COAL GASIFICATION

QUARTERLY REPORT

Philip C. White
Assistant Administrator
for Fossil Energy

Raymond L. Zahradnik
Director
Division of Coal Conversion and Utilization

Energy Research and Development Administration
20 Massachusetts Avenue, N.W.
Washington, D.C. 20545

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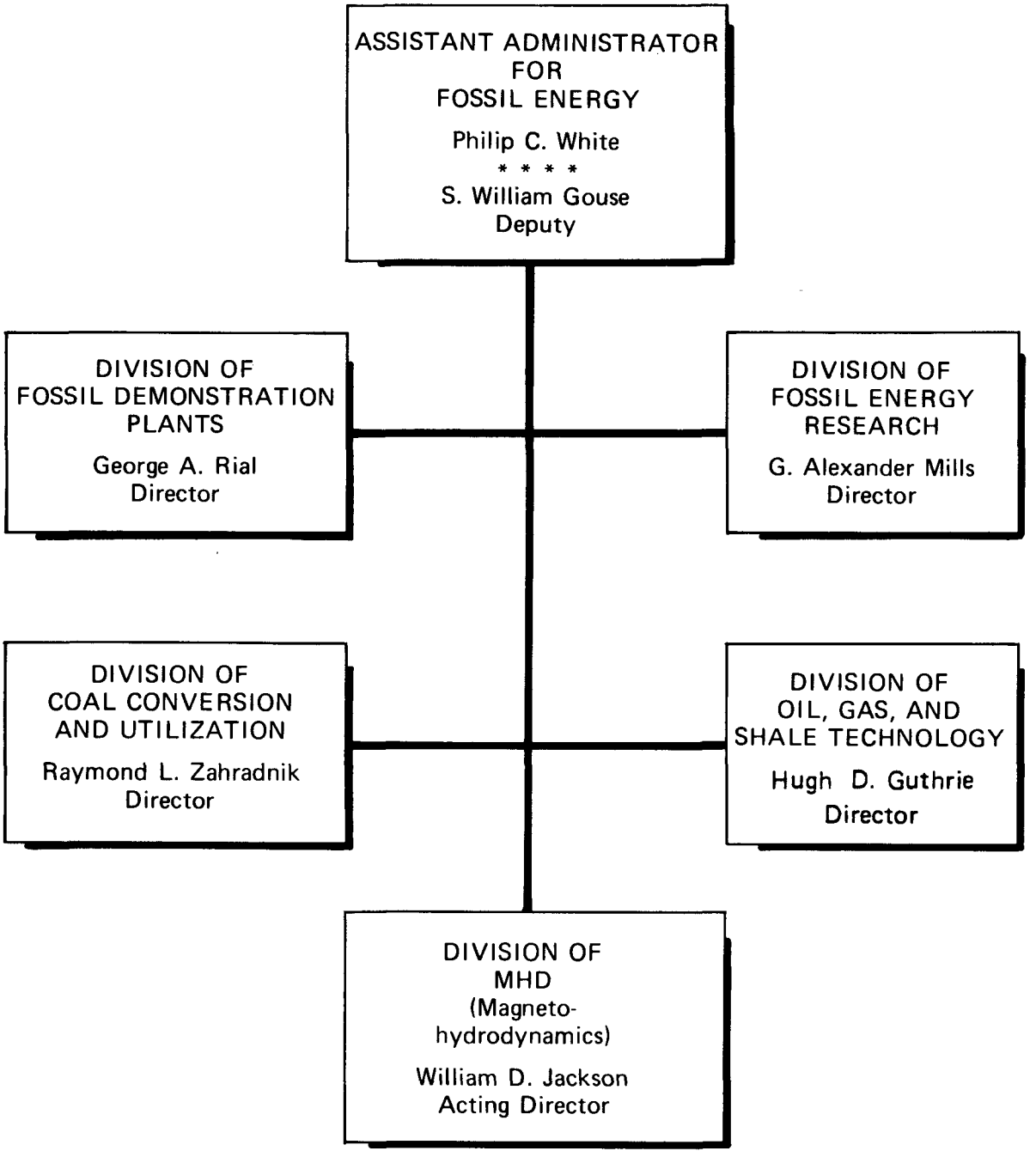

ASSISTANT ADMINISTRATOR FOR FOSSIL ENERGY
Philip C. White
* * * *
S. William Gouse
Deputy
DIVISION OF FOSSIL DEMONSTRATION PLANTS
George A. Rial
Director
DIVISION OF FOSSIL ENERGY RESEARCH
G. Alexander Mills
Director
DIVISION OF COAL CONVERSION AND UTILIZATION
Raymond L. Zahradnik
Director
DIVISION OF OIL, GAS, AND SHALE TECHNOLOGY
Hugh D. Guthrie
Director
DIVISION OF MHD (Magneto-hydrodynamics)
William D. Jackson
Acting Director

EXECUTIVE SUMMARY

The United States has more energy available in coal than in petroleum, natural gas, oil shale, and tar sands combined. Nationwide energy shortages, together with the availability of abundant coal reserves, make the commercial production of synthetic fuels from coal vital to the Nation's total supply of clean energy. In response to this need, the Office of Fossil Energy of the Energy Research and Development Administration (ERDA) is conducting a research and development program to provide technology that will permit rapid commercialization of processes for converting coal to synthetic fuels and for improved direct combustion of coal. These fuels must be suitable for power generation, transportation, storage, and residential and industrial uses.

The technologies selected for development—gasification, liquefaction, and combustion—satisfy an urgent need for a particular type of fuel, are potentially feasible both technically and economically (in terms of the costs of research and development and the final product), and will not exceed the air, water, and solid pollution standards established by the Environmental Protection Agency (EPA). The emphasis given each technology varies, depending on such things as technical complexity, development stage (laboratory research, including bench-scale tests as well as experiments with process development units, and pilot plant design, construction, and operation), variety of uses for the fuel produced, and urgency of the need that the technology is designed to satisfy.

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

HIGH-BTU GASIFICATION

High-Btu natural gas has a heating value of 950 to 1,000 Btu per standard cubic foot, is composed essentially of methane, and contains virtually no sulfur, carbon monoxide, or free hydrogen. The conversion

of coal to high-Btu gas requires a chemical and physical transformation of solid coal. However, because coal has widely differing chemical and physical properties, depending on where it is mined, it is difficult to process. Therefore, to develop the most suitable techniques for gasifying coal, ERDA, together with the American Gas Association (AGA), is sponsoring the development of several advanced conversion processes.

Although the basic coal-gasification chemical reactions are the same for each process, the processes under development have unique characteristics. There are, for example, important differences in reactor configurations and methods of supplying heat for gasification. Moreover, because these processes require high temperatures and some require high pressures, temperature-resistant alloys and new pressure vessels must be developed to obtain reliable performance.

A number of the processes for converting coal to high-Btu gas have reached the pilot plant stage. 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. Battelle Memorial Institute is responsible for designing, constructing, and operating a process development unit in West Jefferson, Ohio, for demonstrating the agglomerating burner process. These companies are also responsible for continued laboratory research to develop data for verifying the feasibility of the specific process and for supporting the operation of the plant.

A liquid phase methanation process is being developed by Chem Systems, Inc. C. F. Braun and Company is providing technical evaluations of these 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.

Four pilot plant runs made at the ***Carbon Dioxide Acceptor Process*** pilot plant used Texas lignite and Wyodak subbituminous coal as feedstock. The fourth test run was of sufficient duration to provide the first reliable gasification kinetic data for subbituminous coal. Testing of synthetic acceptors began during the quarter in the new fluidized-bed reactor. Studies of melt composition and corrosion effects also continued.

Work on the ***BI-GAS Process for the Generation of Pipeline Gas*** included life tests of four different methanation catalysts. Repair of the Homer City pilot plant was completed during the quarter and operations began. Baseline conditions were established and maintained until all of the objectives of the test were achieved.

The most successful run to date was completed in the ***HYGAS Process*** pilot plant during the quarter. The run was the last of a series of tests on subbituminous coal, and processed a total of 753 tons of coal wih coal conversion rates of 70 to 80 percent. Evaluation of candidate Illinois Basin bituminous coals began, and results of preliminary tests indicated that the coal from the Peabody No. 10 mine should be used in the initial tests to study the effects of carbon conversion, pretreatment severity, and fines recycling. Several areas of the plant were studied in detail to obtain improved operations for further testing, and necessary modifications and improvements were completed.

The ***Synthane Process*** pilot plant achieved two of the best operating periods to date. After runs of short duration at the beginning of the quarter, new operating conditions to prevent clinker formation were specified, resulting in improved gas production. The inoperability of the internal cyclone in the gasifier, caused by the plugging of the dipleg with fines and tar, continued to be a major problem during the quarter.

A reorientation of project priorities of the ***Agglomerating Burner Process*** occurred during the quarter. The new objective will be to demonstrate that gas can be produced by establishing the basic operability of the PDU within the present time and dollar constraints. Work was designed to obtain and verify data for the calculation of solids circulation rates. Modifications were made in the coal grinding and feeding sections before processing the first shipment of Rosebud coal.

The ***Liquid Phase Methanation Process*** pilot plant was shipped to the IGT HYGAS plant in Chicago, Illinois, during the quarter. It was reassembled and shakedown operations begun. Three catalyst tests were conducted in the bench-scale unit on CRG-A tablets, the extrudate form of the catalyst, and an Englehard nickel catalyst.

Process engineers from C. F. Braun visited the HYGAS, carbon dioxide acceptor, BI-GAS, and Synthane plants for the ***Evaluation of High-Btu Gasification Projects.*** Reports were drafted on the comparison of acid gas removal processes and cost comparisons for fixed-bed methanation processes. The report on the single-step total sulfur recovery was submitted to ERDA-AGA for review. A comparative study of the steam-iron process for hydrogen production and a more conventional process such as Koppers-Totzek was begun. The final

report dealing with the commercial design for Western coal was compiled and sent to be printed.

LOW-BTU GASIFICATION

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

Responsibility for designing, constructing, and operating facilities for testing low-Btu gasification processes has been assigned to Atomics International Division for a molten salt gasification process; Westinghouse Electric Corporation for an advanced coal gasification system for electric power generation; Combustion Engineering, Inc., for low-Btu gasification of coal for generating electricity; Foster Wheeler Energy Corporation for a coal gasification combined-cycle system for electric power generation; Bituminous Coal Research, Inc., for a low-Btu fuel gas process; and the Institute of Gas Technology for the modification and operation of an ash-agglomerating gasifier. In each case, laboratory research is also being conducted to resolve process problems and improve overall process designs.

Air Products and Chemicals, Inc., is conducting a support program involving desulfurization of low-Btu producer gas in a fixed bed of iron oxide on fly ash; a technical data book is being developed by the Institute of Gas Technology to provide a single, comprehensive source of data on coal conversion processes; and Systems, Science, and Software is developing a general computer model of coal gasification reactors.

It was decided that Atomics International (AI) would conduct all the detailed design work for the process development unit (PDU) for the ***Molten Salt Gasification Process.*** The gasifier was redesigned and simplified, site layout prepared, and the soil survey completed. An application to construct the PDU was submitted to the District Director of the Air Pollution Control District in December.

During the quarter an analysis of devolatilizer test data for all the tests conducted in the past year on the ***Advanced Coal Gasification***

System for Electric Power Generation was performed. The effects of various parameters on the growth or attrition of particles on the devolatilization process was determined. In the gasifier section of the PDU, initial shakedown tests were completed. Primary PDU support activities were directed to support the combustor-gasifier operation.

By the end of the quarter, an estimated 38 percent of the entire plant construction of the process development unit for the ***Low-Btu Gasification of Coal for Electric Power Generation*** was complete. The site preparation, prefabricated buildings, and the structural steel and grating work were completed. With the exception of the slag and refractory compatibility evaluations, and study of electric plant applications, all research and development work was completed and preparation of the final task report review was continuing.

Throughout the quarter, Foster Wheeler, in conjunction with the other industry team members, continued to develop the ***Coal Gasification Combined-Cycle System for Electric Power Generation*** pilot plant.

Devolatilization/pretreatment tests of the ***Low-Btu Fuel Gas*** project used Illinois No. 6 seam coal as the feed to Stage I. Tests during the quarter identified a control problem in the system. Consequently, a new system to control bed height was developed, and a cold test was conducted to demonstrate the feasibility of the system. Modifications allowing three-stage operation of the process and equipment development unit were also completed.

During this reporting period, the experimental phases of the ***Desulfurization of Fuel Gas*** contract were completed, and preparation of the final project report began. The report is expected to be completed during the first quarter of 1977.

Data continued to be collected for the ***Coal Conversion Systems Technical Data Book.*** Studies and reviews were presented on the properties of process materials, solids storage, conversion fundamentals, design procedures, and supporting processes.

Communications between S^3 staff members and noted consultants in the gasification field continued in the area of ***Computer Modeling of Coal Gasification Reactors.*** A review of the fluidized-bed computer model was presented at the ERDA Conference on Computerized Mathematical Modeling of Coal Conversion Processes. A paper, summarizing some of the theoretical and numerical aspects of the model, was presented at the Annual Meeting of the American Institute of Chemical Engineers.

The ***Modifications and Operation of an Atmospheric Pressure Ash-Agglomerating Gasifier*** continued during the quarter with the fabrication of the 85-foot-high silo completed. The shop-fabricated four-foot-diameter cold model of the ash-agglomerating gasifier reactor was erected and modification completed in November. The rough plumbing, sewage, and concrete work was completed.

