U.S. DEPARTMENT OF ENERGY
Division of Coal Conversion

QUARTERLY REPORT

April-June 1977

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GAZETTE

MASTER

COAL

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COAL GASIFICATION

MASTER

QUARTERLY REPORT

APRIL - JUNE 1977

U.S. DEPARTMENT OF ENERGY

Division of Coal Conversion

Washington, D.C. 20545

Publication Date: January 1978

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.

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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 only 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 showed that use of dolomite acceptor instead of limestone increased the stability of operation of the char-acceptor interface. Wyodak subbituminous coal was gasified for more the 120 hours while the recirculating acceptor supplied all the heat duty in a successful run completed in June. The methanator was operated at the normal pressure, and, for the first time, at 280 psig. Radian Corporation completed their sampling project on the gasifier, regenerator, and effluent streams.

Seven test periods were completed during the quarter by the *BI-GAS Process for the Generation of Pipeline Gas*. Catalyst life testing as well as analysis of methanation PEDU test data continued.

The *HYGAS Process* plant continued testing of Peabody No. 10 mine coal. The liquid phase methanation unit was operated for the first time during the quarter.

One ore circulation test and one producer feed test were completed during the quarter in the pilot plant for the *Steam-Iron System For Production of Hydrogen*. Laboratory work continued with kinetic studies, char evaluation, attrition studies, and lift line studies.

During the quarter, the gasifier was operated at the *Synthane Process* pilot plant with Rosebud coal. Purpose of the tests were to determine the operating procedures necessary to achieve satisfactory bed level control with low bed densities and fines returned into the bed.

Battelle Memorial Institute is responsible for the design, construction, and operation of a process development unit (PDU) in West Jefferson, Ohio for demonstrating the *Agglomerating Burner Process*. The first gasification run was begun during the quarter but mechanical problems continued to hamper operations. The integrated burner/gasifier was operated for the first time in May; however, gasification was not achieved. Efforts continued throughout the quarter to obtain successful gasification.

A *Liquid Phase Methanation Process* is being developed by Chem Systems, Inc. The first run using HYGAS product as feed was begun during the quarter. A fire during operation in May prevented further operations of the unit until modifications to eliminate fire hazards are completed.

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 monitored by Braun engineers during the quarter. 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 industrial use as well as 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 assorted 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 process 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.

Atomics International Division (AI), Rockwell International Corp., has the responsibility for designing, constructing, and operating facilities for the development of the *Molten Salt Gasification Process*. Design and construction of the facility continued throughout the quarter.

An *Advanced Coal Gasification System For Electric Power Generation* is being developed by Westinghouse Electric Corporation. Three tests were run in the gasifier during the quarter. The last of the series of shakedown tests was followed by modifications to the char feed design of the gasifier,

and two tests run to evaluate the design. Design and procurement continued in preparation for integrated operation.

An estimated 94 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.

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 drafting the final reports.

One three stage test was 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*. Two batch tests were also conducted.

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 *Modification and Operation of an Atmospheric Pressure Ash-Agglomerating Gasifier* by the Institute of Gas Technology continued. Task I, Modification and Shakedown of the Ash-Agglomerating System, was completed during the quarter, and a summary report prepared. Task II began in June with testing to resolve the L-valve feeding problem and to achieve fines recirculation.

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 data to design 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 and prepare the conceptual design for a commercial sized coal gasification plant

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 Figure 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 weight percent to about 16 weight percent. The hot gas, at

Figure I-2. CARBON DIOXIDE ACCEPTOR PROCESS SCHEMATIC

approximately 850°F, is supplied by the combustion of coal fines recovered from mill offgas. The temperature of the furnace flue gas injected into the mills is moderated with recycle of mill offgas.

The crushed and partially dried coal is dried to 0-5 weight percent moisture in flash driers operating at about 240°F. The dried coal is conveyed to fluidized-bed preheaters where the temperature is raised to approximately 500°F. The preheated coal is fed into the gasifier near the bottom of a fluidized bed of char. Rapid devolatilization occurs, followed by gasification of the fixed carbon with steam.

The gasifier temperature ranges between 1480°F and 1550°F. Heat for the gasification reactions is supplied by a circulating stream of lime-bearing material called acceptor. This acceptor, which can be either limestone or dolomite, supplies the heat needed for gasification, primarily through the exothermic carbon dioxide acceptor reaction:

The acceptor, reduced to the desired size distribution (generally 6 x 14 mesh) enters the gasifier above the fluidized char bed, showers through the bed, and collects in the gasifier boot. Steam needed for hydrogasification

enters through the gasifier boot and the distributor ring. Spent dolomite, used during start-up to avoid plugging, is replaced by fresh acceptor after circulation rates are established and the system is at process temperature and pressure. Product gas from the gasifier passes through a steam-generating heat exchanger, then goes to the gas cleanup section.

The regenerator is used for calcining the acceptor. Carbonated acceptor from the gasifier flows through a standleg and is conveyed pneumatically by air or recycle gas to the bottom of the regenerator. Char from the gasifier is sent to the regenerator where it is burned with air, thus raising the temperature of the regenerator to 1850°F. At this temperature, the acceptor is calcined by reversal of the carbon dioxide acceptor reaction. The calcined acceptor is returned to the gasifier through a standleg. Flue gas from the regenerator passes through a heat exchanger to generate steam for the gasifier and the air compressor.

