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U.S. DEPARTMENT OF ENERGY
Division of Coal Conversion

QUARTERLY REPORT

October - December 1977

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Publication Date: May 1978

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COAL CASIFICATION

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Division of Coal Conversion

Washington, D.C. 20545

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FOREWORD

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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 commercial production of synthetic fuels from coal vital to the Nation's total supply of clean energy. In response to this need, the Department of Energy (DOE) 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.

DOE's program for the conversion of coal to liquid fuels was begun by two of DOE's predecessor agencies: Office of Coal Research (OCR) in 1962, and Bureau of Mines, U.S. Department of the Interior, in the 1930's. Current work is aimed at improved process configurations for both catalytic and non-catalytic processes to provide more attractive processing economics and lower capital investment. The advantage of coal liquefaction is that the entire range of liquid products, including heavy boiler fuel, distillate fuel oil, gasoline, jet fuel, and diesel oil, can be produced from coal by varying the type of process and operating conditions used in the process. Furthermore, coal-derived liquids have the potential for use as chemical feedstocks.

To provide efficient and practical means of utilizing coal resources, DOE is sponsoring the development of several conversion processes that are currently in the pilot plant stage. The development of the solvent refined coal process is being carried out in pilot plants at Fort Lewis, Washington and Wilsonville, Alabama. Responsibility for the operation of the *Solvent-Refined Coal (SRC) Process* pilot plant at Ft. Lewis, Washington is assigned to Pittsburgh and Midway Coal Mining Company. During the quarter, two material balance runs were completed with Illinois No. 6 coal, and testing began with Pittsburgh seam coal from Consol's Blacksville No. 2 mine. The Merriam Laboratory continued supporting studies on the Pittsburgh coal with nine SRC II process variable runs completed.

DOE, together with the Electric Power Research Institute (EPRI), has contracted with Southern Services Company, Inc. for the *Operation of a Solvent-Refined Coal Pilot Plant* at Wilsonville, Alabama. Indiana coal from the old Ben No. 1 mine continued to be processed during the quarter.

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.

The planned inactivation of the *Carbon Dioxide Acceptor Process* pilot plant was completed during the quarter. The final report covering the operation of the plant was also completed.

The most successful test to date was completed in November in the pilot plant of the *BI-GAS Process for the Generation of Pipeline Gas*. A 24 hour steady state operating period was achieved while collecting three complete sets of laboratory samples. Bituminous Coal Research, Inc. continued their laboratory support work with methanation catalyst studies.

The *HYGAS Process* plant continued testing with Illinois bituminous coal to acquire data necessary to optimize the design of a commercial demonstration plant using the HYGAS process. Two tests were completed during the quarter with char conversions of up to 85 percent.

Integrated operation of the producer and steam-iron reactor was achieved for a short period during October in the pilot plant for the *Steam-Iron System For Production of Hydrogen*. One ore circulation test and one producer reactor test were also completed during the quarter. Laboratory studies completed included kinetic studies, char evaluation, and attrition studies.

The *Synthane Process* pilot plant continued studies of Illinois No. 6 coal during the quarter. One run of 22 hours was achieved in December.

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*. Work continued toward achieving an integrated combustion/gasification run during the quarter. In a run conducted in December, the capability of the PDU to sustain the gasifier

temperature by burning coal in the combustor only, and to maintain solids circulation, was demonstrated.

The *Liquid Phase Methanation Process* is being developed by Chem Systems, Inc. Evaluation of data from a run performed last quarter resulted in the decision to modify the gas and oil feed system to improve distribution within the reactor.

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 the conversion to high-Btu, and the associated capital costs are lower. Because different low-Btu gasification processes are optimum for converting different types of coal, and because of the need to provide commercially acceptable processes at the earliest possible date, DOE 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, construction, 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. Gasifier tests were conducted during the quarter to complete the evaluation of reactor performance with high fines loading, with FMC char, and with direct coal feed.

Combustion Engineering, Inc. is responsible for the construction of the pilot plant for the *Low-Btu Gasification of Coal for Electric Power Generation*. A dedication ceremony marking completion of pilot plant construction was held at the plant site on October 18, 1977 and the first attempt to fire coal in the gasifier's combustor was made in December.

Three tests were conducted by Bituminous Coal Research, Inc. during the quarter to evaluate the design and operability of the equipment for the production of *Low Btu Fuel Gas*. Testing also continued in the bench-scale reactor with a noncaking Rosebud coal.

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. The first edition of the Technical Data Book was prepared and distributed to Special Consultants for comments and suggestions during the quarter.

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 with tests to determine operating conditions necessary to sustain ash agglomeration with a raw coal feed. One test was made during the quarter with Montana subbituminous coal, and Illinois No. 6 coal was used for the other five runs.

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.: EX-76-C-01-1734

Contract Funding: \$19,900,748
DOE: \$13,267,164
AGA: \$ 6,633,584

INTRODUCTION

The carbon dioxide acceptor process is being developed by the Conoco Coal Development Company (CCDC) under the joint sponsorship of DOE and the American Gas Association (AGA). DOE 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.

LEGEND:
 ▲ BEGIN MILESTONE
 ▼ COMPLETE MILESTONE
 ○ DECISION MILESTONE

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 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 dryers operating at about 240°F. The dried coal is conveyed in 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 calcium oxide called acceptor. This acceptor which can be either limestone or dolomite, supplies the heat needed for gasification, primarily through the reversible exothermic/endothermic 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

Figure 1-2. CARBON DIOXIDE ACCEPTOR PROCESS SCHEMATIC

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, hydrosulfurizer, 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 has a subcontract with CCDC to (1) conduct studies of dolomite sources, activity, and reconstitution, (2) study sodium removal from lignite, (3) investigate the environmental aspects of the acceptor process, and (4) conduct verification analyses using test samples provided from pilot plant operation.

Two other subcontracts were initiated during 1976. The Radian Corporation contracted to conduct an intensive analytical program pertinent to an environmental analysis of the carbon dioxide acceptor process. Stearns-Roger Company initiated a detailed economic analysis of the process, completing Phase I of the study by the end of the year.