I. CARBON DIOXIDE ACCEPTOR COAL GASIFICATION PROCESS

CONOCO COAL DEVELOPMENT COMPANY
LIBRARY, PENNSYLVANIA

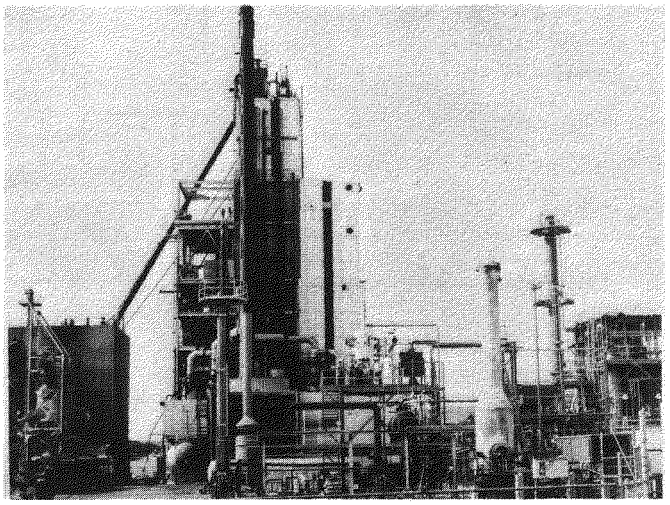
Plant Site: Rapid City, South Dakota

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

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

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

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



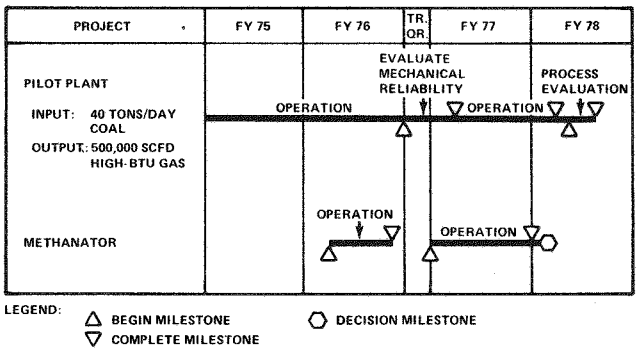


Figure I-1. CARBON DIOXIDE ACCEPTOR PROGRAM SCHEDULE

INTRODUCTION

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

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

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

Figure I-1 shows the development schedule.

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 × 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

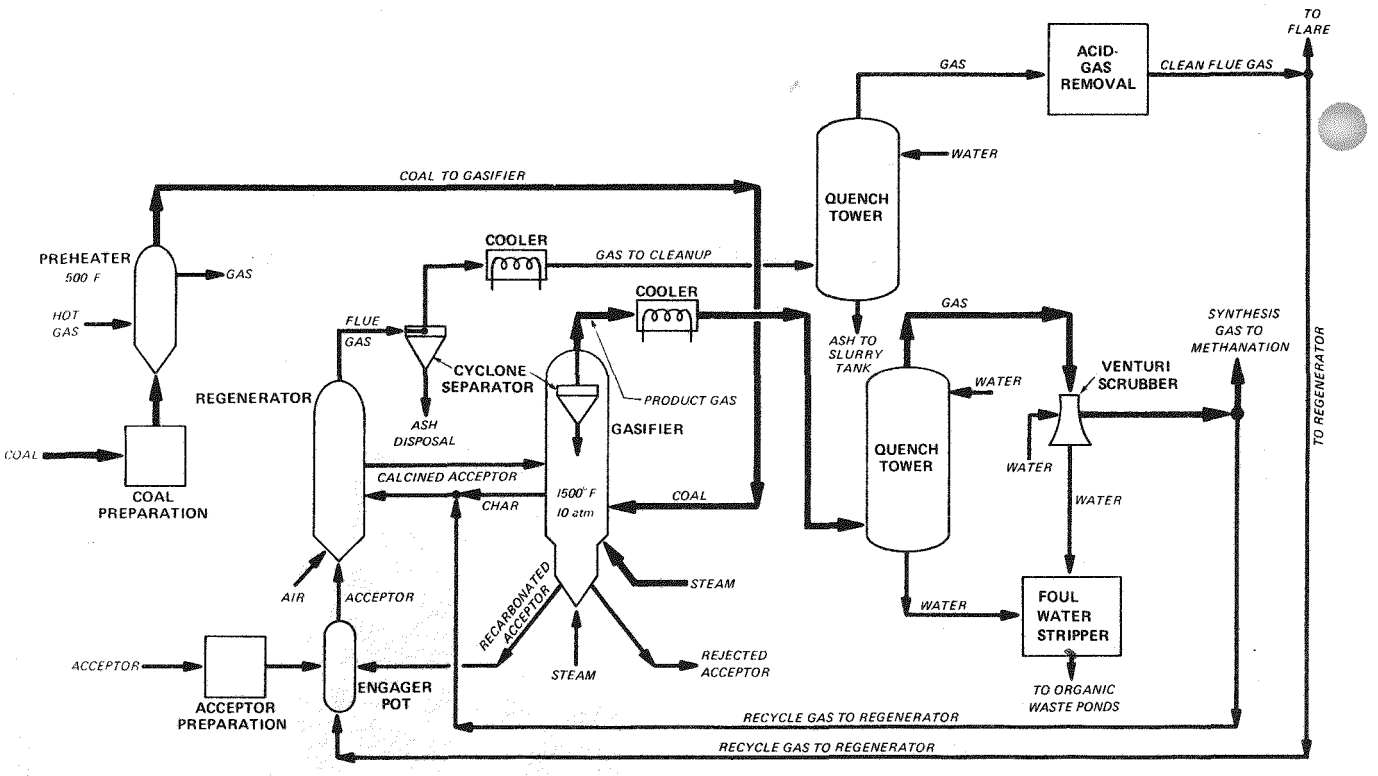


Figure I-2. CARBON DIOXIDE ACCEPTOR PROCESS SCHEMATIC

temperature of the furnace flue gas injected into the mills is moderated with recycle of mill offgas.

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

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

$$CaO + CO_2 \longrightarrow CaCO_3 + \text{heat}$$

The acceptor, reduced to the desired size distribution (generally 6 × 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 team-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. The acceptor is calcined by reversal of the carbon dioxide acceptor reaction. The calcined acceptor is returned to the gasifier through a standleg. Flue gas from the regenerator passes through a heat exchanger to generate steam for the gasifier and the air compressor.

Both the flue gas from the regenerator and the product gas are cleaned, the clean flue gas is either returned to the regenerator or flared, and the clean synthesis gas is sent to the methanation unit to raise the heating value of the gas to pipeline quality, approximately 1,000 Btu per standard cubic foot. The methanation facilities include a shift converter, carbo

dioxide absorber, hydrodesulfurizer, zinc oxide sulfur guard, and a packed-tube methanator. A Dowtherm system is used to remove the heat generated by the strongly exothermic methanation reaction.

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

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

During 1975, runs were made in the pilot plant. Most of the runs were instrumental in locating operational problems. As these problems were solved, progressively longer and more trouble-free runs were made. During one of the successful runs, the system operated for 232 consecutive hours without air to the gasifier and 87.5 hours with 100 percent steam to the gasifier. The unit also operated for 72 hours with no air or recycle gas and all steam. The packed-tube methanation unit was also successfully operated for 48 hours without mechanical difficulty. The heating value of the synthesis gas was upgraded from 373 to 787 Btu per standard cubic foot. It is expected that this will be increased to 900 Btu per standard cubic foot when the newly installed hot potassium carbonate acid gas cleanup system is tuned.

Recent laboratory research has concentrated on studies of acceptor activity and reconstitution. Corrosion studies were also made on various metals and alloys. Pilot plant emissions and effluents were also studied in detail.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

The first pilot plant run using Texas lignite as a feedstock was completed in October. The run was terminated due to an external electric power failure. Following shutdown and cleanup operations, another run with Texas lignite was completed in November. Two steady-state balance periods were achieved before the run was terminated by an upset in the gasifier boot. Results showed that Texas lignite is a suitable feedstock from the standpoint of kinetics, particle size stability, and resistance to deposit formation in the reactor. Prior to the start of the next tests, a new refractory-lined lift line and a new gasifier boot gas distributor were installed.

Runs 41A and 41B were made in December on Wyodak subbituminous coal. Run 41B was of sufficient duration to provide the first reliable gasification kinetic data for subbituminous coal. The new lift line was used in both runs and operated well.

The testing of synthetic acceptors began during the

quarter in the new fluidized-bed reactor. The South Dakota School of Mines studies of melt composition and corrosion effects also continued. Stearns-Roger completed Phase I of the detailed economic analysis of the process and Radian Corporation continued the environmental analysis of the process.

Pilot Plant Operations

Inspection and turnaround work following Run 39 was completed in October, and startup of Run 40 began. Texas lignite and fresh limestone were fed to the gasifier for over 55 hours. The run was terminated after an interruption in purchased power resulted in a plugged acceptor lift line. Investigations following the run showed that the intermediate fines level was higher than expected. It was also determined that the ash content of the feed coal was about twice that found in the initial Texas lignite sample.

Startup of Run 40B began immediately after clean-up operations were completed following Run 40. Texas lignite and Minnekahta limestone were used as feed-stocks. Run 40B produced two steady-state balance periods which lasted 17.5 and 12 hours, respectively. The run was terminated by an upset in the gasifier boot. Inspection of the gasifier after shutdown showed that the gasifier internal cyclone dipleg became de-tached and fell into the transition section of the gasi-fier. Inspection after shutdown also showed that both the regenerator and gasifier were free of deposits. The run demonstrated that dried lignite could be burned reliably in the regenerator. Following the run, the acceptor lift line was replaced with a refractory-lined pipe and a newly designed gasifier boot gas distributor was installed.

Runs 41A and 41B were made in December with Wyodak subbituminous coal to test the operation of the new acceptor lift line and gasifier boot distributor. Run 41A lasted 30 hours after process operating con-ditions were established. The run was terminated due to an upset in the gasifier boot. Run 41B demonstrated that sufficient acceptor could be circulated to maintain a gasifier char bed temperature above 1520° F with-out the need for air injection. The circulating acceptor provided all the gasifier duty for over 35 hours. Shortly after all the recycle gas flow to the gasifier boot was replaced with steam, the control of the char-acceptor interface became unstable and the run was terminated. Inspection of the acceptor lift line follow-ing the run revealed that it was in excellent condition.

Laboratory Research

Testing of the new fluidized-bed reactor at 350 psig and temperatures up to 1750° F was completed in October. The reactor was calibrated and it was dem-mined that the maximum total gas flow rate of 65 standard cubic feet per hour was achieved with a gas mixture containing 80 percent steam. These conditions gave a gas velocity of approximately 0.9 feet per sec-ond in the reactor at 1500° F.

Runs of one and three calcination recarbonation cycles were made in the fluidized-bed reactor during December under calcium carbonate - calcium hydrox-ide - calcium oxide melt-forming conditions using a calcium silicate - calcium carbonate synthetic accep-tor. The results of these runs, coupled with earlier data, suggested that this type of material would be an excellent acceptor. Tests in the automatic cycle tester showed that spent acceptor, reconstituted by the Dorr-Oliver process, should be almost as good as fresh limestone for make-up acceptor feed.

Related Studies

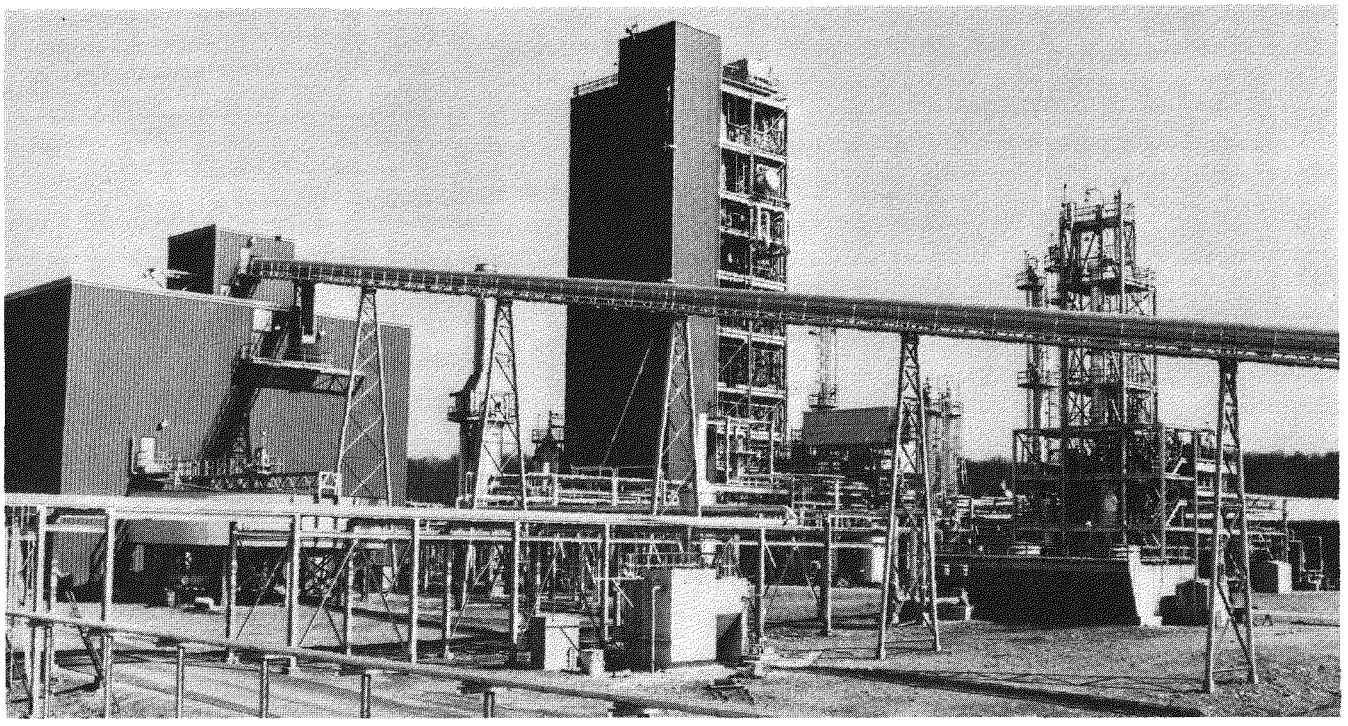
Studies by the South Dakota School of Mines con-tinued on the phase relationship in the calcium car-bonate - calcium sulfate - calcium sulfide system, ef-fects of melt composition on corrosion rates, and monitoring of waste streams from the pilot plant.