Both the flue gas from the regenerator and the product gas are cleaned; the clean flue gas is either returned to the regenerator or flared, and the clean synthesis gas is sent to the methanation unit where the heating value of the gas is raised to pipeline quality, approximately 1,000 Btu per standard 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. In addition, no condensable hydrocarbon liquids are generated during the gasification process.
- Raw gasifier product gas contains 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 had 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 APRIL-JUNE 1977

Summary

Run 43B and Run 44A were completed during the month of April. Both runs used Minnekahta limestone as the acceptor. Run 43B used Velva lignite and Run 44A used Wyodak subbituminous coal as a feedstock. Run 44B was a repeat of Run 44A. The run objectives were not accomplished due to a gasifier boot upset. Run 45, completed in May, was successful as all objectives were achieved. Wyodak subbituminous coal was gasified for more than 128 hours while the recirculating acceptor supplied all the heat duty.

South Dakota School of Mines & Technology and Radian Corporation continued sampling pilot plant runs. Stearns-Roger Company continued a Commercial Design Study.

Pilot Plant Operations

Run 43B was in the initial stages of startup at the beginning of the quarter. The objectives of the run were the same as the previous run, to operate the regenerator at neutral and at oxidizing conditions. Mechanical problems in the coal preparation area prevented the attainment of desired feed rates. The run was terminated when the calcined acceptor transfer could not be transferred to the gasifier.

In Run 44A, the intent was to operate the plant on Wyodak subbituminous coal for a long enough period to allow Radian Corporation to gather enough samples to characterize the quench system operation around both reactors. After a successful startup, the run ended suddenly when the gasifier boot became defluidized. The desired sampling effort was not completed. Post-run inspection showed that the steam flow to the boot had been too low.

A relatively high gasifier boot fluidization velocity was maintained throughout Run 44B. The higher velocity failed to prevent a boot upset which resulted in the termination of the run. The low equilibrium limestone particle density obtained when subbituminous coal is used as a feedstock is believed to be the primary cause of both upsets which terminated Runs 44A and 44B.

To overcome the problem of low equilibrium acceptor particle density, Run 45 featured the use of Tymochtee dolomite acceptor rather than Minnekahta limestone. Run 45 was highly successful since it demonstrated that subbituminous coal could be gasified without the need to inject air or oxygen into the gasifier. The unit was operated on Wyodak subbituminous coal for two periods, one of sixty hours and one of sixtyfour hours, with no air in the gasifier. The regenerator was operated in reducing, neutral, and then oxidizing atmospheres. Radian Corporation completed their sampling project on both the gasifier and regenerator. They also collected a complete set of samples during the neutral and oxidizing regenerator conditions. The methanation unit was operated at the normal 150 psig condition, and, for the first time, at the 300 psig level.

Laboratory Research

Work continued on the testing of reconstituted acceptor samples. The activity pattern was determined from an

extended run in the laboratory cycle test unit. The activity pattern of the Hazen Research reconstituted acceptor appeared to be about equal to that of the previously tested Dorr-Oliver reconstituted acceptor.

A new batch of synthetic acceptor was prepared in April for testing in the cycle tester and the fluidized-bed reactor. The synthetic acceptor contained a higher percentage of free calcium than used previously in order to establish the limits of operability with respect to free calcium content.

Samples of spent acceptor were examined with the electron microprobe to help define the mechanisms responsible for shell formation which may be the key to the variable acceptor density problem in the pilot plant.

Related Studies

The South Dakota School of Mines continued supportive laboratory studies involving the refinement of special analytical techniques in conjunction with Radian Corporation. All final reports were in preparation at the end of the quarter.

In their CO₂ Acceptor Commercial Design Study, Stearns-Roger Company submitted the heat and material balances for all remaining sections during April. The flow sheets were completed and approved during the month of June.

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 sub-contractors.

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 pre-heater. 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 2200°F is attained rapidly and the coal is converted

Figure II-1. BI-GAS PROGRAM SCHEDULE

Figure II-2. BI-GAS PROCESS SCHEMATIC

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 methan-

ation. 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 APRIL-JUNE 1977

Summary

Seven test periods were completed during the quarter at the BI-GAS pilot plant. BCR continued catalyst life testing as well as analysis of methanation PEDU test data.

Pilot Plant Operations

At the beginning of the quarter, the plant was down for inspection and repairs. Attempts to operate the gasifier during April were hindered by mechanical problems.

On May 1, the plant was shut down following a short test in which coal was fed to the gasifier for a total of 33-1/2 hours. The gasifier was opened, inspected, cleaned, and repaired during May and started up again on May 30. A test begun on May 31 was terminated after 22 hours because of a plugged slag tap hole.

Tests G-2B through G-2G were completed in June with coal and char being fed into the gasifier for a total of 47 hours. Slagging was observed for the first time during Test G-2E through the television and observation port. Although slagging operation was observed in some of the tests following G-2E, consistent steady state slag tapping was not achieved.

Laboratory Research

A life test of four separate catalysts was initiated at the beginning of the quarter and concluded after 820 hours. All of the samples showed good useful conversion following temperature cycling, and one, No. 3766, showed extremely high activity (96 percent useful conversion) at

the end of the test. Efforts were made to secure additional samples for PEDU testing.

Evaluation of data from previous PEDU tests was completed. The original conclusion that the overall heat transfer coefficient for the bare-tube loop was approximately four times larger than the finned tube loop was confirmed.

PEDU Test No. 25, with a third batch of the Homer City methanation catalyst, was conducted over a five-day period. The early part of the test was conducted at lower pressure (750 psig) to simulate initial operating conditions at the BI-GAS pilot plant. About halfway through the test, approximately 31 percent of the catalyst charge was removed from the bed. The remainder of the test was conducted at normal pressure (1000 psig) with the partial catalyst charge to obtain data at the higher space velocities.