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

PROGRESS DURING OCTOBER-DECEMBER 1977

Routine shutdown maintenance was completed following Run 47B at the beginning of the quarter. Plant inactivation procedures were initiated which included the complete final inspection of all vessels and lines by inspectors from Conoco's Maintenance Engineering Department. By the end of the quarter, the planned plant inactivation had been completed. Equipment records and inactivation procedures were filed.

Writing of the final report which covers the operation of the Rapid City pilot plant was also completed.

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

BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

Plant Site: Homer City, Pennsylvania
Contract No.: EF-77-C-01-1207
Contract Funding: \$66,000,000
DOE: \$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 DOE and the American Gas Association (AGA) as part of the effort to develop a method for producing high-Btu pipeline gas from coal. The pilot plant operational program is being managed by Phillips Petroleum Company.

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

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

Figure II-1 shows the overall program plan.

PROCESS DESCRIPTION

The BI-GAS process is a two-stage, high-pressure, oxygen-blown system using pulverized coal and steam in

an entrained flow. A diagram of the BI-GAS process is provided in Figure II-2.

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

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

Figure II-1. BI-GAS PROGRAM SCHEDULE

Figure II-2. BI-GAS PROCESS SCHEMATIC

rise through Stage 2, leave the gasifier at about 1700°F, and are quenched to 800°F by atomized water prior to separation in a cyclone. The Synthesis gas (containing carbon monoxide, carbon dioxide, hydrogen, water, hydrogen sulfide, and methane) passes through a scrubber for additional cooling and cleaning. The clean gas, along with the desired amount of moisture, is sent to

a carbon monoxide shift converter to establish the proper ratio of carbon monoxide and hydrogen required in the methanation process.

Three process steps follow shift conversion: hydrogen sulfide removal, carbon dioxide removal, and methanation. Three process alternatives are planned for investi-

gation. 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-product 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 OCTOBER-DECEMBER 1977

Summary

The most successful test to date was completed in November in the pilot plant when a 24 hour, steady-state

operating period was achieved while collecting three complete sets of laboratory samples. BCR also continued their laboratory support work with methanation catalyst studies.

Pilot Plant Operations

In the six tests conducted during the quarter, the gasifier was operated at a pressure of 750 psig with both fuel gas and char being fed to Stage I while coal was fed to Stage II.

Flux addition to reduce the viscosity at a given temperature of the slag formed in Stage I of the gasifier was adopted in early September. This practice was continued during the two tests in October. The last test in October caused solid deposits containing some partially calcined limestone to form in the lower half of Stage II. In an effort to eliminate these deposits, flux addition was reduced during the three tests in November. This reduction caused the percentage of calcium oxide in the formed slag to decrease from about 37 to about 29 percent. In addition, the quantity of deposits found in Stage II after each of the three November tests was less than that found after the last test in October.

The major objective of the tests at the beginning of the quarter was to maintain steady state, slag tapping operation for a 24 hour period. This was achieved in the second test in November. Coal was fed continuously to the spray drying system at a rate of three tons per hour for 46.5 hours. The gasifier was under pressure for 92 hours, with a total of 140 tons of coal fed.

The major objective of the third November Test, as well as the one test run in December, was to build a level of char in the char feed legs and the char cyclone vessel and to feed char in the "as designed" mode. This was not

accomplished, and at the end of the quarter, the plant was down for equipment repairs and modifications.

Ammonia formation of concentrations higher than 25 ppm in the settling pond continued to be a problem throughout the quarter.

Laboratory Research

Methanation catalyst studies continued during the quarter. The life tests of eight different samples of possible catalysts were completed. A recheck of two of the catalysts is planned for the future. The activities of the others were not sufficiently high to justify further consideration as PEDU candidates.

Data from PEDU Test No. 26 conducted in the previous quarter were evaluated. Results showed that the catalysts could be activated under the BI-GAS pilot plant start up conditions of 750 psig pressure, 520° F feed gas temperature, 550° F initial catalyst bed temperature, with a feed composition of 47 percent hydrogen, 16 percent carbon monoxide, 14 percent carbon dioxide, 8 percent methane, and 15 percent nitrogen. It also showed that the methanator could be operated successfully under conditions enhancing combined shift and methanation at hydrogen/carbon monoxide ratios as low as 1.1.

Methanation PEDU Test No. 27 was conducted in November. The primary objective of the test was to obtain data at feed gas hydrogen/carbon monoxide ratios in the range of 1.5 to 1.0. After the test was initiated, it was evident that the catalyst activity was lower than in previous PEDU tests with this catalyst. The reason for the low activity was uncertain and investigations were underway at the end of the quarter to determine the cause of catalyst deactivation.

III. PIPELINE GAS BY HYDROGASIFICATION (HYGAS PROCESS)

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois
Contract No.: EF-77-C-01-2434
Contract Funding: \$22,718,212
DOE: \$15,145,475
AGA: \$ 7,572,737

INTRODUCTION

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

The objective of this contract is to operate the HYGAS pilot plant facility with a mildly caking Illinois Bituminous Coal in order to develop an improved data base for the design of a commercial demonstration plant based on the HYGAS process. 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. Non-caking 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

Figure III-1. HYGAS PROGRAM SCHEDULE

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 from 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 the more reactive part of the incoming coal, forming additional methane. Approximately one-third of the methane in the final product gas is produced in this step.

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

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 of IGT under the sponsorship of AGA began in 1946, and continued under joint sponsorship with the Office of Coal Research (OCR). Responsibility has since been transferred to DOE. 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 high caking 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 OCTOBER-DECEMBER 1977

Summary

Two tests were conducted during the quarter to acquire data necessary to optimize the design of a commercial demonstration plant using the HYGAS process.

Discussion of Activities

Test 66 was conducted during October. The reactor was operated for nine days at coal conversions up to 85 percent. Steady-state self-sustained operations were achieved at a char feed rate of about two tons per hour.

Pretreater operation during the test was excellent. Eleven and one-half days of operation were recorded at an average coal feed rate of 1.9 tons per hour. A total of 534 tons of raw coal was processed through the pretreater at a temperature of about 760°F, producing non-agglomerating char from the HYGAS reactor. The quench section operated satisfactorily during Test 66. The purification section was put on stream during the test. Foaming continued to be a problem in the absorber tower. Due to the unsteady operation of the purification section, the methanation section was not put on-line for the test. The effluent cleanup section operated satisfactorily.

