stage 2 where the entrained tars and oils are gasified. The remaining char from Stage 2 is

consumed in Stage 3 by fluidized combustion. The ash discharged will contain only a minimum amount of carbon.

The advantage of this process is that both caking and noncaking coals can be used. In addition, low-Btu fuel gas is the only product; no wastes or by-products such as tars and oils are produced. The end use of the gasification product dictates the operating conditions as well as the gasifying medium. For example, gasifying with air and steam will yield a low-Btu fuel gas, gasifying with oxygen and steam will yield a medium-Btu gas, and gasifying with carbon dioxide will yield a gas rich in carbon monoxide that could serve as fuel for power generation by magnetohydrodynamics.

HISTORY OF THE PROJECT

Initial development of the low-Btu fuel gas process involved laboratory investigations to obtain kinetic data for various chars, or devolatilized coal, that would be produced in the first step of a multiple fluidized-bed gasification process. A small fluidized-bed batch reactor system was then used to verify proposed rate equations, determine the reaction rate between steam or carbon dioxide and char, and provide physical data such as minimum fluidizing velocity, attrition rate, elutriation losses, etc. The successful laboratory studies led to the

LEGEND:

- △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure XIII-1. LOW-BTU FUEL GAS PROGRAM SCHEDULE

design of a process development unit with a capacity of 100 pounds of coal per hour. The design and definitive costs estimates were completed in December 1972. Responsibility for constructing the unit at BCR's Monville, Pennsylvania, laboratory was awarded to Blaw-Knox Chemical Plants Division of Dravo Corporation, and construction was completed in September 1975.

Mechanical checkout and pressure testing of the system was completed during the fourth quarter of 1975, and operation of the unit was started. A variety of problems were encountered during the pressure testing and start-up operations, however, most of these have been resolved. Pretreatment testing of a Western non-caking coal (Montana Rosebud) was completed in the Stage 1 reactor. Correlations were developed for the properties of the product char as a function of Stage 1 operating temperature. Subsequently, testing of a caking coal (Illinois No. 6) was conducted in the Stage 1 reactor. A noncaking product char was obtained at pretreatment temperature of less than 800°F and in the presence of oxygen. Further testing at 900° to 1000°F demonstrated the ability to devolatilize the coal while avoiding caking. The product char from this testing was free flowing and did not cake when subjected to laboratory testing at Stage 2 operating temperatures. A data-acquisition system was installed to sample selected test points, convert the data to engineering units, and store the values on magnetic tape.

Concurrent with the construction effort, BCR is conducting laboratory research in an effort to further refine the low-Btu fuel gas process. During 1975, laboratory research included using a cold flow model of the

gasifier bed to study bed fluidization. Fluidization was improved when a 45-degree conical, rather than flat, distributor was installed in conjunction with special nozzles that direct the fluidizing gas downward toward the distributor base and horizontally toward adjacent nozzles. Among other fluidization studies were those to observe the behavior of char in a fluidized bed, determine whether the purge flows on the pressure taps were necessary, and study the effect of purge flows on pressure drop in the unit. A computer model to predict the conversion in the fluidized-bed gasifier was also developed. The results showed the effects of mass diffusion and bubble diameter on conversion and product gas concentration.

PROGRESS DURING JANUARY-MARCH 1977

Summary

Four devolatilization/pretreatment tests were completed in the Stage 1 reactor during the quarter. In addition, four process development unit (PDU) tests were conducted with the integrated system including the first attempt with the integrated system at operating temperatures.

Laboratory tests were run to determine the fluidizing characteristics of the Illinois No. 6 char produced in PDU Test No. 22.

Process Development Unit

Four devolatilization/pretreatment tests were completed in January in the Stage 1 reactor using Illinois No. 6 seam coal. The new system to control bed height functioned satisfactorily. The first test at 1000° F resulted in agglomeration. Results of the next test, No. 22, indicated that 875° F was a good operating condition for Stage 1. The following 2 tests were directed at duplicating Test No. 22 for a longer time period.

During February, two PDU tests were conducted with the integrated system. The first test was made to determine the heat loss characteristics of the replacement line between Stage 3 and Stage 1. Results showed a significant reduction in heat loss over the refractory-lined pipe previously used. The second test was a cold test to observe flow characteristics of Rosebud coal through the complete system. Smooth solids transport occurred everywhere except out of Stage 2. A pressure difference caused the transfer problems between the two stages.

A new char transfer system was installed between Stages 2 and 3. A test conducted after modification was completed in March demonstrated that smooth solids flow could be achieved between Stage 2 and 3 with the

new transfer system. The next test was the initial attempt with the integrated system at operating temperatures. Heat losses prevented Stage 1 from reaching operating temperatures. The Stage 3 reactor and all associated subsystems operated satisfactorily.