Phase I of the detailed economic analysis of the carbon dioxide acceptor process was completed by Stearns-Roger Company. A report issued in December discussed alternative approaches in the following areas:

- Coal preparation and drying
- Gasification
- Raw gas cooling
- Regenerator overhead gas handling
- Gas treating
- Solids cooling
- Sulfur removal and recovery
- Ammonia recovery
- Methanation
- Carbon dioxide removal

Radian Corporation collected test samples from the gasifier runs during the quarter for use in an environ-mental analysis of the carbon dioxide acceptor process.

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



BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

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

INTRODUCTION

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

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

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

Figure II-1 shows the overall program plan.

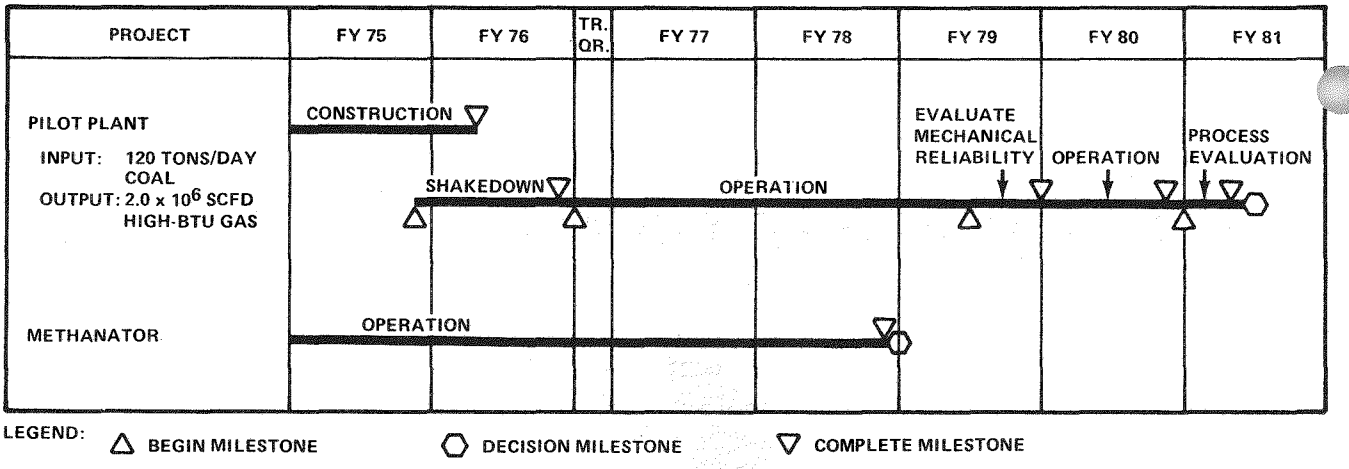


Figure II-1. BI-GAS PROGRAM SCHEDULE

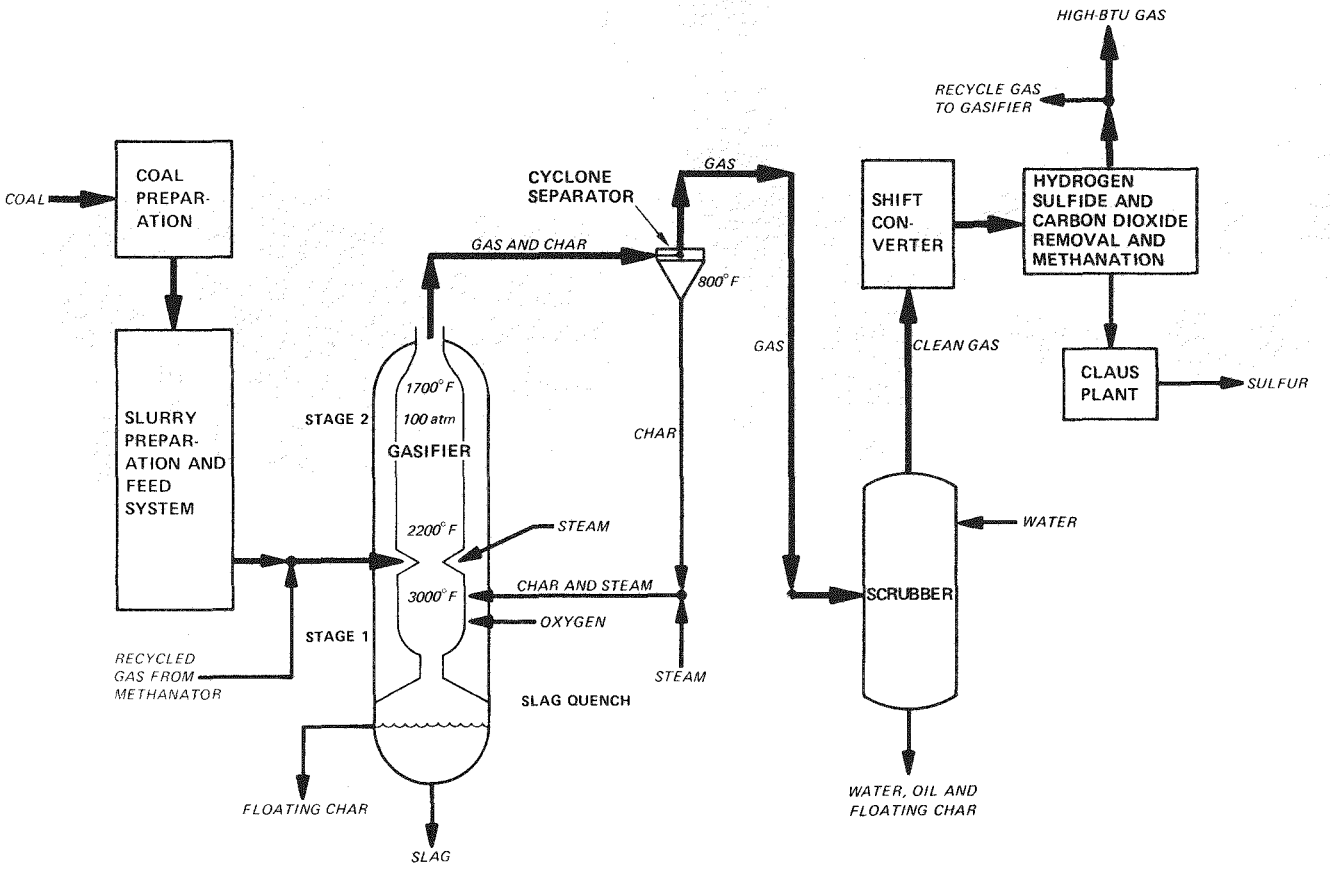


Figure II-2. BI-GAS PROCESS SCHEMATIC

PROCESS DESCRIPTION

The BI-GAS process is a two-stage, high-pressure, oxygen-blown system using pulverized coal and steam in an entrained flow. A diagram of the BI-GAS process is provided in Figure II-2.

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

generate the desired concentration, and fed to the downstream high pressure feed system.

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

The coal enters the gasifier through injector nozzles near the throat separating the stages. Steam is introduced through a separate annulus in the injector. The two streams combine at the tip and join the hot synthesis gas rising from Stage 1. A mixing temperature of about 2200° F is attained rapidly and the coal is converted to methane, synthesis gas, and char. The raw gas and char rise through Stage 2, leave the gasifier at about 1700° F, and are quenched to 800° F by atomized water vapor 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 converted to establish the proper ratio of carbon monoxide and hydrogen required in the methanation process.

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

The BI-GAS process has several advantages:

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

Potential operating problems are:

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

HISTORY OF THE PROJECT

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

used in the experiments. During these experiments, BCR found that the physical design of the Stage 2 process development unit influenced methane yield. Therefore, a cold flow model of Stage 1 and the bottom of Stage 2 was developed to investigate methods for improving the flow patterns in Stage 2 and to establish design criteria for the slagging section of the gasifier.

BCR developed the basic design criteria for a fully-integrated pilot plant capable of processing five tons of coal per hour and producing 100,000 standard cubic feet of clean pipeline-quality gas per hour. Stearns-Roger was awarded the contract for constructing the $34 million facility on July 11, 1972. The pilot plant management contract was subsequently awarded to Phillips Petroleum Company in November 1974. The gasification vessel to be used in the pilot plant was designed and built by Babcock and Wilcox, a Stearns-Roger subcontractor.

Approximately 92 percent of the pilot plant equipment had been inspected and approved by the end of 1975 and the entire plant was completed by mid-1976. Laboratory investigations have dealt primarily with studies of fluidized-bed catalytic methanation. Promising catalysts, supplied by a variety of vendors, were screened in a bench-scale methanator for activity and conversion levels. 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 1976

Summary

A life test of four catalysts containing nickel/molybdenum and colbalt/molybdenum was terminated prematurely after 560 hours. The comparatively low activity of all four samples precluded their further consideration as PEDU test condidates. After the tests, the unit was cleaned in preparation for tests of new catalysts. Because the bench-scale methanator was being repaired, there were no reaction tests during the quarter.

The evaluation of the results of methanation PEDU Test No. 22 was completed during November. In 18 steady-state data periods of the test, useful conversions were in the range of 85 to 95 percent and produce gas carbon monoxide concentrations were almost consistently one percent or less. The catalyst compared favorably with its predecessor, evaluated during PEDU Test No. 19.

Methanation PEDU Test No. 23 was conducted in November and preliminary analysis of the data showed that the catalyst could be reduced with a three-to-one synthesis gas ratio rather than the nine-to-one hydrogen to carbon monoxide ratio normally used. Repair of the gasifier system at the Homer City pilot plant was completed during the quarter and operations proceeded toward startup of the plant.

The flash drying system and gasifier system were operated successfully during the month of December. Baseline conditions were established and maintained until the objectives had been achieved. Coal feed was maintained for a period of 51 hours. Although the coal feed rate was less than desired and feed had to be discontinued because of a number of problems, the run was a major accomplishment for the plant.

Laboratory Research

The life tests of catalysts BCR Lots No. 3516, 3617, 3618, and 3619 was terminated after 560 hours. All four samples showed relatively low activity and some thermal deactivation after the first 800 to 1100° F temperature cycle. After the test of these four catalysts, the unit was cleaned in preparation for tests of the new catalysts.

No bench-scale methanation studies were conducted during the quarter as the unit was being repaired and cleaned.

The evaluation of the results of PEDU Test No. 22, conducted to evaluate the performance of catalyst BCR Lot No. 3631, was completed during the quarter. The primary objective of the test was to evaluate the effect of four variables on three responses: the useful conversion, carbon monoxide content of the product gas, and methane yield. The four variables selected were: temperature, pressure, feed flow rate (space velocity), and carbon dioxide content of the feed gases.

The main conclusions of the evaluations were:

- Reactor temperature was the most important variable affecting the three responses.
- The addition of carbon dioxide to the feed gas

had a large and beneficial effect on useful conversion, although its effect on the product carbon monoxide concentration was of minor importance.

- Except for the possibility of a temperature-feed carbon dioxide interaction in the case of the useful conversion response, no other significantly large combined variable interactions were observed.
- Some uncertainties were involved in interpretation of the test data because of the factorial design of the experiment.

Methanation Test No. 23, using a charge of the spent catalyst recovered from PEDU Test No. 22, was completed in November. Ordinarily, the catalyst is reduced during startup with a hydrogen-rich synthesis gas in which the hydrogen to carbon monoxide ratio is nine to one. As it would be more convenient to effect the catalyst reduction in the Homer City methanator using normal synthesis gas (hydrogen to carbon monoxide at a ratio of three to one) the feasibility of this approach was investigated during PEDU Test No. 23. Reduction of the catalyst was initiated with a methane-rich synthesis gas, and the methane content was gradually decreased to the normal level of 20 percent.

From the test results, it would appear that the catalyst can be safely and efficiently reduced with a normal three to one synthesis gas.

Pilot Plant Operations

Repair of the gasifier system was completed in November, and operations proceeded toward startup of the plant. Several attempts were made to light the slag heating and char burners. There was moderate success, but burner flame outs occurred for various reasons. The TEA ignition system was revised to eliminate plugging problems and to permit better viewing for the flame detector in that system.

Prior to successfully establishing base case conditions and feed to the gasifier, problems were encountered in keeping the gasifier operational. Some of the problems were caused by the extremely cold weather. As operations proceeded, various instruments froze and had to be thawed and winterized.

The flash drying system and the gasifier system were operated successfully. Baseline conditions were established and maintained relatively steady for 16 hours, achieving established objectives during that time. Baseline conditions were designed to match, as nearly as possible, the gasifier conditions that would exist when operating with 750 psig, 2675° F Stage I temperature, and 1700° F Stage II temperature with a 3.5 ton per hour coal feed rate. The objectives of the test were to determine the heat loss from the gasifier system under those conditions and to establish the reliability of equipment, instrumentation, and the data acquisition system to provide information adequate to perform heat and material balances.