Test 67 was conducted in November for the purpose of high char conversion and a high char throughput during an extended run. Over 14 days of self-sustained operation were achieved, including six hours of operation at a feed rate of three tons per hour and at char conversions exceeding 85 percent. Sixty-five hours of char feed were logged at 2.5 tons per hour. Char conversion ranged from 46 to over 80 percent. Seven hundred and one tons of coal were fed to the pretreater and 589 tons of pretreated char were fed to the reactor over a feeding period of 328 hours.

The test was terminated because of problems in transferring char from the second stage gasifier to the steam-oxygen gasifier. Despite changes aimed at reducing foaming in the absorber tower, foaming still occurred although it was controlled at a steady rate.

During December, post-run plant inspection was completed following Test 67, and the plant was found to be in satisfactory condition. Preparations were made for Test 68, including a hot pressure test of the reactor necessitated by the extremely cold weather.

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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: \$13,502,647
DOE: \$9,335,432
AGA: \$4,167,215

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 DOE and the American Gas Association (AGA). DOE 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.	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 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 OCTOBER-DECEMBER 1977

Summary

Integrated operation of the producer and steam-iron reactor was achieved for a short period during October. One ore circulation test and one producer reactor test were also completed during the quarter. Laboratory studies completed included kinetics studies, char evaluation, and attrition studies.

Pilot Plant Operation

Ore circulation Test 10 was in progress at the beginning of the quarter. During the test, the ore circulation rate reached 70 tons per hour for over one hour. This was reduced to about 30 tons per hour because the bed-level valves operated too slowly at the higher circulation rates and allowed ore to accumulate in the upper beds.

During Test 11, completed in October, the producer and steam-iron reactors were operated simultaneously. Although the operation was of short duration (three hours) and temperatures were too low to produce hydrogen, iron ore circulation was maintained in the steam-iron reactor with the simultaneous gasification of char in the product reactor.

Test 12 was started early in November after the ore lift-line system was isolated from the steam-iron reactor. The objective of the test was to conduct a char feed test in the producer reactor while modifications were being made on the lift-line. Bed temperatures were elevated above 1600°F to study the effect on reducing-gas quality. Twelve hours of self-sustained operation were accumulated in the producer at bed temperatures ranging between 1600° and 1700°F and at a reactor pressure of 500 psig. Reducing gas was steadily produced, and concentrations of hydrogen and carbon monoxide exceeded 25 percent on a dry basis. During the test, a total of 126 tons of char was fed to the reactor at an average rate of one ton per hour. The slurry heater was by-passed during the test, and a char-water mixture was fed directly into the preheater zone and vaporized. Preliminary results indicated that carbon conversion in the preheater zone was higher because of the additional heat required to vaporize the slurry. The test demonstrated that preheater bed temperatures could be controlled while introducing air to the preheater zone and converting about 25 percent of the carbon in the bed.

After the test, modifications to the lift-line were completed and both reactors inspected. Heat up for the next test was started late in December.

Laboratory Tests

Kinetic Studies

The results of reactivity and attrition tests conducted previously with several iron-containing solids were evaluated. Three preferred materials, sintered Girdler Catalyst G—3A, IGT Iron-Magnesia 8, and Iron-Chromia 27 were selected for more detailed evaluation. Fifteen tests were conducted during November to determine the effects of temperature, pressure, and gas composition on the rate constants for the individual oxidation and reduction reactions encountered in the steam-iron reactor.

Char Evaluation

An analysis of the last two tests conducted during the previous quarter was completed. A final report was being prepared for this task.

Attrition Studies

Four tests were conducted with four size fractions of Husky lignite char to determine the effect of particle size on attrition in a cyclone. Results showed that increasing particle size from 91 to 160 microns increased the particle-size reduction due to attrition from 7.7 to 13.1 percent of the feed particle size. This completed the attrition studies and a final report was being prepared. A final report of Lift-Line Studies was also in preparation at the end of the quarter.

V. SYNTHANE PROCESS

THE LUMMUS COMPANY
BLOOMFIELD, NEW JERSEY

Plant Site: Allegheny County,
Pennsylvania

Contract No.: EY-76-0-02-0003-000

Contract Funding: \$37,180,000
(100% DOE)

INTRODUCTION

The Synthane process was developed by the Bureau of Mines and is now the responsibility of DOE. 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 40 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 gasifier fluidized bed through an injection pipe. Steam and oxygen enter the gasifier just below the fluidizing gas distributor. The gasification reaction occurs within the fluidized bed. Char flows downward into a bed fluidized and cooled with steam, and is removed with transport steam, slurried in water, and depressured through let down valves. In a commercial plant, 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 carryover 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

Figure V-1. SYNTHANE PROGRAM SCHEDULE

Figure V-2. SYNTHANE PROCESS SCHEMATIC

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 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 bench scale unit also yielded large quantities of high-Btu gas per unit weight of catalyst

(240,000 standard cubic feet per pound 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 to 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.
- No tar and oil with deep bed coal feeding.

Some of the disadvantages of the process are:

- Char is produced which must be utilized for steam production in an environmentally acceptable manner.
- Without deep bed coal injection, 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, Bruceton, Pennsylvania. Development work started with scattered research in several areas.

In 1961, work was started on methods of pretreating caking coals in fluidized beds. A preliminary design contract was awarded to M. W. Kellogg Company in August 1970 to determine if the data were sufficiently complete to proceed with design of the pilot plant. The contract was extended for additional gasifier tests and further evaluation of the Synthane project. Based on the results of the gasifier tests and the evaluation, the Bureau of Mines concluded that the process was feasible and the design could begin.

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

Construction of the Synthane pilot plant was completed in March 1975, and all areas and systems were transferred from the construction contractor to ERDA (DOE, as of October 1977). Through 1975 work concentrated on installation of auxiliary equipment and the

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

PROGRESS DURING OCTOBER-DECEMBER 1977

Summary

Efforts during the quarter were directed toward operating the pretreater with the mildly caking Illinois No. 6 coal which is an agglomerating coal. The 18-inch diameter pretreater was operated with fluid velocities ranging from 0.3 to 0.5 feet per second. In order to prevent agglomeration, it appears that this must be increased, and future plans include operation at higher velocities and possibly installing a smaller diameter pretreater to reduce the steam requirements. One run of 22 hours was achieved in December.