Laboratory Studies

The char produced in the pretreatment stage of the PDU has a wide distribution of particle size; and no available correlation predicts the fluidization characteristics for such a distribution. As a cold-model facility can generate data which predicts the fluidization characteristics of the gasification and combustion stages in the PDU, a small four-inch fluidized-bed reactor was fabricated. A number of tests were made on the char produced in PDU Test No. 22.

In addition, a small 2-inch laboratory reactor was built to study the gasification reactions expected in Stage 2. The unit provides a means to rapidly determine the reactivities of char produced in Stage 1, and allows a prediction of gasification rates in Stage 2. Four tests were made to study expected tar problems.

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XIV. THE COAL CONVERSION SYSTEMS TECHNICAL DATA BOOK

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Contract No.: E(49-18)-2286

Contract Funding: \$840,000
(100% ERDA)

INTRODUCTION

The Coal Conversion Systems Technical Data Book is being prepared by the Institute of Gas Technology (IGT) under ERDA sponsorship. The overall objective of this project, initiated in October 1974, is to provide a single, comprehensive source of data on coal conversion systems. IGT is to provide up-to-date information for the research, development, design, and engineering of coal conversion processes and/or plants. In addition, IGT is to identify those areas where data are required and to suggest research programs that will provide the necessary data not available otherwise. The data book will be published with a loose-leaf binding and loose-leaf sheets will be published periodically for the timely distribution of new and revised data.

PROGRAM DESCRIPTION

IGT's tasks involve collecting information from published literature and reports submitted by ERDA's contractors. The data are then surveyed, compiled, evaluated, correlated, and prepared in a form most useful to scientists, designers, and engineers involved in coal conversion activities. Initially, IGT is concentrating on publishing critical data that are not readily available. As the need for the more urgent and unique material is fulfilled, previously published material will be updated and added to the book.

The outline of the data book is shown below:

- Section I: *PROPERTIES OF PROCESS MATERIALS*
- A. Properties of Gasification Products
 - B. Properties of Intermediates and Conversion Products
 - C. Properties of Related Processing Materials
- Section II. *SOLIDS STORAGE, PREPARATION, HANDLING AND PRETREATMENT*
- A. Coal Storage and Handling
 - B. Coal Preparation
 - C. Weighing and Metering of Solids Flow
 - D. Feeding of Solids
 - E. Chemical Treatment of Coal
- Section III. *CONVERSION FUNDAMENTALS*
- A. Gasification
 - B. Pyrolysis
 - C. Liquefaction
 - D. Fluidized-Bed Combustion
 - E. Advanced Power Generation
 - F. Chemical Equilibrium and Heats of Reaction
- Section IV. *DESIGN PROCEDURES*
- A. Conversion Tables and Constants
 - B. Fluidization
 - C. Fluid Flow
 - D. Heat Transfer
 - E. Phase Separations

- F. Integrated Reactor Design
- Section V. *SUPPORTING PROCESSES*
 - A. Gas Treating
 - B. Gas Purification
 - C. Shift Conversion
 - D. Methanation
 - E. Environmental Control
- Section VI. *MISCELLANEOUS PRODUCTS*
 - A. Methanol
 - B. Acetylene
 - C. Ammonia
 - D. Fischer-Tropsch Liquids
- Section VII. *MATERIAL OF CONSTRUCTION*
 - A. Refractories
 - B. Ceramics
 - C. Metals and Alloys
 - D. Plastics
- Section VIII. *EQUIPMENT SPECIFICATIONS*
- Section IX. *PROCESS ECONOMICS*
 - A. Cost Data
 - B. Costing Procedures
- Section X. *PROCESS FLOW SHEETS*
 - A. Liquefaction
 - B. High-Btu Gasification
 - C. Low-Btu Gasification
 - D. Fluidized-Bed Combustion
 - E. Advanced Power Generation

PROGRESS DURING JANUARY-MARCH 1977

Summary

Solubility data was the main area of investigation of the properties of process materials during the quarter. Conversion fundamentals dealt with sulfur removal in fluidized-bed combustion and various pressure effects in conversion processes. Design procedures involved bubble growth correlation and lift line pressure drop correlation. Slurry properties were compared and a mathe-

matical model for simulating slurry viscosity behavior on heating was developed under design procedures.

Properties of Process Materials

Data on the solubility of benzene in water have been extended to the critical solution end point. Data on the solubility of cyclohexane in water in the three-phase region was collected. A summary table was prepared that indicated the systems investigated, sources of information, and ranges of temperature and pressure for the data collected on the solubility of oils in water and those of water in oil. Data on the solubility of hydrogen sulfide in water were again reviewed, and the effect of dissolved hydrogen sulfide on its activity was considered. A correlation for estimating the equilibrium constant for formation of ammonium hydrosulfide in the $\text{NH}_3\text{-H}_2\text{S-H}_2\text{O}$ system was developed. The solubilities of water in petroleum fractions were given as a function of temperature.