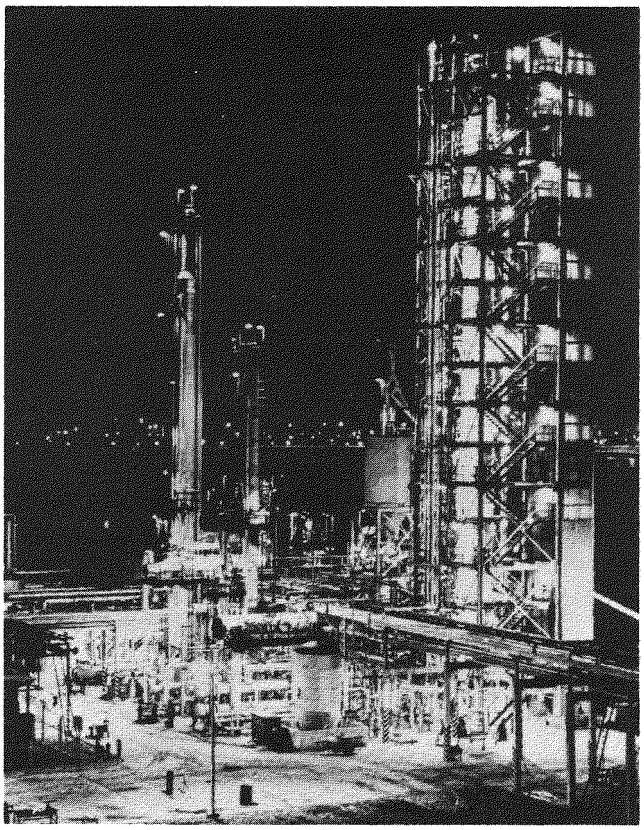
Problems encountered in the coal feed system included: high pond level, high solids concentration in the pond, high ammonia concentration in the pond, a leak of coal slurry in the rod mill, a high concentration of hydrogen sulfide in the recycle gas, and operational difficulties with a number of pumps and compressors.

During December the plant's natural gas allocation curtailment was increased from 40 to 65 percent, effective January 1. Unless an alternate source of gas is made available, operations will be directed toward maintenance and operating studies that could not be scheduled during gasifier operations.

III. PIPELINE GAS BY HYDROGASIFICATION (HYGAS PROCESS)

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

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



INTRODUCTION

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

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

- Development of a high-pressure hydrogasification process that uses all types of coal.
- Determination of the technical and economic feasibility of using the steam-oxygen and the electrothermal processes as hydrogen-generating systems for the HYGAS pilot plant.
- Improvement of the internal coal cycling system.
- Demonstration of the feasibility of ash agglomeration as a technique to increase carbon utilization.
- Demonstration of a methanation system for converting coal-derived gas to pipeline quality.

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

PROCESS DESCRIPTION

Several processing steps are required to convert coal to high-Btu gas with the HYGAS process. A key feature is the use of hydrogen and steam in hydrogasification. A diagram of the process is provided in Figure III-2. Coal preparation involves crushing the coal to —8 mesh. Caking coal is pretreated in a fluidized bed at 660° F to 750° F and at atmospheric pressure to destroy caking tendencies and produce a free-flowing coal. Noncaking coal is fed directly to the slurry tank. The coal is mixed in this tank with an aromatic recycle oil to form a thick slurry and is pressurized to

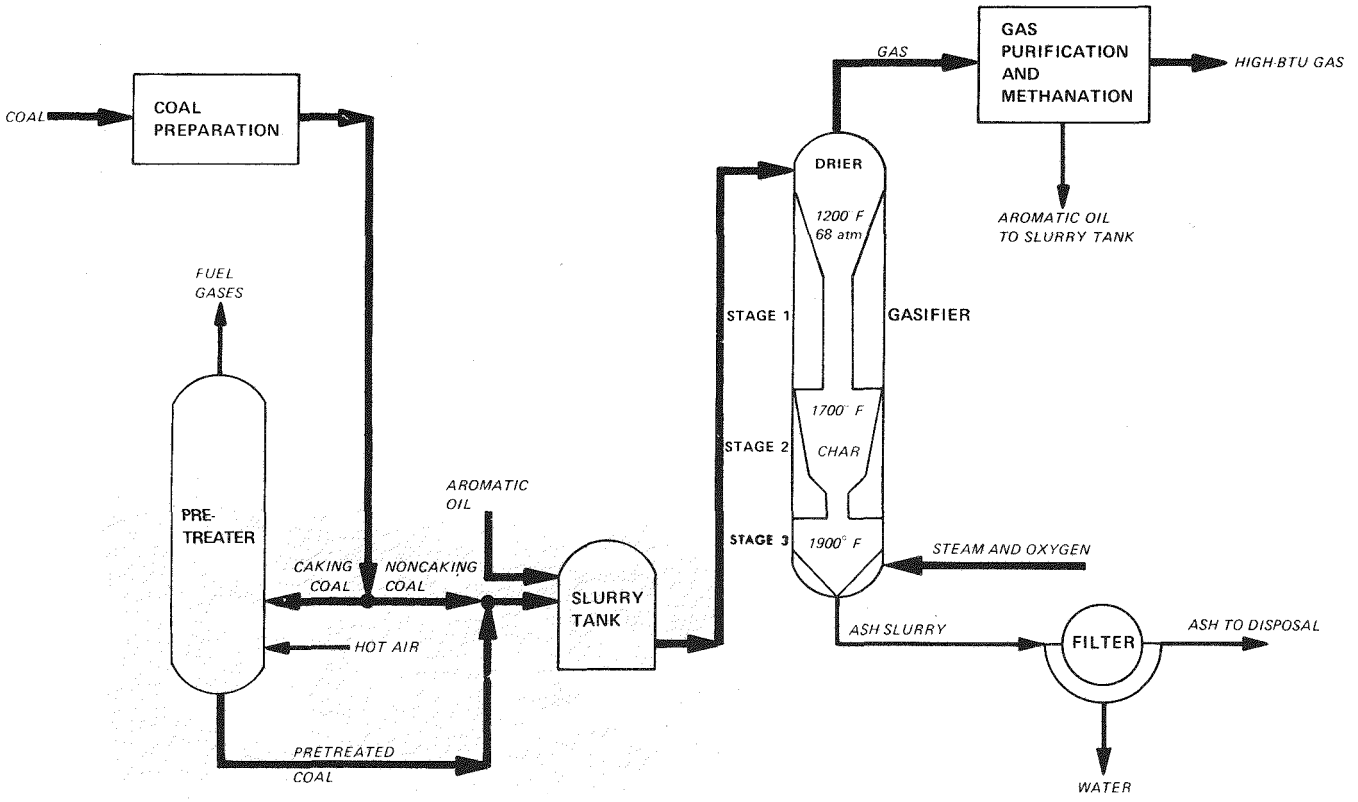


Figure III-1. HYGAS PROGRAM SCHEDULE

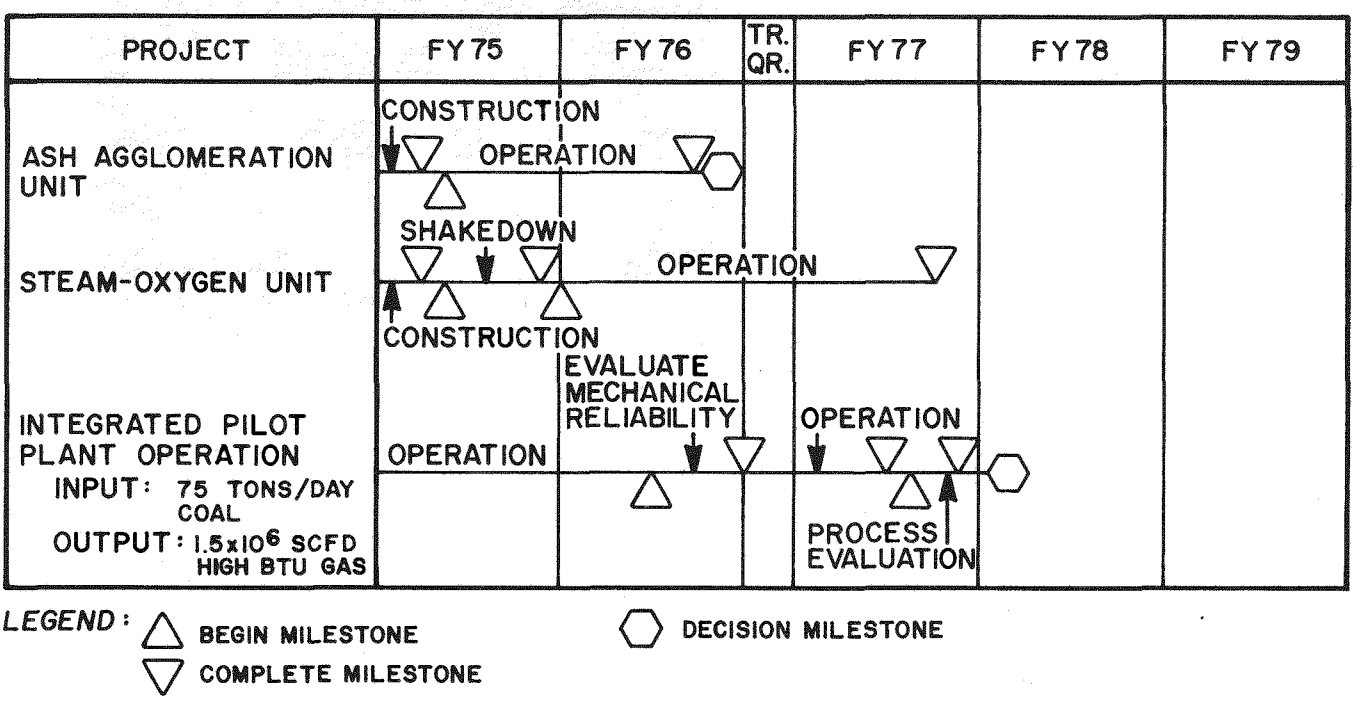


Figure III-2. HYGAS PROCESS SCHEMATIC

1000 psig. The slurry is then sprayed onto the drying section of the gasifier. Oil is vaporized and removed, together with the hot gases passing upward from the first stage of the gasifier. Vaporized oil is recovered for reuse by quenching the effluent of the gasifier.

The dried coal drops into the first stage of the gasifier where it is heated rapidly by internally-recycled hot char and hot reaction gases rising from the second-stage reactor. The relatively low temperature environment of the first stage provides for conversion of approximately 20 percent of the feed coal to methane. At the top of the first stage the diameter of the reactor increases rapidly, thus reducing the velocity of the upward flowing gases and solids. At these lower velocities, the partially spent char is separated from the gas and channeled downward. Part of this hot char is recycled to provide heat to the first stage and the remainder is sent to the second hydrogasification stage, a high-temperature fluidized-bed reactor. An additional 25 percent of the raw coal feed is converted to methane in the hydrogen-rich environment of this stage. Hot residual char moves from this stage into the steam-oxygen section in the bottom of the reactor. Here, the steam, oxygen, and char react in a fluidized-bed, producing a hydrogen-rich gas. This gas is transferred up into the hydrogasification sections as a source of hydrogen for methanation reactions. Ash is removed from the bottom of the steam-oxygen stage.

The product gas (containing methane and other raw gases, particulates, trace elements, and water and oil vapors) passes through a drier and is quenched, purified, and passed to the methanator. The ratio of hydrogen to carbon monoxide in the purified gas entering the methanator is adjusted to about three to one. The purified gas passes through a nickel catalyst at 800-900° F and is transformed to pipeline quality gas with an average heating value of 1,000 Btu per standard cubic foot.

HISTORY OF THE PROJECT

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

During 1975, eleven test runs were made in the HYGAS pilot plant.

The longest run was 363 hours, during which 575 tons of lignite were fed to the gasifier. Based on the success of this test, authorization was given to begin testing with Illinois No. 6 bituminous coal.

Also during 1975, twenty-six runs were made with the ash-agglomerating gasifier. Process parameters were varied to determine the optimum operating conditions. During one run, 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, lock hopper design, and methanation catalyst evaluation.

Of major technical and economic importance to this process is the production of the hydrogen-rich gas required for hydrogasification. Three techniques for producing this gas are being investigated: steam-oxygen, electrothermal, and steam-iron. A steam-oxygen unit, which gasifies char, has been constructed and installed in the base of the HYGAS pilot plant hydrogasification reactor vessel and has been operated successfully. A low-pressure ash-agglomerating gasifier has also been constructed and operated to investigate ways to increase carbon utilization in the process. Shakedown runs and batch tests of the two-megawatt electrothermal gasifier for producing hydrogen-rich gas have been conducted. Although this technique has been demonstrated to be technically feasible, it appears to be too costly due to the large quantity of electrical power required and has, therefore, been placed on standby. 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 at the HYGAS pilot plant site. Currently, facilities exist at a single site for comparative technical evaluation of these three techniques. Results of economic studies indicate that the most economical source of supplemental hydrogen for hydrogasification of coal will be the steam-iron process, followed by the steam-oxygen process, then the electrothermal technique.

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 1976

Summary

Tests on Montana Rosebud subbituminous coal were completed during the quarter. Test 58, the last of the series of tests completed in November on the subbituminous coal, was the most successful to date. The 227-hour self-sustained test processed a total of 753 tons of coal with coal conversion rates of 70 to 80 percent.

Evaluation of candidate Illinois Basin bituminous coals for use in the HYGAS plant began in December. Twenty-five-ton batches of coal were obtained for testing from two different mines. The two coals were evaluated by crushing tests, fluidization tests, proximate and ultimate analyses, ash fushion temperature determinations, and batch pretreatment tests. Results of the tests indicated that the coal from the Peabody No. 10 mine should be used in the initial tests to study the effects of carbon conversion, pretreatment severity, and fines recycling.

Several areas of the HYGAS plant were studied in detail to obtain improved operations for the test with the bituminous coal. Necessary modifications and improvements were also completed.