Discussion of Activities

The pretreater was operated during three runs in October. Carbon dioxide was used as the transport medium for the first two runs which were stopped after approximately one hour of operation due to agglomeration in the pretreater. The third run in October used steam as the coal transport medium. When the pretreater was opened after the third run, the vessel contained some agglomerated coal, but most of the bed was free-flowing and pretreated.

In November, two runs were made to operate the pretreater on Illinois No. 6 coal using carbon dioxide as the transport medium. Shortly after coal and oxygen were added, the pretreater agglomerated.

Four pretreater runs were completed in December using 1000°F superheated steam for coal transport rather than carbon dioxide. The use of 1000°F steam provided a mix temperature of 460°F to 550°F. Oxygen was also added in the lift line prior to entry in the pretreater to achieve some pretreatment in the line. The use of steam to transport the coal feed improved the pretreater operation, but did not prevent agglomeration. One run of 22 hours was achieved in December with all products from the pretreater analyzing 0.5 or less Free Swelling Index indicating satisfactory pretreatment.

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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: \$15,379,885
DOE: \$14,707,576
AGA: \$ 672,309

INTRODUCTION

The agglomerating burner gasification process is being developed by Battelle Memorial Institute, under the sponsorship of DOE. 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		

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 the 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, and currently, DOE.

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.

PROGRESS DURING OCTOBER-DECEMBER 1977

Summary

Attempts to achieve an integrated gasification run continued during the quarter. In a run conducted in December, the capability of the PDU to sustain the gasifier temperature by burning coal in the combustor only, and to maintain solids circulation was demonstrated.

Process Development Unit

One gasification attempt was made in October in the 25 ton-per-day coal gasification PDU, but was terminated when solids circulation lines were plugged and fused bed material accumulated in the combustor.

Approximately 2.5 hours of operation were completed during which time the system made producer gas.

In November, several modifications were made to the air distribution piping to reduce pressure losses, and a gasification run attempted. The modifications permitted operation at 90 psig while maintaining solids circulation between the combustor and gasifier. Inability to feed coal continuously, due to the high moisture content of the coal, caused the run to be terminated.

In a gasification attempt in December, solids circulation was maintained at a sufficient rate to provide adequate heat to the gasifier from combustion of coal in the combustor. The system pressure during much of the run was 90 psig with a period of operation at the design pressure of 100 psig. This run was the most successful attempt at an integrated gasification run to date, although it was terminated prematurely by a failure of a gasket in the gasifier.

VII. LIQUID PHASE METHANATION PROCESS

CHEM SYSTEMS, INC.

HACKENSACK, NEW JERSEY

Plant Site: Hackensack, New Jersey

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

Contract Funding: \$2,355,730
DOE: \$1,435,530
AGA: \$ 920,000

Contract No.: EX-76-C-01-2036

Contract Funding: \$1,483,744
DOE: \$1,303,996
Industry: \$ 179,748

INTRODUCTION

The liquid phase methanation process is being developed by Chem Systems, Inc., under the auspices of DOE and the American Gas Association (AGA). DOE 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 than can be used in the methanation process.
- Determine the catalyst particle size that will produce 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, recover, 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 in a single pass through the reactor. The effluent gases from

LEGEND:

- △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure VII-1. LIQUID PHASE METHANATION PROGRAM SCHEDULE

Figure VII-2. LIQUID PHASE METHANATION PROCESS SCHEMATIC

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 completed 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 aro-

matic and paraffinic hydrocarbon liquids can be used without being subjected to noticeable degradation and that commercially available catalysts are equally flexible. However, to maintain catalyst activity, it is necessary to maintain a hydrogen atmosphere when the system is not in operation.

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

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

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

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

All tasks under contract E(49-18)-1505 were completed during 1976 and work under contract E(49-18)-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 shakedown operations begun. By the end of the year all systems had been checked out.

PROGRESS DURING OCTOBER-DECEMBER 1977

Summary

Evaluation of data from pilot plant Run #4 performed last quarter resulted in the decision to modify the gas and

oil feed system to improve flow distribution within the reactor. A catalyst support screen was designed for catalyst withdrawal. The gas and oil spargers were modified to eliminate the use of inerts at the bottom of the reactor.

Laboratory support work during the quarter consisted of five runs in the bench-scale unit and the PDU.

Pilot Plant Operations

Analysis of results following Run #4 conducted last quarter indicated that there were hydrodynamic problems in the pilot plant reactor, possibly caused by spouting of the gas through the catalyst bed. To remedy this problem, several alternatives were considered to improve the flow distribution. A catalyst support screen was designed with a central hole and plug for catalyst withdrawal. The oil sparger was eliminated and replaced with a disperser plate. Gas sparger holes were decreased to half their cross-sectional area. With this arrangement, inerts are not required. The support system was ordered in November and installation began on December 28.

Alternate distribution systems were also studied. A prototype of an alternate design will be tested in the PDU next quarter. The pilot plant will remain at IGT until completion of the present development phase and experimental program. The next run is scheduled for January 1978.

Laboratory Studies

An improved Grace CRG-A extrudate was the subject of the laboratory support work during the quarter since this catalyst will be used in the pilot plant in the future. When the catalyst was reduced as recommended by the manufacturer, results indicated an unusually high activity, but poor physical strength. At lower reduction temperatures, the catalyst exhibited an activity comparable to other catalyst candidates and the physical strength was greatly improved. Further testing is necessary to verify an optimum reduction procedure where plugging of reactor and filter due to catalyst disintegration does not occur before the catalyst can be utilized in the pilot plant.

Construction of the carbon formation experimental unit began in October. The skid, consisting of five identical reactor systems, a master control panel, a gas booster compressor module and an analytical unit, was nearly completed.

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
DOE: \$3,819,679
AGA: \$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 DOE and the American Gas Association (AGA). DOE is providing two-thirds of the funds and AGA, 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 DOE 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 OCTOBER-DECEMBER 1977

Braun engineers visited the HYGAS, Carbon Dioxide Acceptor, BI-GAS and Synthane plants during the quarter to secure impact data for conceptual design of commercial size plants.