Conversion Fundamentals

Sulfur removal in fluidized-bed combustion of coal was investigated. The distributor pressure drop in fluidized-bed combustors was also discussed. The effect of pressure on pyrolysis was discussed, and pressure effects on tar yields in the Lurgi gasifier were considered.

Design Procedures

Bubble growth correlations were compared with published data on bubble sizes in coal and char fluidized beds. A recommended correlation was made for pressure-drop in inclined lift lines. The literature on gas-solids vertical downflows encountered in standpipes was reviewed.

The calculated and measured values of slurry properties (density, heat capacity, and thermal conductivity) were compared and a mathematical model for simulating slurry viscosity behavior on heating was developed.

XV. COMPUTER MODELING OF COAL GASIFICATION REACTORS

SYSTEMS, SCIENCE, AND SOFTWARE

LaJOLLA, CALIFORNIA

Contract No.: E(49-18)-1770

Contract Funding: \$1,270,000
(100% ERDA)

INTRODUCTION

Under the terms of this ERDA contract, Systems, Science, and Software (S³) is to develop a general computer model of coal gasification reactors. The model will combine theoretical descriptions of the thermomechanical interactions between the solid and gas phases with a kinetic model of chemical reactions based on the best experimental data available at the time of program development. The model will be used to expedite the development, aid in optimization, and assist in the scale-up of coal gasification reactors. The model will first be applied to high-Btu fluidized-bed gasification processes and later expanded to include low-Btu fluidized-bed reactors, entrained-flow reactors, and fluidized-bed combustors.

PROGRAM DESCRIPTION

This project began in June 1975 and will require three years to complete. Work during the first year dealt with multiphase fluid flow without chemical reactions and heterogeneous chemical reaction without fluid flow. The objective of these studies was to establish a firm theoretical description of the thermodynamics, hydrodynamics, and chemical behavior of high-Btu gasification reactors through the development of computer models of the essential features of the processes. The results of the studies will then be compared with experimental mea-

surements and the optimum mathematical formulations will be used in the model. The specific goals of the first year's research are:

- Problem formulation, documentation, and information gathering
- Development of a one-dimensional fluidized-bed model and computer program
- Development of a two-dimensional fluidized-bed model and computer program
- Development of a boundary layer model and computer program
- Development of a chemical reaction model and computer program.

During the second and third years, the computer model will be expanded to apply to high-Btu gasification, low-Btu gasification, and entrained-flow processes. The computer programs developed during the first year will be combined and the resulting prototype programs will be used to verify the accuracy of the formulations and provide preliminary results relevant to coal gasification. A boundary layer formulation will be incorporated into the model and tested on configurations of various dimensions. A method to describe particle size distributions will be developed and integrated into the two-dimensional thermomechanical-chemical model, with heterogeneous chemistry coupled directly to the heat and mass transfer processes. The model will be verified using pilot plant data and applied to specific problems of interest to ERDA. The computer model will then be developed further to include three-dimensional effects, internal heat transfer surfaces, and combustion chem-

istry, so that it can be applied to the broad spectrum of fluidized-bed and entrained-flow processes being considered for coal conversion and utilization.

HISTORY OF THE PROJECT

Work during 1975 was primarily directed toward formulation programming of the one (spatial) dimension (axial distance and time) model for the fluidized bed. This model was completed in 1976 and consisted of a set of differential equations for the conservation of solid mass, conservation of gas mass, conservation of solid momentum, conservation of gas momentum, and conservation of energy.

A 5000 Fortran statement program was written for the two-dimensional model. A program was also written for the model of chemical reactions in the fluidized bed, allowing for a variety of gas and solid feeds to the bed and including the kinetic equations for the reactions.

In April 1976, the basic structure of the chemistry code for the carbon dioxide acceptor process was completed. When tested against data from the carbon dioxide acceptor plant in Rapid City, South Dakota, the steady state calculated results were in good agreement.

PROGRESS DURING JANUARY-MARCH 1977

During the quarter, a subcontract to West Virginia

University was approved and signed. The subcontract, with Professor C. T. Wen as the principal investigator, provides for the development of a homogeneous reactor model of steam-oxygen gasification. The model will be used in studies of chemical kinetics parameters for such processes.

Consulting agreements with Professor Joseph Yerushalmi of the City University of New York and Professor Julius Siekmann of the Technische Hochschule, Darmstadt were also approved.