Pilot Plant Operation

The series of tests using Montana Rosebud subbituminous coal were completed during the quarter. Self-sustained steady-state conditions at a feed rate of two tons per hour were maintained for 11 hours in Test 56 and for 48 hours in Test 57. Tests 55 and 56 were terminated because of plugging caused by mechanical problems. No unusual operating conditions or mechanical upset led to the plugging of the coal transfer from the slurry dryer bed to the first-stage lift reactor which terminated Test 57.

Test 58, completing the series of tests on the subbituminous coal, extended for 277 hours, processing a total of 753 tons of coal in the most successful test to date. All sections of the plant were activated, and the methanation section was on line for 43½ hours. Complete carbon monoxide conversion was obtained and process temperatures in the catalyst reactor were successfully controlled. The test was terminated abruptly due to a severe leak.

The principal process change made prior to the test was a return to a —14-mesh coal size feed material. Fluidization tests indicated a —14-mesh size would achieve complete fluidization. The three previous tests on subbituminous coal were made with a —8-mesh feed material because that size had been used successfully in lignite tests.

Coal conversion rates during Test 58 were between 70 and 80 percent for most of the operating period. Because of limitations in coal feed rates which caused interruptions and/or cutbacks in the oxygen feed rate, the oxygen/coal ratio and the temperatures in the steam-oxygen gasification zone could not be increased sufficiently to achieve a conversion greater than 80 percent.

In December an evaluation of two candidate Illinois Basin bituminous coals began. One coal was a run-of-mine coal from Consolidation Coal Company's Hillsboro mine. The other coal was a washed product from Peabody Coal Company's No. 10 mine. Twenty-five-ton batches of both coals were obtained for full-scale pilot plant crushing tests, batch pretreatment tests, fluidization tests, and process development scale steam-oxygen gasification tests. Based on fluidization tests and ash content, Peabody No. 10 mine coal was selected for the initial test series and arrangements were made to acquire 1,500 tons of Peabody No. 10 mine washed coal. Fluidization tests with the two coals having the same size fraction indicated that the velocity for complete fluidization of the Peabody coal was 40 percent lower than that of the Hillsboro coal. This is an important parameter in establishing a homogeneous, well-mixed reaction system. A low fluidization velocity would also reduce the possibility of clinker formation in the pretreator. The ash content of the run-of-mine coal would require 17.4 percent more coal to obtain equivalent carbon feed rates. Run-of-mine coal will be tested in the future.

In order to improve operations for the coming test, modifications and improvements were made in the coal preparation system, pretreatment section, and the reactor system. Considerable effort was expended during December on laboratory tests to determine the caus

of the foaming which was experienced in the purification section in previous tests.

Methanation Tests

The fixed catalyst bed methanation section was put on stream during the later portion of Test 57. The series combination of zinc oxide (Zanguard 1000) sulfur-guard and MC-100 methanation catalysts were tested for the first time. Good activity of the MC-100 catalysts in the second-stage reactor and satisfactory sulfur removal from the process gas stream through the zinc oxide sulfur guard catalyst was achieved.

The fixed-bed system was on standby at the end of the quarter, while the liquid-phase methanation system was prepared for test operations. Work continued on the instrument and electrical systems, with the installation of steam tracing and insulating. Approximately 1500 gallons of catalyst slurry oil were received and successfully circulated.

IV. STEAM-IRON SYSTEM FOR PRODUCTION OF HYDROGEN

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois

Contract No.: E(49-18)-2435

Total Funding: $9,282,647
ERDA: $6,188,431
AGA: $3,094,216

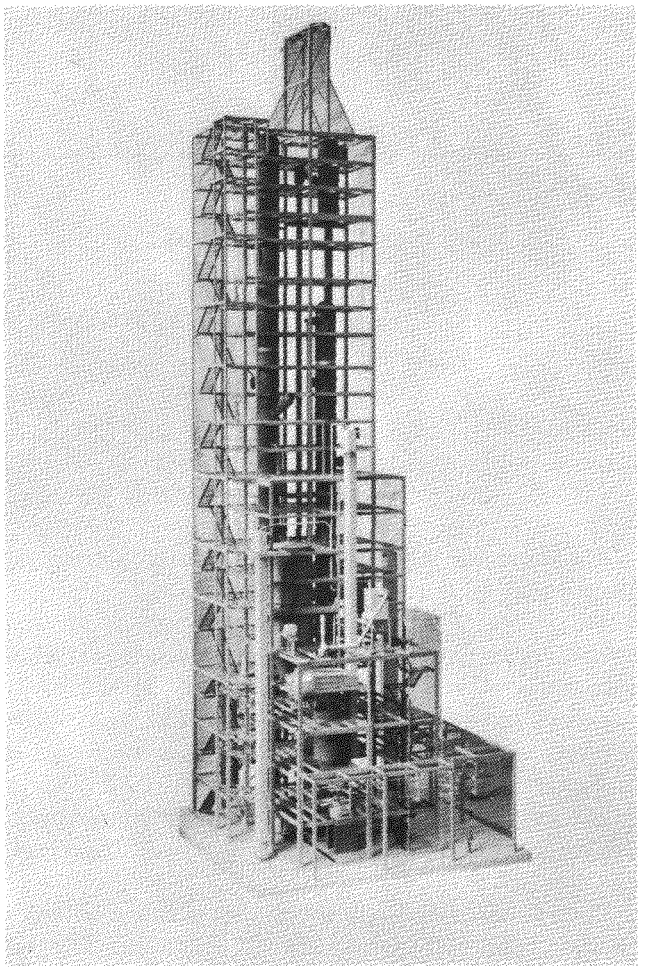
INTRODUCTION

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

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

PROCESS DESCRIPTION

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



In the process, 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

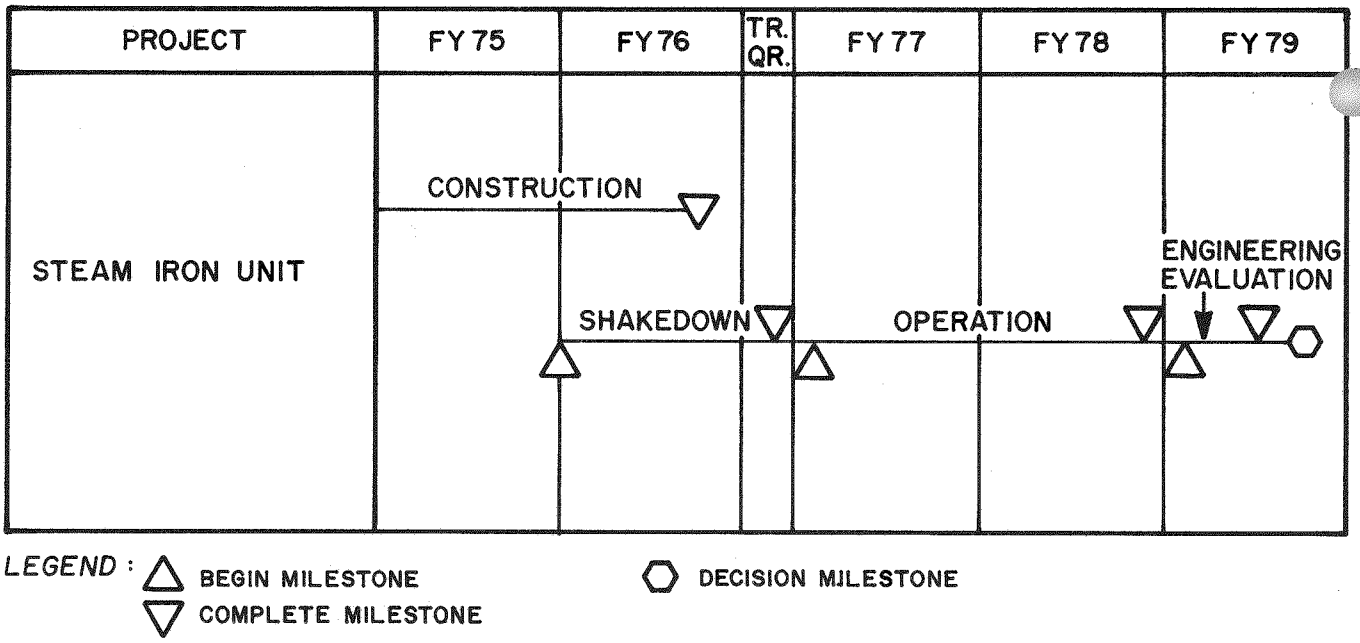


Figure IV-1. STEAM-IRON SYSTEM PROJECT SCHEDULE

with additional steam and discharged from the producer vessel at about 1000° F. The 2000° F reducing gas is then directed to the reducer/oxidizer vessel.

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 Fe_3O_4 in the upper stage. Steam fed to the lower oxidizer section converts FeO to Fe_3O_4 plus hydrogen. Conversion in this bed is limited to about 30 percent.

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.

Compared to other methods for producing hydrogen, the steam-iron process is relatively complex because it introduces another reactor system into the overall coal-to-gas process. This reactor system requires solids recirculation at high pressure. The advantages of this complex system include:

- Elimination of the need for a large oxygen or power 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 by proper adjustment of the steam-hydrogen ratio.
- 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 mixture of hydrogen and unreacted steam. Continuous

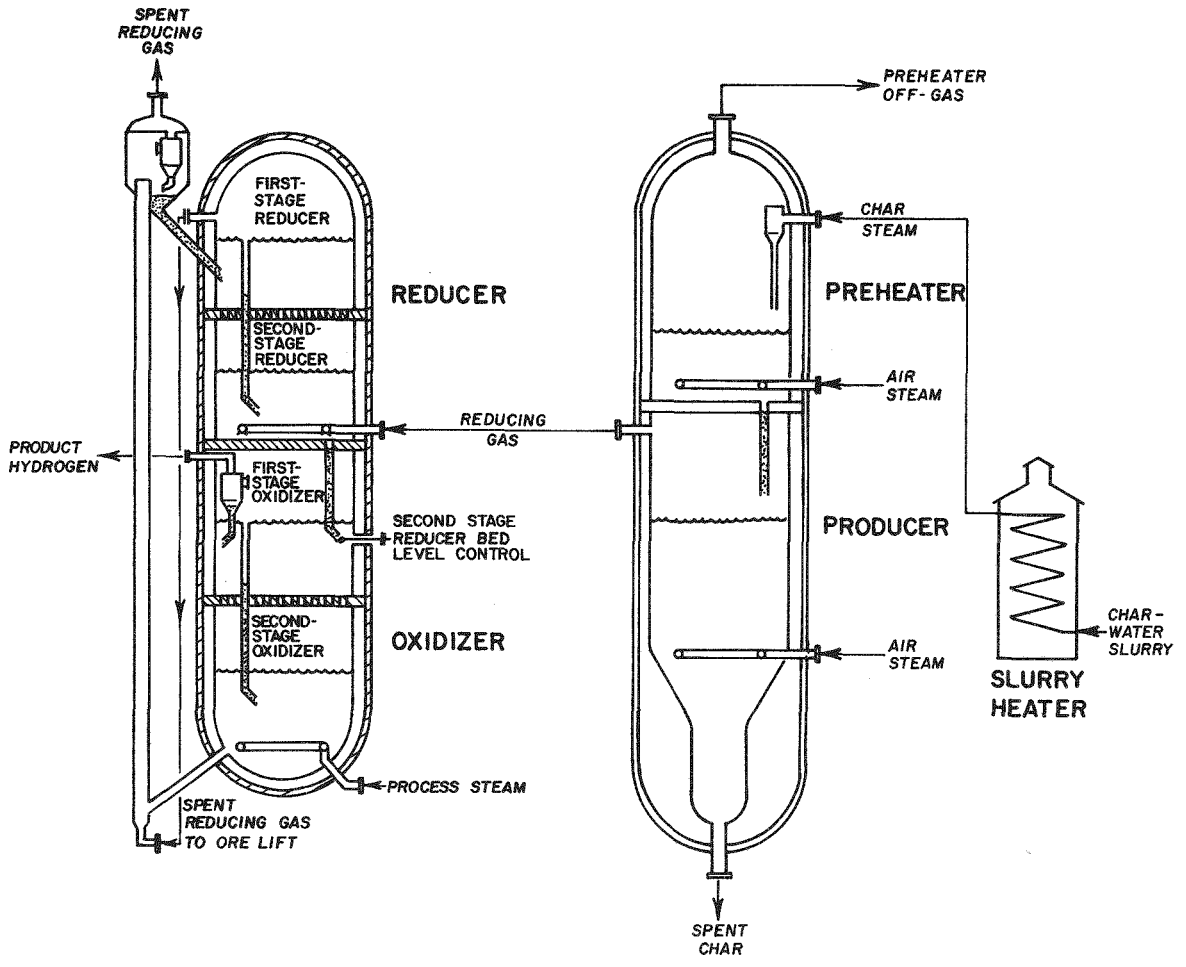


Figure IV-2. STEAM-IRON PROCESS SCHEMATIC

hydrogen production was provided by using two beds that were cyclically reduced and oxidized. This process was neither economic nor compatible with high pressure operations and was dropped in favor of steam reforming of natural gas as a method for producing hydrogen. The process was revised in the late 1950's by the U.S. Bureau of Mines for use in producing hydrogen for coal gasification. In 1961, IGT began working on the process and continued until 1971. This work was performed under the sponsorship of Fuel Gas Associates. In 1973, IGT resumed work on the project and has been developing the process under the joint sponsorship of the Office of Coal Research (OCR, now a part of ERDA) and AGA.