Major conclusions from the evaluation of the data are:

- The Homer City catalyst can be activated under the process conditions expected in the pilot plant, except that the bed temperature must be at least 550°F and it may be necessary to raise the feed gas temperature to above 520°F.
- Acceptable conversions can be obtained with up to 34 percent inerts in the feed and a reactor pressure of 750 psig.
- Acceptable conversions can be obtained, under normal operating conditions, at space velocities at least 1.5 times higher than those used in other PEDU tests.
- Most of the methanation takes place near the inlet to the catalyst bed, and the shift reaction predominates in the upper (cooler) portion of the bed.
- Carbon deposition in the methanator is definitely possible, and appears to be enhanced when bed temperatures decrease to the point that the bulk of the feed gas is passing through the bed unreacted.
- The overall heat-transfer coefficient of the bare tube heat exchanger is about four times higher than that of the finned tube.

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.
- Determination of steady-state conditions and acquisition of scaleup data at high carbon conversions at maximum plant capacity.

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 diagram of the process is provided in Figure III-2. Coal preparation involves crushing the coal to -14 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 lower stages 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 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 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.

*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		OPERATION
STEAM-OXYGEN UNIT		OPERATION
INTEGRATED PILOT PLANT OPERATION INPUT: 75 TONS/DAY COAL OUTPUT: 1.5×10^6 SCFD HIGH BTU GAS	OPERATION				CRITICAL PROCESS EVALUATION

LEGEND: BEGIN MILESTONE DECISION MILESTONE
COMPLETE MILESTONE

Figure III-1. HYGAS PROGRAM SCHEDULE

Figure III-2. HYGAS PROCESS SCHEMATIC

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 930 to 950 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 (Test 37) 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.

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. 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 electric power required. No further investigations of this unit will be made. Two techniques for producing this gas are now 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 a separate contract (see Section IV). Currently, a pilot plant for demonstrating this technique has been constructed adjacent to the HYGAS pilot plant site.

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 APRIL-JUNE 1977

Summary

Pilot plant operations with Peabody No. 10 mine coal continued with efforts designed to improve plant operation stability. The liquid phase methanation unit was operated for the first time during the quarter.

Pilot Plant Operation

Test 60 was conducted during April and 186 hours of self-sustained operation were achieved. The pretreater operated satisfactorily, with modifications made before the test alleviating most of the coal feeding problems experienced in Test 59. Coal feed rates to the pretreater ranged from 2.5 to 3 tons per hour; and operating conditions were set at 775° F, with oxygen-to-coal ratios of 2 to 2.5 SCF of oxygen per pound of coal. After Test 60 was ended, the pretreater was operated at 700° and 750° F with coal feed rates of about 2 tons per hour, to determine

pretreater performance at these conditions. Results showed that nonagglomerating feed could be produced at pretreater temperatures of 750°F and higher. The pretreater was consequently operated at 750 to 775°F during Test 61 and provided nonagglomerating coal feed to the reactor.

Gasifier operation was extremely smooth during Test 61, and a high coal conversion of over 90 percent was achieved for the first time with a bituminous coal.

Tests 62 and 63 were conducted during June. The pretreater operated satisfactorily during Test 62 to produce nonagglomerating char for the reactor with temperatures ranging from 765° to 775°F. One hundred thirty one tons of coal were fed to the pretreater at a rate of 3 tons per hour over a period of 67 hours. The test was terminated because of operational problems in the product-gas quench system.

The objective of Test 63 was to conduct a long, steady-state test at high coal conversions. A total of 266 tons of

pretreated coal was fed to the reactor over a period of 139 hours. Seven days of self-sustained operation were logged. The test was terminated because solids could not be transferred from the reactor and from the second-stage gasifier to the steam-oxygen gasifier.

Liquid-Phase Methanation Unit

The liquid phase methanation unit was operated for two hours during Test 60, until a process upset caused flooding in the quench system. This, in turn, caused a carry-over of diglycolamine solution into the liquid phase methanation unit, reducing the activity of the catalyst by two-thirds, necessitating replacement of the catalyst.

The liquid-phase methanation unit was not put on line for Test 61 because a fire occurred during its operation in May. Modification to eliminate fire hazards were begun during this quarter and should be completed early in the next quarter.

IV. STEAM-IRON SYSTEM FOR PRODUCTION OF HYDROGEN

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois
Contract No.: EF-77-C-01-2435
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. Q.R.	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 APRIL-JUNE 1977

One ore circulation test and one producer feed test were completed during the quarter. Laboratory work continued with kinetic studies, char evaluation, attrition studies, and lift line studies.

Pilot Plant Operation

Analysis of the first producer feed test performed during the last quarter indicated excellent performance of the slurry heater. Slurry concentrations averaged 25 weight percent and outlet temperatures ranged between 500° and 590°F psig indicating complete water vaporization in the heater. The char feed rates to the producer were 25 percent of design.

During April, the newly cast refractory linings in the preheater combustion chamber and the lift-line J-bend were cured, and ore circulation tests were resumed. Ore circulation Test 4 was completed in May. Continuous ore circulation was achieved over a period of 30 hours, with all bed-level control valves on automatic. Ore circulation rates were estimated at 6.4 tons per hour. Reactor pressure was controlled at 150 psig, and a minimum temperature of 400°F was maintained in the fluidized beds. Results of the test indicated over 20 hours of circulation of 5.1 tons per hour, and toward the end of the test, rates of up to 36.3 tons per hour were logged for several hours. During the higher circulation periods, flow up the lift-line was not as smooth as at the lower rates.

Producer feed Test 5 was completed in June. A total of 47 tons of char was fed to the producer reactor over a period of eight days. Slurry concentrations were controlled to contain between 15 and 25 weight percent char, and a fluidized bed was established in the producer. Char feed rates were gradually increased to 0.75 tons per hour, and bed temperatures were raised to 1275°F in the producer zone to initiate char gasification. Temperatures were limited to 1275°F in the producer bed because of erratic level control caused by solids bypassing the discharge valve.