Consulting assistance was furnished to Chem Systems on the problems of proper distribution of inlet streams to the Liquid Phase Methanation reactor. (See Section VII).

Work also continued on process study areas during the period. In the area of effluent treatment, the estimation of installed capital cost for each of the process designs continued. Utility, catalyst, and chemical requirements were determined.

The final report comparing production of sulfuric acid as a by-product with the production of sulfur was prepared and submitted to DOE-AGA in December.

In the plant size study, the analysis of factors other than plant costs on the size of gasification plants continued throughout the quarter. Constraints on plant size considered were coal and water availability, social and economic impact on the localities, support distribution and gas price effects on the natural gas markets, and the financial limits on plant construction.

The final report of a comparison of Steam-Iron and Koppers-Totzek processes for commercial hydrogen production from char was completed and submitted to DOE-AGA, IGT, and Koppers. Capital cost estimates using private investor financing methods for the Steam-Iron and Koppers-Totzek processes were completed. An alternative also estimated was an integrated hydrogen plant where char and utilities were furnished at cost from a large parent coal liquefaction plant instead of produced from dedicated equipment. For this case, char storage and transportation costs were minimal. The hydrogen product specification was also relaxed by permitting higher levels of carbon oxides and sulfur compounds. The costs of producing hydrogen for the integrated plant were developed by using both private investor and utility financing methods as shown in the Gas Cost Guidelines.

A new Selexol design for BI-GAS was completed. Significant improvements were made on the selective Selexol units for Steam-Oxygen, BI-Gas and Synthane processes.

All design changes on the factored estimate work on lignite for the Carbon Dioxide Acceptor and Lurgi processes were completed and submitted for cost estimation during the quarter.

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: \$11,729,990
(100% DOE)

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 DOE. Figure IX-1 shows the program schedule.

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

PROCESS DESCRIPTION FOR GASIFICATION/COMBINED CYCLE POWER SYSTEM

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 gasi-

fication, (2) electric power generation, and (3) sodium carbonate regeneration. Figure IX-2 provides a schematic of the process.

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

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

LEGEND : △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure IX-1. MOLTEN SALT GASIFICATION PROGRAM SCHEDULE

Figure IX-2. MOLTEN SALT GASIFICATION/COMBINED CYCLE POWER SYSTEM PROCESS SCHEMATIC

taining 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, and recycled. The crystals are dried in a rotary kiln, and recycled to the molten salt furnace as regenerated sodium carbonate. The key advantages of the molten salt coal gasification process include the following:

- The process allows the use of a complete range of coal particle sizes, from $\sim 1/4$ in. down to fines. There is no requirement for close sizing of the coal, removal of fines, or coal pulverization. Only crushing is required to a size small enough to allow pneumatic transport of the coal ($< \sim 1/4$ 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, Predecessor of DOE, 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, predecessor of DOE, 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 responsible for the entire detailed design and this work began in November 1976. By September 1977, detailed design, most of the procurement, and a large part of the construction had been completed.

PROGRESS DURING OCTOBER-DECEMBER 1977

Design and construction of the one-ton-per-hour Process Development Unit continued throughout the quarter.

In order to keep on schedule, AI established a task force to produce specifications and drawings for installing the solids handling equipment. During the quarter,

the preparation of an engineering package for construction of the solids handling system was completed. Requests for bids were solicited in mid-December with replies requested by the first week in January.

Preparations were also initiated during the quarter for startup of the PDU. A preliminary plan of action was prepared showing the anticipated program activities, related schedules, and manpower levels which will be required to support the PDU startup and subsequent operation. Work was also initiated on the preparation of an Operation and Maintenance Manual.

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)
DOE: \$29,303,105
Industry: \$ 4,000,000

INTRODUCTION

The advanced coal gasification system for electric power generation is being developed by Westinghouse Electric Corporation. DOE 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

system. 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 advance 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

Figure X-1. ADVANCED COAL GASIFICATION PROGRAM SCHEDULE

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

coal and temper the hot inlet gases flow downward in the fluidized bed surrounding the draft tube. The fluidizing 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 gasification zone by combustion gases flowing upward and by char circulating between the combustion and gasification zones. 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 OCTOBER-DECEMBER 1977

Summary

Gasifier tests were conducted during the quarter to complete the evaluation of reactor performance with high fines loading, with FMC char, and with direct coal feed.

It was demonstrated that air transport of fines through the coaxial feed nozzle was a viable means of reducing freeboard velocities. One test in November demonstrated

that the gasifier could be operated with a wide range of feedstock characteristics in terms of composition, particle size, and reactivity.

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

Process Development Unit

Gasifier Test TP-012-6 was begun in October. The top of the air tube was nine inches below the bottom of the grid plate and the coaxial fines feed line recessed three inches in the air tube. No annulus area reduction was used, and the combustor was not used. Air transport of char fines were employed to reduce heat load and freeboard velocity. Approximately 72 hours of run time at combustor agglomerating temperatures of 1990°F were achieved. Although the test was prematurely shut-down, the following accomplishments were achieved:

- Char fines were transported to the reactor using air instead of recycle gas for the first time, resulting in net savings on gas throughput and reactor heat load.
- It was found that adequate ash/char separation could be maintained in the ash collection annulus at substantially lower fluidizing rates than had been previously used. This resulted in throughput and heat load advantages.
- FMC char produced in the COED pilot plant was fed to the reactor for the first time. This highly reactive char increased the gasification efficiency of the unit and produced product gas with about 20 percent carbon monoxide, nine percent hydrogen, and nine percent carbon dioxide. During this portion of the test, about 700 pounds per hour of FMC char were fed to the reactor along with 540 pounds per hour coke breeze. About 509 pounds per hour carbon were consumed.
- Only a minimal slag buildup was noted on the reactor walls and exit pipe following the test. The clean condition of the reactor was apparently the result of operating at a lower temperature than had previously been used.