Concurrent laboratory studies have involved the determination of attrition properties and kinetic behavior of various sizes of siderite ore and types of char. Also studied were correlations between fines carryover and gasification parameters, effects of heat loss on performance, and equilibrium relationships in the methane-formation reaction.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

Solids circulation Tests 1 and 2 in the steam-iron reactor were completed during the quarter. In Test 1, iron ore was successfully circulated in the reactor at a rate of 33 tons per hour, which is slightly less than the design range of 45 to 90 tons per hour. About 20 days of intermittent operation were required before continuous solids recirculation was achieved. The test was terminated because of operating difficulties. After inspection of the reactor internals, several minor repairs were made before Test 2 was initiated.

The second solids circulation test was started in the reactor at 500° F. The solids flow through the four fluidized beds and the lift line was smooth. The test was interrupted because of solids discharge from the ore-disengaging tower and, on two other occasions, the necessity to clear ore from the fluidization grid.

Kinetic studies during the quarter included 13 reactivity and 16 attrition tests with various iron-containing solids. The coprecipitated materials containing alumina, iron, and silica showed that their attrition resistance decreased with increased silica content. Three solids prepared by coprecipitation showed slightly higher reactivity and about the same attrition resistance as the siderite.

In addition, three attrition tests were performed in December with solids prepared by coprecipitation in order to determine the effects of sintering time and initial particle size. Char evaluation tests continued with Montana subbituminous char to determine the effect of fluidization velocity on the sintering characteristics of the char at variable operating temperatures.

Attrition studies were conducted with Husky char to determine the effect of the gas velocity and bed weight on the attrition characteristics of Husky lignite char, and the effect of gas density on the attrition characteristics of siderite. Results showed that the rate of fines generation was directly proportional to the square root of the gas density.

Attrition tests were also conducted to determine the effect of gas velocity and solids loading on the attrition characteristics of various size fractions of siderite ore. A mechanistic mathematical model was developed for the attrition characteristics of siderite ore.

In the lift-line studies, the shakedown tests were completed with the solids-circulation equipment and testing began.

Pilot Plant Operation

The first iron ore solids circulation test was made during October at low pressure and an average temperature of approximately 600° F. Both start up burners on the producer vessel were fired to maintain this temperature in the four steam-iron reactor fluidized beds. Iron ore was successfully circulated through all of the beds. Bed levels were controlled automatically using the internal control valves at the bottom of the seal legs. The average pressure drop in the lean and dense-phase lifts was about 0.042 and 0.70 psig per foot. As there was no way to measure the precise recirculation rate of solids in the closed-loop system, the lean-phase pressure drop correlation developed earlier in the program was used to estimate the solids-circulation rate at about 33 tons per hour.

After 20 days of intermittent operation, solids circulation was achieved. The following difficulties were encountered during operation and eventually caused termination of the test:

- Periodic interruption of solids flow from the upper oxidized bed.
- Loss of the solids seal leg from the ore-disengaging tower.
- Localized hot spots on the start up burner.
- Loss of solids from the ore-disengaging tower.

The second ore-circulation test was started in November. During the heat up period, several plant modifications were made which delayed start up. The ore circulation test was begun after the temperature in the fluidized beds reached 500° F. The iron ore flowed freely through the four fluidizing beds, through the lift line, and to the ore-disengaging tower. Discharging solids from the ore-disengaging tower was difficult, however, and considerable carry-over occurred, accumulated downstream in the quench tower. The test was interrupted to examine the ore-disengaging tower internals. After inspection and modifications of the tower, the circulation test continued. Pressure was increased to 300 psig during circulation, and temperatures were increased to maintain a minimum of 500° F in the system to prevent condensation during ore-charging periods. The test was interrupted on two occasions to clear ore from a fluidizing grid.

Winterization of equipment was conducted to achieve steady control. Construction of the service building also began.

Laboratory Testing

Kinetics Studies

Seven reactivity tests were conducted in October. Runs TI-57 and TI-58 were conducted with siderite ore sintered in air at 1400° C for one and four hours. Although rate constants were not greatly affected, oxygen transfer capacities decreased by approximately eight percent.

IGT Iron-Alumina 7, containing three percent silicon dioxide, prepared from sulfate salts by coprecipitation procedure #4, showed 27 percent higher oxygen transfer capacity than that of siderite.

Seven attrition tests, Runs TA-26 through TA-32, were also conducted. Siderite, sintered in air, showed a slight decrease in attrition resistance. IGT Iron-Aluminas 7, 8, and 9 prepared from sulfate salts, using coprecipitation procedure #4, exhibited a trend toward decreasing attrition resistance with increasing silica content.

No material tested during October exhibited an attrition resistance superior to that of siderite. Eight more coprecipitation procedures were developed. Six reactivity tests, Runs TI-63 through TI-68, were conducted with iron-containing solids prepared by coprecipitation procedures #5 and #7. Test results showed that all of the materials have 10 to 40 percent higher relative oxygen transfer rates during oxidation. However, the corresponding reduction rates were either slightly lower or very slightly higher than those for siderite. Test results also showed that resintering siderite ore, received as a crushed sinter, did not improve its attrition resistance. Attrition resistances of the materials prepared by coprecipitation procedure #5 are very similar to those of siderite.

Nine attrition tests, Runs TA-33 through TA-41, were also conducted in November. Analyses of test results showed that IGT Iron-Aluminas 9, 10, and 11, prepared by coprecipitation procedure #5, have the same attrition resistance as siderite.

These attrition tests, Runs TA-42 through TA-44, were conducted in December with IGT Iron-Aluminas 2 and 3 prepared by coprecipitation procedure #1. For Runs TA-42 and TA-43, the solids were prepared by resintering the solids prepared earlier for Runs TA-20 and TA-18. The objective of the tests was to determine the effect of sintering time on attrition resistance. Results showed that an increase in sintering time from two to ten hours increased the attrition resistance by about 30 percent for IGT Iron-Alumina 2 and 45 percent for IGT Iron-Alumina 3.

Char Evaluation

Char evaluation tests with Montana subbituminous coal were continued during the quarter. The objective of these tests was to develop gasification and ash-sintering data over a wide range of fluidization velocities and temperatures. The tests were conducted with a 66-inch, fluidized char bed, using a six-port feed-gas distributor with 5/32-inch diameter ports.

There was no sintering in Runs CE-30 and CE-31 conducted at maximum temperatures of 1955° F and 1985° F and at fluidization velocities of 0.74 and 0.67 feet per second, respectively. In Runs CE-32 and CE-33, conducted at maximum temperatures of 2045° F and 2015° F and at fluidization velocities of 0.60 and 0.95 feet per second, respectively, there was some ash sintering.

There was no char sintering in Run CE-34, performed at a fluidization velocity of 0.85 feet per second and a maximum temperature of 2010° F. Char sintering was experienced in Run CE-35 at a fluidization velocity of 0.75 feet/second and a maximum temperature of 2025° F. There was no char sintering in the char bed in Run CE-36, performed at a fluidization velocity of 0.93 feet per second and a maximum temperature of 2070° F; however, the two-inch bottom section of the thermowell that was immersed in the char bed was coated with a layer of sintered char.

Run CE-38 and CE-39 were performed with char which was partially gasified in earlier tests, to determine the performance of the higher ash-content char when gasified at 2000° F. In Run CE-37, at a fluidization velocity of 0.44 feet per second and a maximum temperature of 1890° F at the bottom of the char bed, there was no ash sintering. Char sintering did not occur in Run CE-38 when the previously gasified char was gasified at a maximum temperature of 2085° F with a fluidization velocity of 0.85 feet per second. However, in Run CE-39, at a fluidization velocity of 0.77 feet per second and a maximum temperature of 2040° F, there was a significant amount of char sintering at the bottom of the fluidized bed.

Attrition Studies

During October, two attrition tests, Runs AH-13 and AH-14 were conducted with a −60 +80 U.S.S. size fraction of Husky lignite char to determine the effect of the orifice jet velocity on the attrition rate of char at the gas distributor. The present test equipment was modified in order to study the effect of gas density on the attrition of siderite and char.

In November, 18 attrition tests were conducted. Runs AH-15 and AH-16 were conducted with a −60 +80 U.S.S. size fraction of Husky lignite char to determine the effect of bed weight on the attrition characteristics of char near the gas distributor. The

remaining 16 tests, Runs CA-19 through CA-34, were conducted with —100 +120 and —120 +140 U.S.S. size fractions of siderite to determine the effects of gas velocity and solids loading on the attrition characteristics of those size fractions in the cyclone.

In December, Runs A1-34 and A1-35 were conducted with a —60 +80 U.S.S. size fraction of siderite to determine the effect of gas density on the attrition characteristics of siderite. The other two tests, Runs AH-17 and AH-18, were conducted with —60 +80 U.S.S. Husky char to determine the effect of orifice gas velocity on the attrition characteristics of the char. The results showed that the rate of fines generation was directly proportional to the square root of the gas density.

Eight cyclone attrition tests, Runs CA-11 through CA-18, were also conducted with a —140 + 170 U.S.S. size fraction of siderite ore, in order to determine the effects of cyclone inlet velocity and solids loading on the attrition characteristics of that size fraction of ore. Results showed that the attrition rate is roughly proportional to the square root of the inlet velocity and that it is not affected by solids loading in ranges from 30 to 100 grams of solids per cubic foot of gas.

The same conditions were the basis for tests in November, with the exception that the feed sizes of the siderite were —100 +200 and —120 +140 U.S.S. The results showed that the effect of loading was not significant.

A mechanistic model for the attrition characteristics of narrow-size-range particles of siderite was developed. Preliminary results showed that the model could predict the rate of fines generation and the size distribution of the atributed material to within about ±20 percent.

Lift-Line Studies

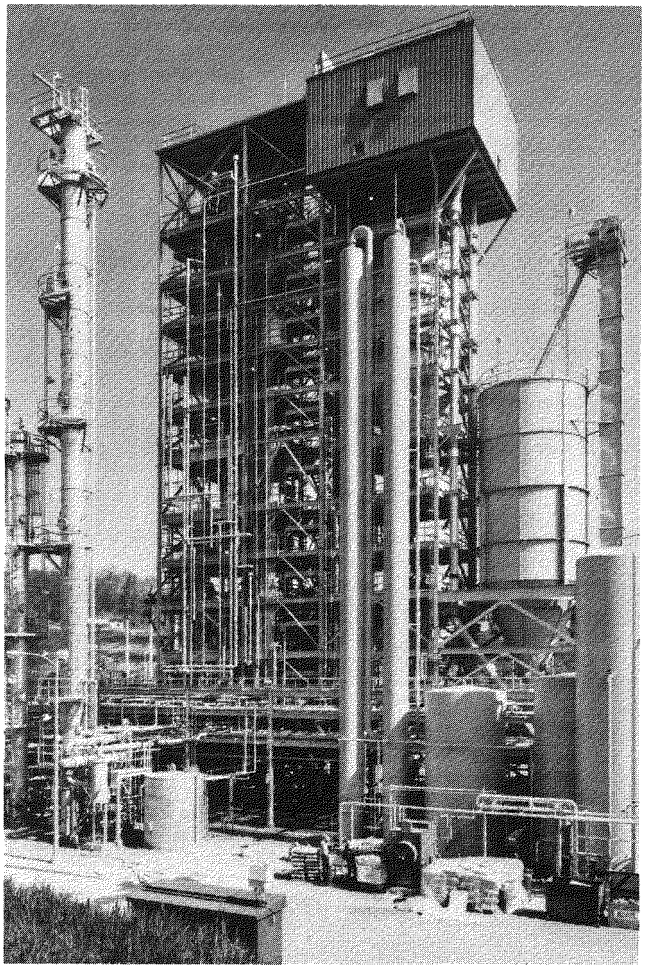
Shakedown of the equipment constructed to conduct lift-line studies was completed. The equipment was designed to simulate the solids flow configuration of the steam-iron reactor and was constructed by modifying existing low-pressure solids recirculating equipment. The results of initial tests showed that for siderite having a vibrated bulk density of 189 pounds per cubic foot, the inventories of solids in the vertical standpipe, dense-phase, and transition zone were 187, 162, and 60 pounds per cubic foot, respectively.

Nine tests were conducted in December to determine the effects of aeration rate and aeration configuration in the lateral downcomer on the operation of the dense-phase lift. The results showed that increasing aeration from 2.1 to 4.8 standard cubic feet per minute decreased the solids inventory in the dense-phase lift from 168 to 156 pounds per cubic foot.

V. SYNTHANE PROCESS

THE LUMMUS COMPANY
BLOOMFIELD, NEW JERSEY

Plant Site: Allegheny County, Pennsylvania
Contract No.: E(49-18)-0003
Total Funding: $24,000,000
(100% ERDA)



INTRODUCTION

The Synthane process was developed by the Bureau of Mines and is now the responsibility of ERDA. The government-owned Synthane pilot plant is being operated by The Lummus Company. The objective of this contract is to obtain definitive process information, sufficient to 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 high methane content is produced directly. A schematic of the Synthane process is provided in Figure V-2. There are four major steps in the process: coal pretreatment, coal gasification, shift conversion and purification, and methanation.