The test was terminated to allow inspection of the discharge valves from the producer and preheater zones. During the inspection and modification of the discharge valves, preparations were made for an ore circulation test in the steam-iron reactor, and ore circulation was established toward the end of June.

Laboratory Tests

Kinetic Studies

Thirty-five reactivity and 35 attrition tests were conducted during the quarter. Three of the materials tested during April had higher reactivities than siderite. However, the attrition resistance of all the reactive materials was significantly lower than that of siderite.

Efforts during May were concentrated on improving the attrition resistance of IGT Iron-Chromia 5, which had been identified earlier to be twice as reactive but only one-sixth as attrition resistant as siderite. Pelletizing Iron-Chromia 5 (without silica) prior to sintering, significantly improved the attrition resistance of the material and made it almost as attrition resistant as siderite. However, the reactivity of the material also decreased significantly and made it less reactive than siderite.

Tests in June were made to investigate the effect of silica as a means of increasing the attrition resistance of reactive materials. IGT Iron-Magnesia 8, with four percent silica, established the highest attrition resistance of any of the coprecipitated samples prepared to date and was as reactive, within 95 percent confidence limits, as siderite.

Char Evaluation

Four char evaluation tests, two with Montana subbituminous coal char, and two with a Western Kentucky bitu-

minous coal char were conducted during the quarter. Results showed that with the Montana subbituminous coal char, at a gasification temperature of 2025°F, ash sintering starts when the fluidization velocity is reduced to 0.63 feet per second. When the Kentucky bituminous coal char was used at a char-bed temperature of 1890°F, ash sintering began when the fluidization velocity was lowered to 0.44 feet per second.

Attrition Studies

Two tests were conducted to determine the effect of gas velocity at the distributor orifice on the attrition characteristics of Husky lignite char. Two tests were conducted to determine the effect of gas density on the attrition characteristics of siderite at a constant gas velocity at the orifice and a constant gas flow through the porous plate.

Nine attrition tests were conducted during June. Five of these were conducted with siderite ore to determine the effect of gas density on attrition in the cyclone. The remaining four tests were conducted with Husky lignite char to determine the effect of the cyclone-inlet gas velocity on char attrition.

Life-Line Studies

Twelve tests were conducted to determine the effect of solids flow rates on the solids inventory in the three sections of the transition zone.

V. SYNTHANE PROCESS

THE LUMMUS COMPANY
BLOOMFIELD, NEW JERSEY

Plant Site: Allegheny County,
Pennsylvania
Contract No.: EX-76-C-02-0003
Contract Funding: \$28,000,000
(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 produces 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 reactor (TWR) system. The HGR methanator is composed of parallel plates that are flame sprayed with Raney nickel catalyst. Excellent temperature control is achieved by recycling some of the exit gas that has been cooled in a separate heat exchanger. Because the pressure

Figure V-1. SYNTHANE PROGRAM SCHEDULE

Figure V-2. SYNTHANE PROCESS SCHEMATIC

drop in the HGR is less than in conventional reactors, the compression costs are relatively low. The TWR methanator is composed of two-inch-diameter tubes with the Raney nickel catalyst flame sprayed on the inside, a practical technique that allows easy replacement of the catalyst. The TWR system removes the heat of reaction by means of conduction through the catalyst-coated tubes, which are in contact with boiling Dowtherm. The purified gas entering the methanator is diluted by recycled gas to increase the reaction rate by reducing the water content. Long-term catalyst life of over 2,800 hours has been successfully demonstrated in the TWR system in the laboratory. The plant has also yielded large quantities of high-Btu gas per unit weight of catalyst (240,000 standard cubic feet per pounds of catalyst). As a final step, the gas produced with both the TWR and the HGR methanators is passed through a small vessel packed with

conventional methanation catalyst to minimize residual carbon monoxide in the product gas.

The Synthane process offers several advantages in the production of high-Btu gas:

- Caking coals can be used directly as can a wide range of other coals, including lignite.
- Hydrocarbons released during pretreatment are retained within the system, thereby maximizing the efficiency of coal conversion to gas.
- 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 scat-
tered 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, prepar-
ing 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 com-
pleted 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 pro-
duced 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 APRIL-JUNE 1977

Summary

During the quarter, the gasifier was operated with
Rosebud coal with the purpose of determining the oper-
ating procedures necessary to achieve satisfactory bed
level control with low bed densities and fines returned
into the bed.

Pilot Plant Operations

At the beginning of April, the plant was in operation
for six days. Gas was produced for a total of 76 hours, the
longest continuous operation being 37 hours. Feed rates
and bed heights were varied at operating temperatures of
1500°F in an attempt to achieve over 70 percent carbon
conversion. The plant was shut down after a clinker,
which prevented the removal of char, was found in the
gasifier. Carryover of fines was excessive during the runs
indicating that the cyclone was not functioning. Carbon
conversions up to 70 percent were achieved during the
last stages of the run.

The next two runs were attempts to improve the
cyclone performance. Both runs were terminated due to
the formation of clinkers. During both runs the cyclone
began performing as bed densities dropped from 20 to 8
pounds per cubic foot when fines were returning to the
bed. Bed height could not be controlled, as the levels
increased uncontrollably from 15 to 24 feet. After the run,
the plant remained down from April 28 to May 15 for
cleanup, inspection, and revision.

The gasifier was operated for a period of eight days in
May at varying conditions, in an attempt to achieve
better operability with low bed densities. Gas was pro-
duced for a total of 112 hours. The gasifier, however, was
shut down after a crack developed in an Incoloy 800 nozzle
before the test program could be fully completed. The
nozzle failed as a result of stress corrosion cracking.
These findings necessitated the removal of all the Incoloy
800 nozzles. All Incoloy 800 fittings are being replaced
with carbon steel fittings that are monel overlaid. The
repairs continued during the remainder of the quarter
and are expected to be completed in late July. While
repairs were performed an inspection of process equip-
ment was made.