Following the test, the reactor was cleaned and prepared for Test TP-014, a feasibility demonstration with PDU and FMC chars. The same air-tube configuration was used as in the previous test. During TP-014-1, a number of equipment and operational problems occurred. Despite this, controlled combustion and gasification were achieved with PDU Minnehaha char, and ash agglomerates ranging in ash content from 60 to 70 percent were continuously produced at 1800°F. The test

demonstrated that greater than 90 percent carbon utilization for the overall process can be achieved using Indiana No. 7 seam coal as devolatilizer feedstock. Fines elutriation was reduced by using air as a transport medium for fines and resulted in a lower freeboard velocity and high fine utilization in the combustion jet.

The second test conducted in November, TP-013-2, was a feedstock evaluation test. Since the previous demonstration test had been terminated after 60 hours of operation, TP-013-2 was planned as a long duration test to demonstrate gasifier operability. The primary goal was to operate the gasifier combustor-agglomerator successfully with Pittsburgh and Upper Freeport seam coal chars produced in the PDU and with FMC-COED chars produced from Utah and Western Kentucky Coals. In addition, test periods with two coal feedstocks, Indiana No. 7 and Wyoming subbituminous coals, were planned to evaluate the ability of the gasifier to operate the undevolatilized and unpretreated materials. Some equipment difficulties were experienced during the test, but despite these difficulties, all of the test points were achieved and the test successfully completed all the major objectives. The test was successful in demonstrating that the gasifier could be operated with a wide range of feedstock characteristics in terms of composition, particle size, and reactivity. During the test, 16.5 tons of coke breeze were processed along with 14 tons of PUD char, 2.8 tons of Minnehaha coal, 16.5 tons of FMC Utah char, and 12.5 tons of FMC Western Kentucky char. Agglomerated ash was produced in all cases, and reactor temperatures were held between 1775°F and 1990°F. Ash concentrations in the agglomerates ranged from 60 to 80 percent giving overall process carbon utilization of 90-96 percent. The run marked the first time FMC char was successfully agglomerated to produce 80 percent ash product. It was also the first time PDU Pittsburgh seam char was successfully combusted, gasified and agglomerated; and it was the first successful use of direct coal feed to the gasifier without benefit of pretreatment or devolatilization. The test was terminated by loss of ash withdrawal.

Following the test, a minor equipment change was implemented prior to Test TP-013-3, conducted in December to evaluate gasifier operability with various coal feedstocks. The primary goal of the test was to explore the feasibility of feeding coal directly to the gasifier without the benefit of pretreatment or devolatilization. The candidate coals chosen were a non-caking Wyoming subbituminous coal, a mildly-caking Indiana No. 7 from the Minnehaha mines, and a highly-caking Pittsburgh seam from Consolidated Coal's Champion facility. The operating philosophy for the two caking coals was to feed them coaxially with the air jet and recycle the fines through the radial port. Wyoming

coal, being non-caking, was fed radially into the reactor. A total of 75 hours of gasifier operation was logged in the test. During that time, 15 tons of Minnehaha coal, 5 tons of Champion coal, and 16.8 tons of Wyoming coal were processed. In addition, 11 tons of coke breeze and three tons of FMC Utah char were used as substitute feed material during periods of inventory changeover. Reactor temperatures were held between 1720° and 1770° F. The heating value of the product gas fell in the range of 69-129 Btu/scf. The ash particles discharged from the agglomerator were angular in shape with ash contents of 37 to 69 percent. At the conclusion of the test, an emergency shutdown was initiated as a consequence of a fire on the PDU structure due to a procedural failure. Post test inspection revealed no damage to the refractory, and fire damage to the process structure consisted of minor wiring and instrumentation overheating.

Support Studies

Laboratory studies included support tasks for the current PDU combustor-gasifier test program, preparation for integrated operation, coal behavior studies, ash behavior studies, and reactor analysis. Study of the mechanism of deposit formation on the walls of the gasifier also continued throughout the quarter.

The first phase of the test program for the distributor plate design studies for integrated operation was completed. Altogether, two distributor plate designs were studied in the test program. The 60° conical plate was located at three different positions, 14.1 cm, 21.7 cm, and 29.3 cm from the draft tube inlet. The 45° conical plate was studied only at one location, 21.7 cm from the draft tube inlet. The preliminary conclusions were:

- The solid circulation rate depends on the distance of the distributor plate from the draft tube inlet; the greater the distance (over the range tested) the higher the solid circulation rate.
- The performance of the 60° and 45° conical plates was essentially similar in terms of solid circulation rate; however, a stagnant region exists on the 45° conical plate, but not on the 60° cone. The distributor plate location at 29.3 cm and the jet nozzle at 21.7 cm gave the best performance at similar operating conditions. That configuration minimized the startup problem by locating the jet nozzle at the higher position and also took advantage of higher solid circulation rate by lowering the distributor plate position.

Porosity measurements and ash agglomeration experiments also continued during the quarter.

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XI. LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT

Plant Site: Windsor, Connecticut
Contract No.: EX-76-C-01-1545
Contract Funding: \$24,609,084
DOE: \$16,439,389
Industry: \$ 8,169,695

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 DOE and an industry team composed of Combustion Engineering and the Electric Power Research Institute. DOE is providing two-thirds of the funds and the team, one-third. The overall objective of this program is an economical low-Btu coal gas to generate electricity 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 pilot plant. The objectives of this program are to:

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

Combustion Engineering also has a continuing research program to refine the process and verify its technical and economic feasibility. The schedule for

development of this low-Btu gasification process is provided in Figure XI-1.

PROCESS DESCRIPTION

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 endothermic 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. The 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 is produced by the Stretford process. The clean low-Btu gas (127 Btu per standard cubic foot) can then be delivered to the

Figure XI-1. LOW-BTU GASIFICATION PROGRAM SCHEDULE

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

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 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, located at Windsor, Connecticut, has a capacity of five tons of coal per hour. The objectives of this phase included (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 the 1975, the designs of many of the subsystems were nearly completed, and request for quotations were issued for various components. About 30 percent of the major equipment for the process development

unit had either been approved for purchase or released for fabrication by the end of 1975. Plot plans and general equipment arrangements were completed, and preparation of the construction site for excavation and foundation installation was started. Some work had been done on establishing operating procedures and developing a test plan for evaluating the performance of the gasifier during steady state operation. Construction was completed in Fall 1977 and operations are expected to continue until early-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 OCTOBER-DECEMBER 1977

All Research and Development Task of Phase I of the contract were completed and reports issued for all but two of the tasks: Evaluation of Design Parameters for Slagging Furnaces and the Study of Electric Plant Applications.