Coal, crushed to —20-mesh, is dried, pressurized to approximately 70 atm, and is transferred into the fluidized-bed pretreater by means of high pressure steam and oxygen. Pretreatment provides a mild oxidation of the coal particle surface so that caking coals will not agglomerate in the gasifier. The coal overflows from the pretreater into the top of the fluidized-bed gasifier about ten feet above the bed level, falls through hot gases rising from the fluidized bed, and is devolatilized. This devolatilization contributes significantly to the methane yield. Steam and oxygen enter the gasifier just below the fluidizing gas distributor. The gasification reaction occurs within the fluidized bed. Unreacted char flows downward into a bed fluidized with steam and water sprays and is removed through lock hoppers. This char can then be burned to produce

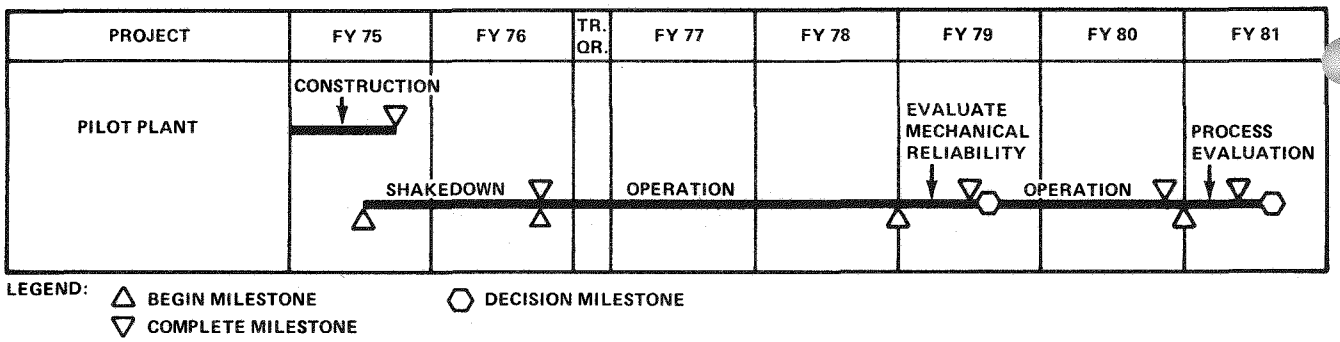


Figure V-1. SYNTHANE PROGRAM SCHEDULE

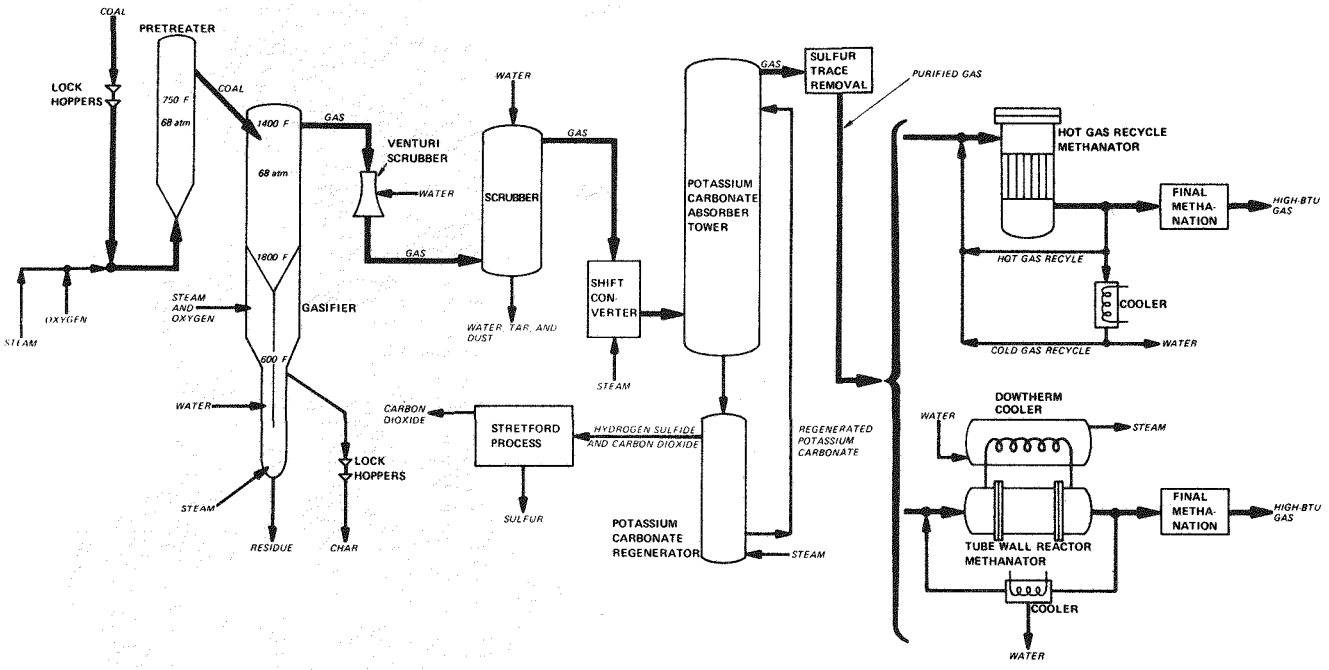


Figure V-2 SYNTHANE PROCESS SCHEMATIC

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 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 tech-

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

Some of the disadvantages of the process are:

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

HISTORY OF THE PROJECT

The Synthane process was developed by the Bureau of Mines at the Pittsburgh Energy Research Center, 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. The plant is now operational and schedules test runs are in progress.

Construction of the Synthane pilot plant was completed in March 1975 and all areas and systems were transferred from the construction contractor to ERDA. Through 1975 work concentrated on installation of auxiliary equipment and the repair and modification of the plant due to faulty equipment and design changes. During the first quarter of 1976 these repairs and changes were made and initial testing began.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

The Synthane pilot plant achieved two of the best operating periods to date during this quarter. After runs of short duration during the beginning of October, new operating conditions to prevent clinker formation were specified, resulting in improved gas production and run times in excess of 15 hours.

The plant was shut down from November 1 to November 19 for repairs, cleanup, and modifications. When operations resumed, plant operation was intermittent due to various problems and it was shut down again on November 23 for revisions and cleanup.

In December, after modifications were made to the process equipment, a 37 hour run was achieved with carbon conversions of 57 to 63 percent. All of the support systems and utilities operated satisfactorily. The run was terminated due to erosion of the bypass valve around the gasifier overhead pressure controller. The inoperability of the internal cyclone in the gasifier, caused by the plugging of the dipleg with fines and tar, continued to be a major problem during the quarter.

Pilot Plant Operations

During the first three runs of the quarter, the Synthane pilot plant operated for periods of short duration. A plugged dip tube between the gasifier and char cooler caused the first outage after a short run of 4.5 hours. The problem of dip tube plugging had been a persistent occurrence, being caused by putting wet steam into the purges of the dip tube. The branch steam header, although coming off the superheated steam line, was of such a length that the steam condensed before entering the gasifier. The line was electrically traced, and an additional purge was added to the leg.

During the second run, started October 10, the unit was operated continuously for 14 hours at feed rates of two tons per hour and under a controlled temperature of 1550° F. Coal and oxygen feeds were stopped due to low carbon dioxide inventory. Restart was hampered and then curtailed because a large clinker had formed over the cone, and the shroud was buckled due to overheating. To prevent clinker formation, the feed rate was increased to three tons per hour, thus reducing residence time. Fluidization velocities were increased to improve mixing in the bed. Bed temperatures were maintained below 1550° F and oxygen addition was carefully controlled during startup. With these conditions, an 11-hour run was achieved on October 29, but was curtailed due to a plugged slurry line. On October 30, a 15-hour run was achieved, but curtailed due to loss of coal feed resulting from the plugging of the coal feed nozzle. On October 31, a 23.7-hour run was achieved. During this three-day period, the gasifier was producing gas for a total of 49 out of 68 hours, the best achievement to that date. The gasifier was operated at 1400° F, three tons per hour coal feed rate, a 0.4 foot per second fluidization velocity, and a ten-foot bed height. These conditions brought about improved gasifier operation in which no clinkers were formed. Carbon conversion was low, however, at 49 percent.

After termination of the test, the gasifier was inspected and the outlet of the cone was found to be plugged with a hard ash-type material that formed directly under the manway and continued across the cone to the outlet nozzle. The plant remained down from November 1 to November 19 for repairs, cleanup, and modifications.

When the plant was restarted, it operated for periods of 17 hours, nine hours, eight hours, six hours, and two periods of five hours. The various runs were terminated due to plugging of the line from the char cooler to the slurry system, an instrument failure of steam to the gasifier, lack of carbon dioxide header pressure due to the inability to vaporize enough carbon dioxide, plugging of the feed line, and the inability to remove char from the gasifier.

In December, run R1-T, using Rosebud coal fed at a rate of three tons per hour, with bed temperatures at 1450° and 1475° F, lasted 37 hours, the longest run to this point. Oxygen and coal feeds were steady and uninterrupted. Gasifier pressure control and all instrumentation functioned properly. Char was manually removed from the gasifier through the trickle valve without problems, however, bed level and temperature control did vary because of the manual operation. The removal of char from the char cooler to the filter area was accomplished with a minimum of problems. Support systems such as carbon dioxide vaporization and compression, the Petrocarb coal feed system, oxygen supply, steam production, filtration, and the coal handling and grinding systems operated adequately during the run. Previously, these systems had caused outages in the gasifier operation. Coal fines carryover into the scrubbing system necessitated frequent blowing down of the scrubber surge tank to the char pond. An inspection of the dipleg after the run showed that it was plugged with a hard tar-like material.

After the run, the plant remained down for the remainder of the month for cleanup, maintenance, and revisions. Plant modifications dealt primarily with the fines carryover problem.

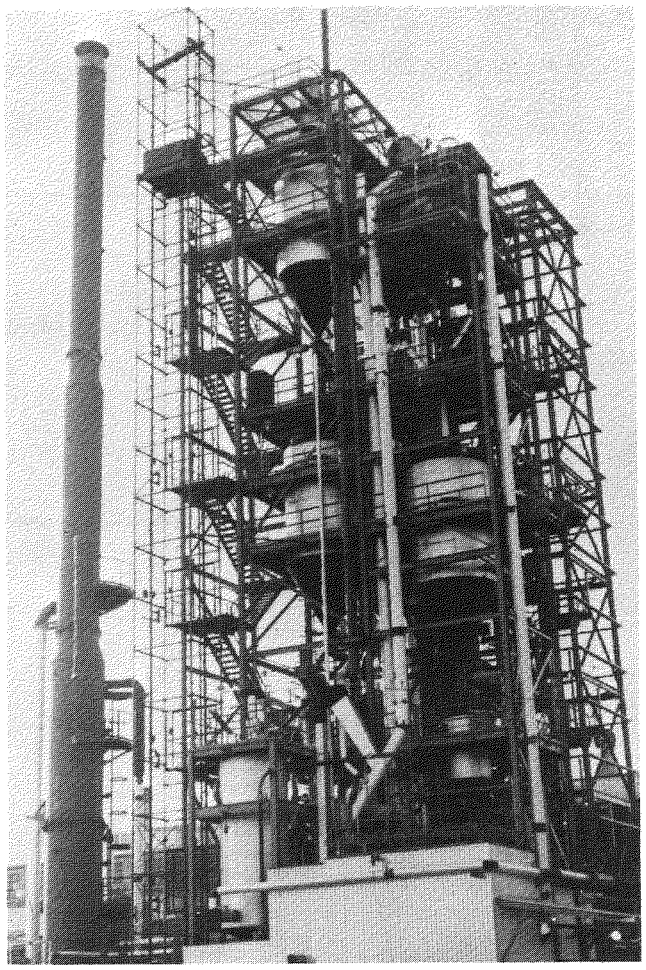
VI. AGGLOMERATING BURNER PROCESS

BATTELLE MEMORIAL INSTITUTE
COLUMBUS LABORATORIES
COLUMBUS, OHIO

Plant Site: West Jefferson, Ohio

Contract No.: E(49-18)-1513

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



INTRODUCTION

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

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

Concurrent with the operation of the process development unit, Battelle will perform process engineering studies which will result in a conceptual design of a scaled-up version of the agglomerating burner process. Also, Battelle will perform the necessary engineering, design, and related technical effort to enable the procurement of a small gas turbine (which can be installed in the system for more efficient utilization of process energy), but will not include the actual purchase of the unit. Figure VI-1 shows a revised schedule for the development of the agglomerating burner process for the latest contract modification.