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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

PROJECT	FY 75	FY 76	TR. QR.	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

mode yields hot flue gases that, because they are sufficiently 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

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 govern-

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

PROGRESS DURING APRIL-JUNE 1977

Summary

The first gasification run was begun during the quarter. Mechanical problems continued to hamper operation, however. The integrated burner/gasifier was operated for the first time in May; however, gasification was not achieved and efforts to obtain successful gasification continued.

Process Development Unit

The first gasification run was started in March, with start-up interrupted twice. The first interruption was the result of plugging in the burner cyclone and scrubber. When the run was resumed, difficulties with the oil-fired bed start-up heater necessitated the second interruption. The run was resumed and after 1500 pounds of coal had been burned, the run was interrupted because the lift line appeared to plug and circulation was lost, caused in part by extensive erosion in the refractory lining at the bottom of the loops. While these sections were being repaired, a series of tests were made with the burner alone to provide further information on the agglomerating characteristics of western coal and to investigate the effect of superficial fluidizing velocity in the burner bed. Results indicated that, at least in the absence of solids circulation, the

present burner design can be operated at superficial bed velocities up to six feet per second without excessive carryover of bed material into the cyclone.

In May, the integrated burner/gasifier system was operated for the first time with hot solids circulation and with the system temperatures maintained for an extended period solely by the burning of coal. The run was interrupted before gasification was achieved, in part because of a failure in a process air compressor, and in part, because of continued plugging of the transfer loops by chunks of refractory.

After modifications were made, the burner/gasifier system was reassembled and pressure tested and another run begun. Circulation was erratic throughout most of the run. Inspection showed the burner lining in poor condition. It will likely continue to spall and will eventually have to be replaced or repaired in a major way. Temporary expedients will be continued in an attempt to complete successful gasification runs before shutting down to reline.

Related Studies

On-site and off-site consultation actively was initiated at the beginning of the quarter by E. I. DuPont de Nemours and Company. DuPont will provide consultation from their engineering group during the period of initial start-up and operation of the PDU. Assistance and guidance of PDU operations continued throughout the quarter.

The design of the static test rig was completed, and the initial test specimen materials were selected.

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.: EX-76-C-01-2036

Contract Funding: \$1,483,744

ERDA: \$1,303,996

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 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 fixed bed unit where complete reaction occurs adiabatically.

LEGEND:

- △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure VII-1. LIQUID PHASE METHANATION PROGRAM SCHEDULE

Figure VII-2. LIQUID PHASE METHANATION PROCESS SCHEMATIC

ically 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 sub-contractor 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)-2036 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 shake-down operations begun. By the end of the year all systems had been checked out.

PROGRESS DURING APRIL-JUNE 1977

Summary

Run #1 was begun on the liquid phase methanation (LPM) unit during the quarter with HYGAS product as feed. A fire during operation in May prevented further operations of the unit until modifications to eliminate fire hazards are completed.

Pilot Plant Operations

HYGAS product was fed to the liquid phase methanation (LPM) unit for the first time in April. The gas contained approximately 40 percent hydrogen, 32 percent methane, 19 percent nitrogen, and 9 percent carbon monoxide. The HYGAS feed abruptly stopped due to malfunctions in the HYGAS cleanup section, and a large amount of diglycolamine entered the LPM unit without warning. Feed to the unit was halted immediately and the unit was returned to a standby mode until the extent of the damage could be determined.

A single data point was salvaged for calculation of test results. At 500 psig and 560°F, the temperature was still rising, but a carbon monoxide conversion of 81.5 percent was obtained. The gas space velocity was 2,060 per hour and the hydrogen to carbon monoxide mole feed ratio was 4.6. A kinetic rate constant corrected to 650°F of 1.47×10^{-6} lb-mole/(atm-lb cat-sec) resulted from the analysis which is comparable to the kinetics obtained in the PDU.

The used catalyst was removed from the reactor. The unit was cleaned completely and loaded with a batch of fresh catalyst.

Run #2 was begun in May with steam-methane reformer gas feed at a rate of 24,000 standard cubic feet per hour. IGT gradually reduced the steam to methane ratio to 4.2 in the reformer which lowered the reformer product from its initial ratio of hydrogen to carbon monoxide of 10 to approximately 6.5 which is the composition intended to be supplied by IGT to the LPM unit for all future testing. The LPM pilot plant was running continuously for 44 hours of accumulated reaction time when feed gas was interrupted. After additional interruptions, the run was terminated due to a fire which did not result in any significant damage to the plant.

Work during the remainder of the quarter was devoted to main process oil filter revisions including piping, insulation, and hydrotesting.

VIII. EVALUATION OF HIGH-BTU GASIFICATION PROJECTS

C. F. BRAUN AND COMPANY

ALHAMBRA, CALIFORNIA

Project Site: Alhambra, California

Contract No.: EX-76-C-01-2240

Contract Funding: \$5,729,518
ERDA: \$3,819,679
GRI: \$1,909,839

INTRODUCTION

Several high-Btu coal gasification projects are being evaluated by the engineering firm of C. F. Braun & Co. The project, initiated in March 1972, is sponsored by ERDA and the Gas Research Institute (GRI). ERDA is providing two-thirds of the funds and GRI, one-third.

The overall objective of the project is to monitor operations at the selected gasification pilot plants and determine the processes or individual unit operations most applicable for inclusion in a commercial facility. In addition, Braun is preparing a conceptual commercial process design for each of the selected processes using different coal feeds. These evaluations and concept designs will permit early identification of problem areas so as to develop solutions through accelerated mechanical development programs.

PROGRAM DESCRIPTION

The tasks performed by Braun fall into two general categories: technical evaluations and conceptual designs. The technical evaluations are being performed on the following pilot plants.