A dedication ceremony marking completion of PDU construction was held at the plant site on October 18, 1977. Preparations for initial coal firing of the PDU continued throughout November and the first attempt to fire coal in the gasifier's combustor was made on December 4, 1977. Problems were encountered in the plants pulverizing system preventing sufficient coal feed for firing. Necessary corrective actions were taken and coal firing was scheduled for mid-January, 1978.

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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% DOE)

INTRODUCTION

Bituminous Coal Research (BCR) is developing a multiple fluidized-bed coal gasification process for producing low-Btu fuel gas from caking and noncaking coals. The project is being sponsored by DOE. 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 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 Division of Dravo Corporation, and construction was completed in September 1975.

LEGEND:

- ▲ BEGIN MILESTONE
 ▼ COMPLETE MILESTONE

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

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

Concurrent with the construction effort, BCR is conducting laboratory research in an effort to further refine the low-Btu fuel gas process. During 1975, laboratory research included using a coal 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 OCTOBER-DECEMBER 1977

Test No. 3S-10 was completed in the Stage 1 reactor during October. The purpose of the test was to determine the effectiveness of moving the Stage 1 cyclones closer to the reactor and water-jacketing the tar sample pot. The effect of lower oxygen concentration, coupled with higher fluidization velocities, in eliminating ash agglomeration on the Stage 1 grid plate was also explored. Coal was fed to the Stage 1 reactor continuously for about 11 hours until the supply of coal in the lock hopper was exhausted and the test was ended. There were no problems with coal feed or char withdrawal during the entire test. After the reactor cooled, the bottom was removed and no ash agglomerates were found on the grid plate, indicating that gas velocities used during the test (30 times minimum fluidization) were sufficient both to prevent ash agglomeration and to prevent severe elutriation of fines from the reactor.

During November, Test 3S-11 was completed in the Stage 1 reactor. Purpose of the test was to study the decomposition of tars produced in Stage 1 in an oxidizing atmosphere. The devolatilization products from Stage 1 were to be passed through a bed of char in Stage 2. A hole developed in the Stage 2 cyclone requiring the removal of Stage 2 from the system. As a result, the test was

conducted through two separate steady-state periods in which tars produced from the Stage 1 reactor were sampled and analyzed. In addition, the char produced during these periods was sampled for analysis. During Test No. 3S-11, 1600 pounds of Rosebud coal were fed to Stage 1, and 830 pounds of char were removed from the ash lock hopper. Coal and char analysis for Test no. 3S-11 was:

Test 3S-12 was conducted in December to investigate the devolatilization of Illinois No. 6 coal in the Stage 1 reactor. The test was terminated shortly after coal feed was initiated due to a blockage in the Stage 1 outlet line.

	Rosebud Coal (BCR Lot 3785)	1000 F	900 F
Volatile Matter	41.1	*	*
Fixed Carbon	46.9	*	*
Sulfur	0.94	1.38	1.38
Ash	12.0	18.4	17.9
	100	100	100
Moisture	17.2	0.85	0.43
Carbon	66.9	72.8	72.9
Hydrogen	4.45	2.57	2.80
Nitrogen	1.01	1.12	1.18

*Indeterminable due to "sparkling" as explained in ASTM Standard D-271.

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XIII. THE COAL CONVERSION SYSTEMS TECHNICAL DATA BOOK

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Contract No.: EX-76-C-01-2286
Contract Funding: \$840,000
(100% DOE)

INTRODUCTION

The Coal Conversion Systems Technical Data Book is being prepared by the Institute of Gas Technology (IGT) under DOE 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 DOE'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 Heat of Reaction

- Section IV: **DESIGN PROCEDURES**
A. Conversion Tables and Constants
B. Fluidization
C. Fluid Flow
D. Heat Transfer
E. Phase Separations
F. Integrated Reactor Design
- Section V: **SUPPORTING PROCESSES**
A. Gas Treating
B. Gas Purification
C. Shift Conversion
D. Methanation
E. Environmental Control
- Section VI: **MISCELLANEOUS PRODUCTS**
A. Methanol
B. Acetylene
C. Ammonia
D. 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 OCTOBER-DECEMBER 1977

Summary

The first edition of the Technical Data Book was prepared and distributed to Special Consultants for comments and suggestions during the quarter.

Work on the Properties of Process Materials included analysis of equilibrium data, presentation of real gas

properties of benzene and presentation of the properties of coal liquids.

Conversion Fundamentals dealt with pyrolysis yields and synthetic sorbents in fluidized-bed combustion. Design procedures investigated gas-solids transport and coal-liquid slurry heating. In the area of Materials of Construction, data from the HYGAS process were reviewed.

Properties of Process Materials

Correlation equations that were used in the preparation of charts showing partial pressure of NH_3 and H_2S in the $\text{NH}_3\text{-H}_2\text{S-H}_2\text{O}$ subsystem were summarized and the calculation procedure described. The new calorific value correlation was tested with data on coal chars. The material developed on specific heats of coal, char, and ash was prepared for the Data Book presentation. The real gas thermodynamic properties of benzene were presented. The vapor-liquid equilibrium data for hydrogen and four different solvents were given. A table of properties of pure chemical compounds which were expected to be components of coal liquid were also prepared for inclusion in the Data Book.

Conversion Fundamentals

In the area of pyrolysis, work continued on correlation of tar and light oil yields for lignites and subbituminous coals as well as correlation of water produced by pyrolysis and the oxygen content of the coal. Potential synthetic sorbents for absorbing sulfur dioxide in fluidized-bed combustion were reviewed and discussed.

Design Procedures

Pressure-drop correlations were compiled for horizontal, dilute phase gas-solid transport. The work in coal-solvent slurry heating continued with the comparison of experimental and calculated bulk fluid temperatures in additional SRC slurry pre-treater runs.

Materials of Construction

In the area of materials of construction, failure analysis data on HYGAS were reviewed and summarized.