Work continued on the formulation of the chemistry for the steam-oxygen gasification processes during the quarter. The models for the heterogeneous and homogeneous reactions and associated interphase transport for char combustion were completed. The chemistry associated with the oxidation reactions was completed, and work continued on the chemistry of both the gasification and devolatilization process.

The theoretical aspects of the hydrodynamics and mechanical interactions in fluidized beds also continued and included particle size effects, drag relationships, and influences of compressibility.

A major portion of the formulation of the conservation equations and the constitutive relations for turbulent entrained flows was also completed. An examination of the chemistry of entrained flow gasification was initiated in March. The study, which will be related to the ongoing efforts in fluidized-bed gasification chemistry, has concentrated on quantification of the kinetic rates and the relationship of these rates to the time scales associated with the gas dynamic processes in entrained flows.

XVI. MODIFICATION AND OPERATION OF AN ATMOSPHERIC PRESSURE ASH-AGGLOMERATING GASIFIER

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Project Site: Chicago, Illinois
Contract No.: E(49-18)-2336
Contract Funding: \$2,484,318
(100% ERDA)

INTRODUCTION

A seven-ton-per-day process development unit, previously operated by IGT under the HYGAS program, demonstrated the operability of the ash-agglomerating process on coke feedstock. Under the current program, the gasifier will be modified to process coal feed. The specific objectives of the contract are to:

- Demonstrate the use of the ash-agglomerating gasification process in the production of low-Btu gas from coal at high carbon utilization rates for extended periods of time.
- Provide design and cost estimates for both a commercial-scale atmospheric pressure gasifier and a pilot-scale pressurized gasifier.

The 22-month program is divided into the following four tasks:

- Modification and shakedown of the existing gasifier, including the addition of a thermal oxidizer.
- Operation of the process development unit for up to 30-day test periods.
- Preparation of design and cost estimates for a commercial-size atmospheric pressure gasifier.
- Preparation of design and cost estimates for a pressurized test gasifier capable of operating in the 100-350 psi range.

Figure XVI-1 provides a schedule for the ash-agglomerating gasification development.

PROCESS DESCRIPTION

The ash agglomerating gasification process uses a single-stage fluidized-bed reactor which incorporates an ash-agglomerating technique to achieve high carbon utilization and simple residue handling. The process has been previously tested at atmospheric pressure with coke breeze and char as feedstocks. A flow diagram of the process is shown in Figure XVI-2.

Figure XVI-1. ASH-AGGLOMERATING GASIFICATION PROJECT SCHEDULE

Figure XVI-2. ASH-AGGLOMERATING GASIFICATION PROCESS SCHEMATIC

Coal is first crushed to $\frac{1}{4}$ -inch. Coal of any rank may be used, but caking coals may require pretreatment by contacting with air in a fluidized-bed at temperatures in the range of 700-800° F. The coal is introduced into the gasifier, where it is reacted with steam and air (or oxygen) in a single-stage fluidized bed at a temperature of approximately 1900° F. Residence time in the reactor is on the order of 45 minutes with a fluidizing velocity of 1.0-2.5 feet per second. While in the gasifier, the ash is agglomerated into progressively larger and heavier particles, thus facilitating selective separation from the bed. Fines which are elutriated from the bed are returned to the gasifier through both internal and external cyclones. The raw low-Btu gas generated in the gasifier is subsequently combusted in a thermal oxidizer.

tain whether the L-valve had a sufficient range and capacity coincident with a allowable maximum inert conveying gas requirement. As a result of the test program, it was decided to install a two-foot-long horizontal section of L-valve as part of the modifications to the reactor feed system.

The shop-fabricated four-foot-diameter cold model of the ash-agglomerating gasifier reactor was erected and modifications completed in November. The model will be used to study the fluidization and agglomerating zone dynamics at ambient temperatures.

The design of the 85 foot-high 100-ton silo was completed, and the silo fabrication started with delivery anticipated in January of 1977.

HISTORY OF THE PROJECT

The Institute of Gas Technology was awarded the contract in June 1976 and began modification of the existing gasifier equipment.

An L-valve type feeder system with no mechanical parts that could be damaged by the high-temperature fluidized bed was chosen to feed coal directly into the high-heat content bed. A study was conducted to ascer-

PROGRESS DURING JANUARY-MARCH 1977

Modifications of the ash-agglomerating equipment were nearly completed by the end of the quarter. The shakedown of the cold model was completed in February, and a test program schedule was prepared. Fifteen test runs were completed on the cold model. The first mechanical change to the cold model was also scheduled.

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.

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

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

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

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

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

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

diatomite—See Diatomaceous Earth.

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

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

dolomite—a carbonate of calcium and magnesium having the chemical formula $\text{CaMg}(\text{CO}_3)_2$.

Downerm—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.

tall 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.