- HYGAS Steam-Oxygen
- HYGAS Steam-Iron

- Carbon Dioxide Acceptor
- Synthane
- BI-GAS

Braun monitors the operation of the plants and evaluates the plant performance as it relates to the achievement of operational objectives. Based on the evaluations, Braun provides recommendations to ERDA on any redefinition of effort related to the projects. Braun also provides assistance to operators for improving, changing, or adding equipment and procedures to more efficiently achieve the project objectives.

In addition to the evaluation of overall processes, Braun performs design reviews, data analyses, and engineering evaluations of proposals, cost estimates, and monthly reports to provide information considered essential to the overall objectives of the program. These reviews include in-depth component analyses and studies of specific conversion processes and subprocesses required to establish feasibility, safety, and applicability. The unit operations investigated to determine the most practical means of performing the operations in a demonstration or commercial facility include:

- coal preparation and handling
- coal pretreatment
- coal feed injection
- gas purification
- shift conversion
- methanation
- effluent treatment

In the area of conceptual designs, Braun is responsible for the development of conceptual commercial process designs for each of the gasification processes listed above using both Eastern and Western coals as feed and for Lurgi gasification plants as a basis for comparison. Factored estimates and gas cost calculations are also being developed for each of the process/feed combinations for comparison of gas costs with the Lurgi technology.

PROGRESS DURING APRIL-JUNE 1977

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 monitored and evaluations of the pilot plant performance were made.

Work continued in 11 process study areas during the period. Four reports were submitted to ERDA-AGA for approval and one new study was initiated. The case study report on comparison of acid gas removal processes was completed with the exception of design changes to the Benfield process. The report on comparison of shift conversion catalysts was completed and reviewed internally. A report on the selection of materials for commercial plants, based on data obtained thus far in the materials testing program, was drafted and reviewed internally. One of the reports forwarded to ERDA-AGA was that on tradeoffs between carbon dioxide removal costs versus carbon dioxide concentrations in the gas feed to the methanator. An overview report on the manage-

ment of sulfur removal was also sent to ERDA-AGA. This report described the options and logic to be followed in selecting sulfur removal techniques to meet effluent requirements.

The new study which was initiated during the quarter is designed to compare the economics of producing by-product sulfur in the form of sulfuric acid versus the production of elemental sulfur. Efforts on the reports dealing with effluent treatment, combined shift and methanation, and coal slurry feeding were deferred near the end of the quarter in order to concentrate efforts on the Eastern coal commercial concept study.

Work on the mechanical development programs continued, with feasibility testing of the dry solids flow meter and investigations of various slurry injection nozzles in the vertical lift dryer. Components for testing the gasifier temperature measurement device were ordered in May and delivery is expected prior to August.

During the last quarter, the commercial concept designs for the HYGAS, BI-GAS, and Synthane processes using Eastern coal were sent to the process licensors for review. During this quarter, responses were received from the Institute of Gas Technology (IGT) and the Pittsburgh Energy Research Center. IGT also made recommendations to modify the Gas Cost Guidelines for Eastern coal factored estimate designs. Alternatives suggested by IGT which show significant savings will be incorporated. Work also continued on the Lurgi lignite commercial concept design based on the proprietary Lurgi package supplied by American Natural Gas Service Company. This information will be used to compare the Lurgi Process to the Carbon Dioxide Acceptor Process for lignite gasification.

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 tone 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 predominantly 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.

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 advantage 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.
- Entrainment of particulates in the product gas and purification requirements.
- 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 APRIL-JUNE 1977

The overall plant construction specification and supporting drawings were completed by the end of May. All major process equipment and instrumentation/control items have been specified. Vendor evaluations and

supplier submittals were being evaluated on an expedited basis.

Purchase orders were placed for three major subsystems: low pressure solids handling system, high pressure solids handling system, and spray dryer-sulfur dioxide absorber system.

Fabrication of the Gasifier Vessel and Melt Withdrawal Chamber was completed. The two vessels were mated and successfully hydrostatically tested at 465 psig. All material was received for the quench tank and fabrication was initiated. The installation of the Melt Shatter Barrel Inconel 600 lining and weld overlay was also initiated.

Civil construction work continued throughout the quarter. Five bidders were selected for the Balance of Plant Construction Package and bids solicited in June.

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: \$33,303,105
(through fiscal year 1977)
ERDA: \$29,249,922
Industry: \$4,053,183

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 date 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 sys-

tem. This will provide data for developing 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 fluid-

LEGEND: $\triangle$ BEGIN MILESTONE
 ∇ COMPLETE MILESTONE

Figure X-1. ADVANCED COAL GASIFICATION PROGRAM SCHEDULE

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

izing 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 APRIL-JUNE 1977

Summary

Three tests were run in the gasifier during the quarter. The last of the series of shakedown tests was followed by modification to the char feed design of the gasifier and two tests were run to evaluate the new air tube design. Design and procurement continued for integrated operation. Support studies were conducted in the following areas: fluidization and fluid particle studies, coal behavior, ash behavior, and reactor analysis.

Process Development Unit

As a result of problems encountered with Test TP-011-4 completed last quarter, Test TP-011-5 was planned with the following objectives:

- Continued evaluation of combustor temperature on ash agglomeration at levels of 1950° F and 2000° F.
- Evaluation of the effect of increased steam flow to the grid plate on gasification and on reducing bridging of materials in this area.
- Determination of the best method of operating the ash annulus to prevent sintering of material by fluidizing the top of the ash annulus to a mildly slugging condition.

Operational changes were incorporated in Test TP-011-5 as a result of Test TP-011-4. The test ran for about 65 hours at the beginning of the quarter at agglomerating temperatures of 1950° and 2000° F. Ash content in the ash withdrawal was from 30 to 95 percent. Ash content in the bed was from 15 to 50 percent.