XIV. COMPUTER MODELING OF COAL GASIFICATION REACTORS

SYSTEMS, SCIENCE, AND SOFTWARE
LA JOLLA, CALIFORNIA

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

Contract Funding: \$1,352,776
(100% DOE)

INTRODUCTION

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

PROGRAM DESCRIPTION

This project began in June 1975 and will require three years to complete. Work during the first year dealt with multiphase fluid flow without chemical reactions and heterogeneous chemical reaction without fluid flow. The

objective of these studies was to establish a firm theoretical description of the thermodynamics, hydrodynamics, and chemical behavior of high-Btu gasification reactors through the development of computer models of the essential features of the processes. The results of the studies will then be compared with experimental 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 pro-

vide 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, 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.

Theoretical effort continued to provide the structure for modeling interphase exchange processes in the combined chemistry-thermodynamic computer representation of the fluidized bed during 1976. Work also continued on the formulation of the steam-oxygen gasification process.

PROGRESS DURING OCTOBER-DECEMBER 1977

Subcontract work during the quarter included the continuation of analytical studies of the chemistry of steam-

oxygen gasification by Professor C. Y. Wen of West Virginia University. Professor Paul Libby of the University of California, San Diego, also continued his analytical studies of the heterogeneous and homogeneous reactions and transport processes associated with the oxidation of carbon particles. He has extended his model to include the influence of particle porosity upon the overall reaction rate control in such heterogeneous processes.

Research continued on the application of the axisymmetric and planar versions of the fluidized-bed code. Specific calculations of bubble development as a function of mass flow rate, bed height and distributor plate geometry were performed. These calculations were compared with experimental data and theoretical models of bubble formation in a fluidized bed. There was agreement between the numerical representation and both the theoretical and experimental results on such aspects as bubble size, shape and velocity.

The study of the Synthene reactor was continued throughout the quarter. Previous calculations of jet and bubble formation and solid particle mixing at the distributor plate were examined and theoretical representations of jet penetration were studied.

The study of simplifications in the theory and numerical formalism used in the fluidized-bed model continued during the quarter, and modifications made to the methodology used to calculate gas phase transport of chemical species.

A study of transient, three dimensional entrained flows using the entrained flow code developed last quarter was continued. A comparison between the two dimensional transient entrained flow code calculations and exact solutions showed excellent agreement between the numerical and theoretical representations. Experimental data from the Foster Wheeler cold flow model were examined and the potential application of the two and three dimensional models to that and similar design configurations were discussed.

The development of a heterogeneous model for coal/char devolatilization continued. The analytical study of heterogeneous and homogeneous reactions for char particles in a quiescent oxidizing environment was also continued. Both finite rate heating and porous particle structure were examined.

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

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Project Site: Chicago, Illinois
Contract No.: EX-76-C-01-2336
Contract Funding: \$2,484,318
(100% DOE)

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 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.

**Figure XV-1. ASH—AGGLOMERATING
GASIFICATION PROJECT SCHEDULE**

PROCESS DESCRIPTION

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

Figure XV-2. ASH-AGGLOMERATING GASIFICATION PROCESS SCHEMATIC

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

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.

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

PROGRESS DURING OCTOBER-DECEMBER 1977

Summary

Work during the quarter continued with tests to determine operating conditions necessary to sustain ash agglomeration with a raw coal feed. The last test with Montana subbituminous coal was completed in October and tests during the rest of the quarter used Illinois No. 6 coal. The evolved product gas contained no volatiles or

tars. Fluidized-bed temperatures up to 1875°F were attained by gasifying with mixtures of air, steam, and oxygen. Although there was evidence of coal ash in the low carbon agglomerates produced, ash had sintered in the bed.

Gasifier Operations

Two runs conducted during October. Run 111 was the final run with Montana subbituminous coal as the supply was exhausted with the completion of the run. Though fines recirculation had significantly improved carbon conversion to 92 percent, ash agglomeration could not be achieved.

Because of the subbituminous coal's high reactivity and moisture content, which could not be removed without significant size reduction, the operating temperatures in the gasifier were limited to those which precluded ash agglomerate formations. Consequently, a Utah bituminous coal, expected to produce higher operating temperatures, was ordered.

While awaiting delivery of the Utah coal, tests during the remainder of the quarter were conducted with a caking Illinois No. 6 coal. Run 112 in October, was a 60-hour test, and yielded a bed temperature of 1780°F, 100 to 150°F higher than achieved with the subbituminous coal. No tars were evolved with the product gas obtained. Higher fluidized-bed temperatures are apparently needed to achieve complete ash agglomeration with this coal.

Three runs were conducted in November. In each of the three tests, direct feeding of coal to the bed was utilized. There was no direct evidence of coal caking or tar evolution through accumulation on equipment or absorption by the fines. By adding oxygen, temperatures up to 1780°F to 1875°F were attained. While these temperatures were sufficient for coke ash agglomeration, continuous coal ash agglomeration was not demonstrated. In each of the tests, ash sintering or slagging occurred to terminate the flow of venturi discharge material.

Modifications were made to the reactor, consequently, to enable the grid and venturi surface to be visually scanned. The venturi section of the grid was modified to improve turbulence in the center of the unit above the venturi.

During test Run 116 in December, oxygen was introduced directly into the bed after rerouting the oxygen jet line to enter the grid through a fluidizing nozzle. An average fluidizing bed temperature of 1830°F was attained during the 12-hour run period. The run was terminated when the natural venturi discharge ceased.

Run 117 was initiated and was to be conducted at a higher fluidization velocity (3 to 4 feet per second) with direct fines reinjection into bed to provide increased turbulence for the coal particles. An early coke feed interruption while still in the start-up phase necessitated a shutdown when clinker formation occurred.

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

Specific gravity, 60° F/60° F.

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.

62 **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-steam mixture through a hot bed of coke, having a higher heating value of about 120 Btu per standard cubic foot.

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

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

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

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

slurry—a suspension of pulverized solid in a liquid.

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

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

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

solvent refined coal (SRC)—a coal extract derived by solvent extraction; a brittle, vitreous solid (m.p. 300°F to 400°F) 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.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

water gas—gas produced by the reaction of carbon (in coal or coke) and steam to yield mixtures of carbon monoxide and hydrogen; similar to synthesis gas.

water gas shift—the reaction between water vapor and carbon monoxide to produce hydrogen and carbon dioxide or the reverse: $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{H}_2 + \text{CO}_2$.

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