Data on ash withdrawal rate versus ash content in the ash product stream appeared to corroborate the previous observation that ash content can be controlled by the withdrawal rate. There was not sufficiently long steady-state periods at a constant ash concentration to establish the empirical correlation. The purpose of Test TP-011-6 was to develop the correlation further and to achieve a longer steady-state operation of the agglomerator.

A test plan was written in June for a series of tests which will be run to evaluate the new concentric char feed design which introduces char fines into the combustion zone through the air tube. The new air tube assembly was fabricated and installed in the gasifier, and Tests TP-012-1 and TP-012-2 were run in June.

In Test TP-012-1, over 95 hours of test time was achieved following char ignition, 38 of these were at steady-state conditions. Ash agglomerates were uniform in size and composition, and, for the first time, no sintered ash "clinkers" were found in the annulus after the test. It appeared that the new air tube and char feed designs were

successful in eliminating clinker formation. This could be the result of the steam spraying at the top of the annulus, to the change from radial to axial char feed, on to both effects.

Test TP-012-2 was the most successful test carried out to date in the gasifier reactor. The test was operationally smooth with few equipment or process malfunctions, and all test objectives were met. The ash withdrawal was conducted in the automatic mode for the first time for over 18 hours while maintaining a constant char/ash interface. These achievements are important to the scale-up and large scale demonstration of a practical ash agglomerator reactor.

Two steady-state tests points were held for 24 and 30 hours respectively, providing a basis for understanding the results of shakedown tests conducted during Test Series TP-011. In particular, operation of the ash annulus in the "char-stripping" mode as opposed to operation without a clearly defined char-to-agglomerate interface explained many of the effects seen in earlier tests, especially with respect to formation of larger agglomerates.

Design and procurement of hardware for integrated operation of the gasifier and devolatilizer reactors continued throughout the quarter.

Support Studies

The primary support effort was directed to support of the combustor-gasifier operation. The semi-circular model was operated with its internal configuration simulating the devolatilizer to obtain data on the proposed conical distributor plate design. Experiments continued with the conical distributor plate at different locations from the draft tube inlet with different bed materials.

Experiments continued on carbon-steam and carbon-carbon dioxide reactions with coke breeze. The ash agglomeration test unit was operated and modified to improve performance.

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 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 gasifier combustor, thereby increasing the heating value of the product gas from 127 to 285 Btu per standard cubic

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

Figure XI-1. LOW-BTU GASIFICATION PROGRAM SCHEDULE

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 devel-

opment 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 installation 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 APRIL-JUNE 1977

Technical work on all research and development tasks of Phase I of the contract was completed. The only activity on these tasks was the final report editing, internal review, and ERDA review of the reports.

Construction of the process development unit (PDU) was 94 percent complete as of the end of June, exclusive of yard paving, heat tracing, and piping insulation, which are not critical to the start of operation. Principal remaining items necessary to place the plant in operation are completion of certain piping systems and completion of the instrument and controls installation.

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XII. 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 product 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 XII-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 steam 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, and gasifying with oxygen and steam will yield a medium-Btu gas.

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 and char, and provide physical data such as minimum fluidizing velocity, attrition rate, elutriation losses, etc. The successful laboratory studies led to the 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 Monroeville, Pennsylvania, laboratory was awarded to Blaw-Knox Chemical Plants

LEGEND:

- △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

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

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 noncaking 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 APRIL-JUNE 1977

Three-stage Test No. 3S-3 was conducted during May. Operating temperatures were established in Reactors 3 and 1, while maintaining bed levels automatically. The system was operated in this automatic mode for about five hours before it was necessary to terminate the test because of mechanical problems.

Two batch tests were conducted in the Stage 3 reactor with Rosebud char. A fluid-bed temperature of 1500°F was reached during Test No. 3S-4 and 1800°F during Test No. 3S-5. There was no evidence of agglomeration after Test No. 3S-4. Complete analysis of Test No. 3S-5 results is not yet completed.

XIII. 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 Separation
 - 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. Plastics

Section VII: MATERIALS 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 APRIL-JUNE 1977

Summary

Work on the Properties of Process Materials included analysis of equilibrium data as well as work on various correlations for estimating the calorific value of coal from its elemental composition.

Conversion Fundamentals dealt with product distribution in batch pyrolysis. Design procedures investigated gas-solids transport and heat transfer correlations. Materials of Construction tests evaluated the performance of insulating materials in atmospheres expected in coal conversion reactors.

Properties of Process Materials

During the quarter work continued on vapor-liquid equilibrium in the $\text{NH}_3\text{-CO}_2\text{-H}_2\text{S-H}_2\text{O}$ system. Methods of calculating fugacities in gaseous mixtures such as those present in hydrogasification reactor product gas were reviewed.

Work also continued on improvement of the accuracy and precision of methods for estimating the calorific value of coal from its composition. Enthalpy data of coal liquids were given as a function of temperature. Various correlations for estimating the calorific value of coal from its elemental composition were evaluated.

Conversion Fundamentals

Work continued to relate the effects of primary factors—pressure, temperature, coal rank and coal composition, and structure—on product distribution in batch pyrolysis.

Sulfation and regeneration of the acceptor in fluidized-bed combustion was accepted in May. The problems of predicting acceptor activity were discussed.

Design Procedures

In the gas-solid transport area, literature on gas-solids downflow in inclined pipes was received. Standpipe design in packed-bed flow regime was also reviewed.

Work in the area of heat transfer in fluidized beds continued with the objective of recommending suitable heat transfer correlations for fluidized-bed heat transfer.

XIV. 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 combined 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 measurements 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 chemistry, 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 APRIL-JUNE 1977

The liaison and support of the Synthane Pilot Plant work continued during the quarter. The fluidized-bed computational model was used to study solid particle convection in the neighborhood of a simulated Synthane distributor plate.

The programming of the chemistry and species transport relationship for steam-oxygen gasification into the fluidized-bed code was initiated and continued throughout the quarter.

The examination of chemical kinetics and transport associated with devolatilization, oxidation, and gasification of pulverized coal/char in entrained flows was expanded and continued.

XV. 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 XV-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 had been previously tested at atmospheric pressure with coke breeze and char as feedstocks. A flow diagram of the process is shown in Figure XV-2.

Figure XV-1. ASH-AGGLOMERATING GASIFICATION PROJECT SCHEDULE

Figure XV-2. ASH-AGGLOMERATING GASIFICATION PROCESS SCHEMATIC

Coal is first crushed to -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.

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 ascertain whether the L-valve had a sufficient range and capacity coincident with an 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.

PROGRESS DURING APRIL-JUNE 1977

Summary

Task I, Modification and Shakedown of the Ash-Agglomerating System, was completed during the quarter, and a summary report prepared. Task II began in June with testing to resolve the L-valve feeding problem and to achieve fines recirculation. Modifications of the L-valve continued and a three- by two-inch design will be constructed.

Gasifier Operations

Two shakedown tests were conducted in May using coke breeze as the feed material for steam-air gasification in the newly modified ash-agglomeration gasifier. The tests were conducted to reestablish operating conditions for coke with the gasifier-agglomerator and to operate those pieces of equipment and systems added or modified during Task I of this low-Btu project. The coke used as feed was the same material used to conduct tests in the system under the predecessor project. Ash agglomerates had been purchased from this feedstock at several operating conditions, including steam-air, steam-oxygen, and enriched steam-air. The fines recirculation system had been modified to inject fines at 1000° F instead of 500° F from the external cyclones and functioned without failure, but required the addition of oxygen for complete gasification and ash agglomeration. The bed removal valve functioned as designed and was used successfully in each test. The L-valve functioned sporadically during the testing.

During June, Task II was begun and testing continued with coke breeze to resolve the L-valve feeding problems and to activate fines recirculation. Fines recirculation

and simultaneous ash agglomeration were obtained. Also, the gasifier was operated under the steam-air mode supplying gas mixtures containing up to 21 percent oxygen to the grid. Consequently, previously imposed oxygen ratio limitations as applied to the process gas supplied to the grid section were unnecessary and, further, removal of the limitations may improve both agglomerate and product gas quality.

The L-valve was found to function intermittently due to repeated plugging by material up to 1/2-inch in size. A new two-inch by three-inch valve was designed as a replacement and will be operated and calibrated in the next test run.

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

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

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

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

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

effluent gas—gas given off from a process vessel.

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

endothermic reaction—a process in which heat is absorbed.

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

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

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

exothermic reaction—a process in which heat is liberated.

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

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

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

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

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

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

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

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

Fischer-Tropsch process—method of hydrogenating mixtures of

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

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

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

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

flue gas—gaseous combustion products.

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

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

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

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

fractionation—distillation process for the separation of the various components of liquid mixtures.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

hydrogenation—chemical reactions involving the addition of gaseous hydrogen to a substance in the presence of a catalyst under high temperatures and pressures.

hydrogen donor solvent—solvent, such as anthracene oil, tetralin (tetrahydronaphthalene), decalin, etc., which transfers hydro-

gen to coal constituents causing depolymerization and consequent conversion to liquid products of lower boiling range which are then dissolved by the solvent.

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

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

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

industrial gas—see fuel gas.

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

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

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

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

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

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

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

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

low-Btu gas—a gas having a heating value up to 350 Btu per standard cubic foot.

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

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

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

methanation—the production of methane (CH_4) from carbon monoxide or dioxide and hydrogen.

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

methanol—methyl alcohol, CH_3OH .

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

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

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

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

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

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

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

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

phenols—a group of aromatic compounds having the hydroxyl (OH) group directly attached to the benzene ring.

pilot plant—a chemical process plant containing all the processes of a commercial unit, but on a smaller scale, for the purpose of studying the technical and economic feasibility of the process.

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

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

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

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

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

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

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

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

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

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

raw gas—see crude gas.

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

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

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

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

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

refractory—a material capable of withstanding extremely high temperatures and having a relatively low thermal conductivity.

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

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

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

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

semi-water gas—a mixture of carbon monoxide, carbon dioxide, hydrogen, and nitrogen, obtained by passing an air-stream mixture through a hot bed of coke, having a higher heating value of about 120 Btu per standard cubic foot.

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

shift conversion—process for the production of gas with a desired carbon monoxide content from crude gases derived from coal gasification; carbon monoxide-rich gas is saturated with steam and passed through a catalytic reactor where the carbon monoxide reacts with steam to produce hydrogen and carbon dioxide, the latter being subsequently removed in a scrubber employing a suitable sorbent.

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

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

slurry—a suspension of pulverized solid in a liquid.

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

solvent—that component of a solution which is present in excess; liquid used to dissolve a substance.

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

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

space velocity—volume of a gas (measured at standard temperature and pressure) or liquid passing through a given volume of catalyst in a unit time.

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

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

standard cubic foot (SCF)—the volume of a gas at standard conditions of temperature and pressure. The American Gas Association

uses moisture-free gas at 60° F and 30 inches of mercury (1.0037 atm) as its standard conditions. The pressure standard is not universal in the gas industry: 14.7 psia (1.000 atm) and 14.4 psia (0.980 atm) are also used. The scientific community uses 32° F and 1 atm as standard conditions.

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

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

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

substitute natural gas (SNG)—a gas produced from coal, oil sands, or oil shale conforming to natural gas standards.

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

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

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

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

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.