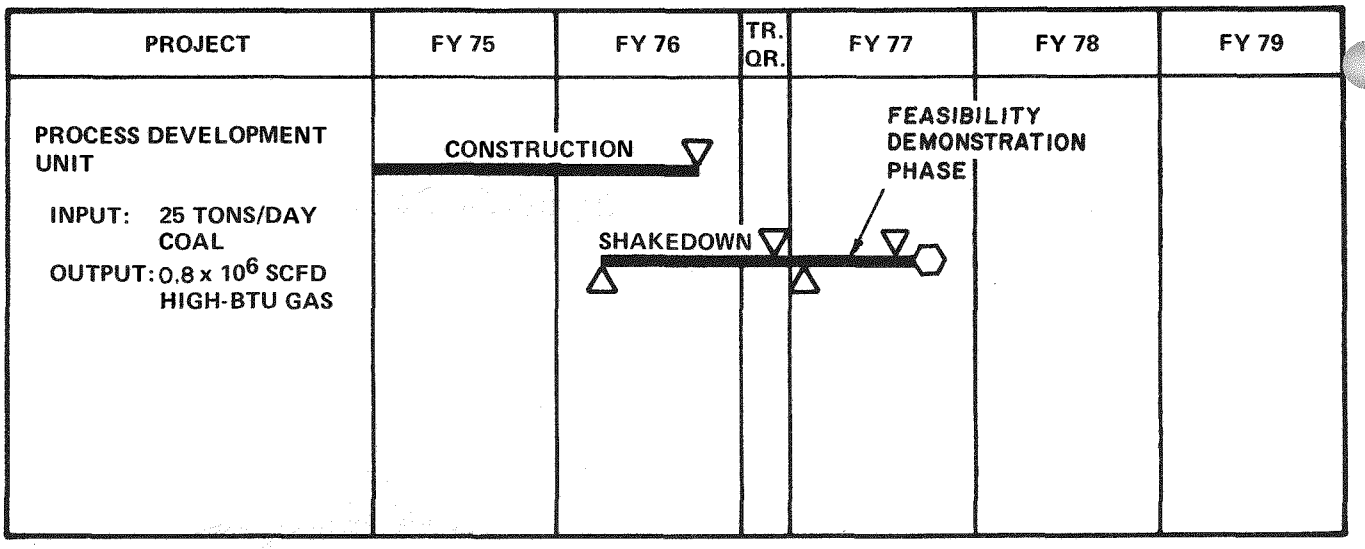


Figure VI-1. AGGLOMERATING BURNER PROGRAM SCHEDULE

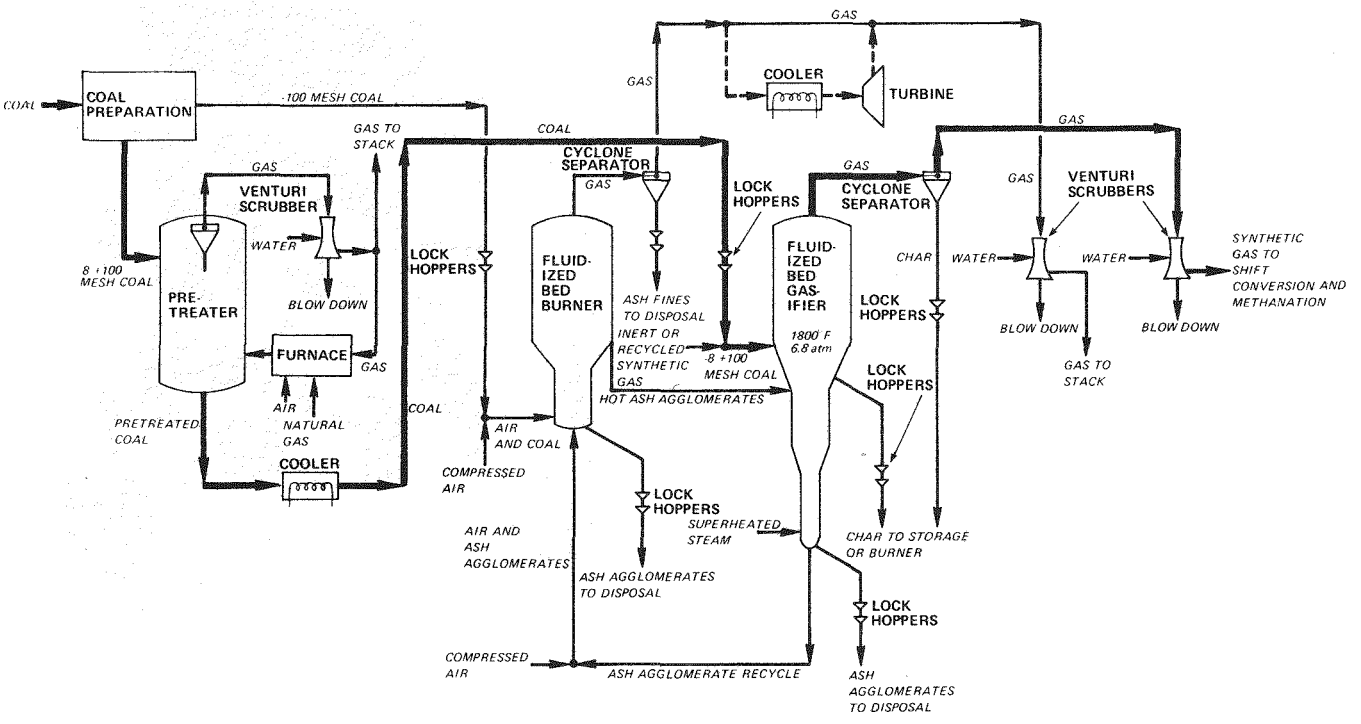


Figure VI-2. AGGLOMERATING BURNER PROCESS SCHEMATIC

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, a 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 burned with air in a fluidized-bed burner in a manner allowing agglomeration of the ash at a temperature approaching the ash fusion point (2100° F). Combustion of coal in this self-agglomerating mode yields hot flue gases that, because they are sufficiently 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 produce 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 fuel gas (free of fly ash) can be expanded through a turbine, thus increasing the overall thermal efficiency of the process.
- Self-agglomerating coals such as eastern bituminous may be converted to synthesis gas by this process.

HISTORY OF THE PROJECT

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

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

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

Research activities have included evaluation of alternatives for the use of natural gas, analysis of sulfur dioxide emission levels (the concentration was well below governmental limits), and studies dealing with alternative designs for the power recovery turbine.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

A reorientation of project priorities occurred during the quarter. The new objective will be to demonstrate that gas can be produced by establishing the basic operability of the PDU within the present time and dollar constraints.

Controlled circulation of solids, with stable bed conditions, was achieved at relatively low temperature and pressure over several periods of continuous operation, each in excess of 100 hours. Preliminary calculations indicated that the design circulation rates of up to 20 tons per hour were achieved.

Modifications were made in the coal grinding and feeding sections to improve operating safety. The coal was fed to the fluidized-bed of the combustor where ignition proceeded without difficulty. Combustion, however, was not as complete as desired and, in fact, occurred above the bed as well as within it.

The difficulties encountered during the attempts to establish autogeneous combustion necessitated maintenance and modifications in December. The hole size in the burner distributor plate was increased, the ash return line was extended to provide a more quiescent bed at the point of coal entry into the system, and the annular openings in the plate around the ash lines were sealed.

Two process flow diagrams were selected for detailed development, and heat and material balance calculations were started for Eastern coal.

Process Development Unit Operation

A reorientation from an experimental-research priority to one directed more specifically to establishing the basic operability of the PDU within the present time and dollar constraints resulted in a different emphasis on some tasks. Effort was expended to establish, with a greater degree of certainty, that solids circulation can be fully controlled before attempting coal feeding and combustion. Additional emphasis was placed on establishing control of solids temperature and burner bed conditions with coal feed before proceeding with gasification. A decreased emphasis was placed on the investigation of gasification parameters and variables. The objective will now be to demonstrate that gas can, in fact, be produced.

Work during October was designed to obtain and verify data for the calculation of solids circulation rates. Calculations were based both on heat transfer between vessels, and on differential pressure measurements. The results of heat transfer calculations indicated that circulation rates in excess of 20 tons per hour were achieved. Differential pressure calculations appeared to verify rates in this range. As there is no known practical method of directly measuring the circulation rate under operating conditions, it is important to develop reliable techniques for making such calculations.

Before processing any of the first shipment of Rosebud coal, modifications were made in the coal grinding and feeding sections to improve operating safety. The grinding, storage, and feeding systems were cleaned of the Eastern coal that had been used in the preliminary commissioning operations, and grinding of the Rosebud subbituminous coal began in November. Operations confirmed that the Western coal could be ground in the Williams mill system; however, the ability to produce the desired split of fine and coarse material, at the desired moisture content, must still be demonstrated. The Rosebud coal, as received, contained a high percentage of fine material. There were also indications that it was much more friable than the Clarion seam coal previously used. As a result, the product produced with the previously established roller settings was extremely fine.

The coal was fed to the combustor, ignited, and burned in the fluidized-bed without the addition of heat from the start-up heater (autogeneous combustion). Under the conditions used in these runs, however, it was not possible to achieve stable solids circulation while maintaining the burner bed temperature exclusively with the burning of coal. As a result, no significant additional data were generated for the calculation of solids circulation rate. It was also found that under the conditions investigated to that date, a significant portion of the coal burned above the bed.

Work in December dealt primarily with the maintenance and modifications necessitated by difficulties encountered in the attempts to establish autogeneous combustion. Flow of fluidizing gas through the annular openings in the distributor plate around the ash lines was a cause of spouting in the burner bed. This was corrected by sealing the annular openings around the ash return and ash discharge pipes. Spouting probably contributed to the burning of coal above the fluidized-bed in the previous coal burning period.

After the annular openings were properly sealed

the pressure drop across the gas distributor plate was excessive. The hole size was consequently increased to provide the desired pressure drop of about two psi under design conditions with a fluidizing gas flow of 2,250 standard cubic feet per minute.

To promote a more quiescent bed at the point where the coal enters the system, the line returning the circulating solids to the burner bed was increased in diameter and extended approximately two feet above the distributor plate.

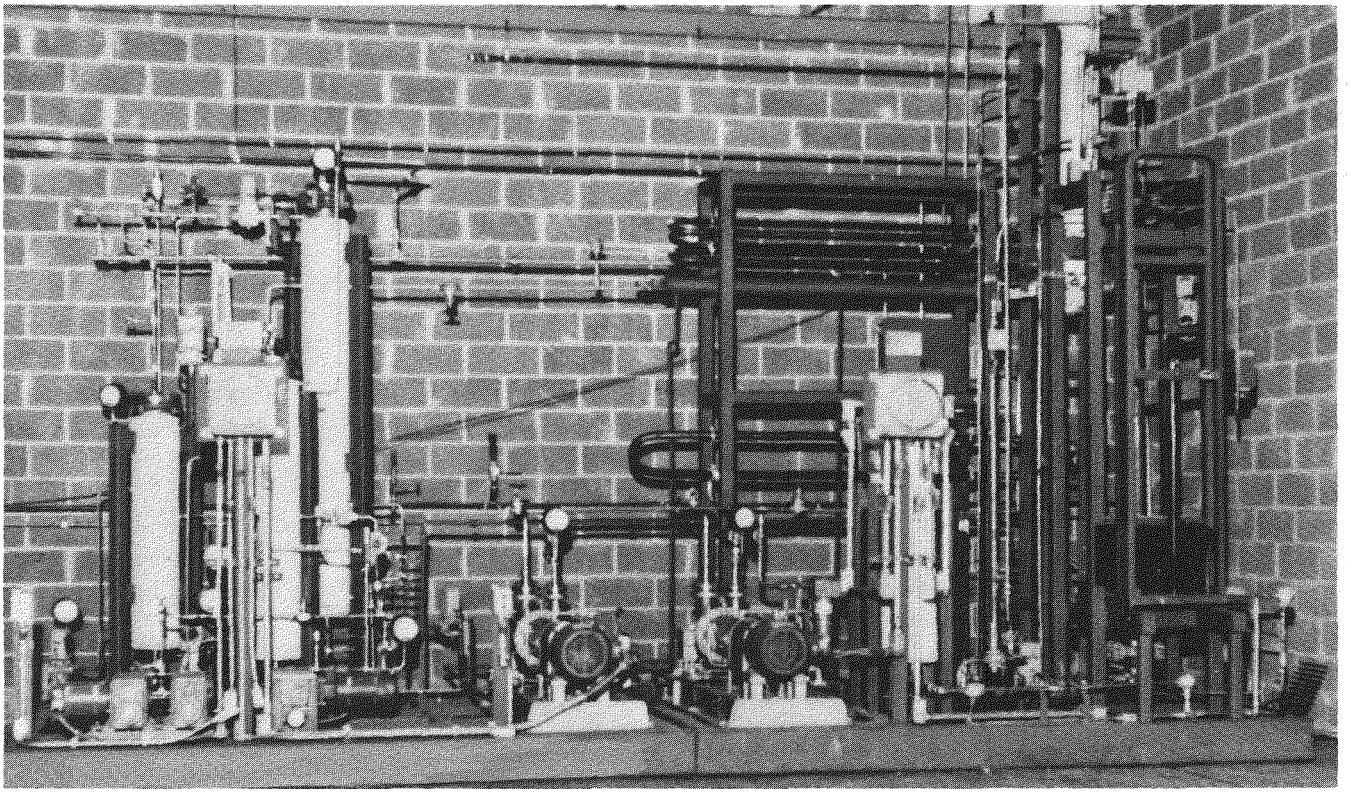
The refractory distributor plate was cracked, possibly allowing the carry-through of unburned coal into the freeboard area above the inert starter bed used in the combustor. A fiber-reinforced ceramic distributor plate for the burner was cast and installed.

Related Studies

Two process flow diagrams using the same upstream systems for coal storage and preparation were selected for detailed development. One flow diagram used only start-of-the-art technology for downstream processing. The other diagram contained two advanced concepts, a high-temperature power recovery turbine and a combined shift/methanation process.

Based on the diagrams selected, detailed heat and material balance calculations were begun for Eastern coal. One set of conditions was chosen and the heat and material balances were extended to processing steps upstream and downstream of the burner-gasifier section. Preliminary process flowsheets, equipment lists, and process design criteria were also initiated. The data generated will be used for sizing equipment and establishing specifications for equipment vendors.

VII. LIQUID PHASE METHANATION PROCESS



CHEM SYSTEMS, INC.

HACKENSACK, NEW JERSEY

Plant Site: Hackensack, New Jersey

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

Total Funding: $2,170,000
ERDA: $ 723,333
AGA: $1,466,667

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

Total Funding: $539,244
ERDA: $3,087,362
Industry: $179,748

INTRODUCTION

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

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

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

- Develop an acceptable process liquid (to suspend catalytic particles) and investigate the use of aromatic and paraffinic hydrocarbons as possibilities.

- Investigate various catalytic materials that can be used in the methanation process.
- Determine the catalyst particle size that will 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, recovery, and regeneration methods
- Liquid life and effectiveness
- The effect of all process variables on performance
- The correlation between the laboratory reaction models and process development unit performance data
- Data needed for engineering designs and cost estimates of large plants

The third phase includes the design, procurement, technical supervision, and construction of a pilot plant methanation unit. The unit will be used to (1) demonstrate the liquid phase methanation process on a synthesis gas actually produced in a coal gasification process and (2) obtain data for detailed design and engineering of a methanation unit for a coal gasification plant having a capacity of about 250 million standard cubic feet per day.

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

PROCESS DESCRIPTION

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

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

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

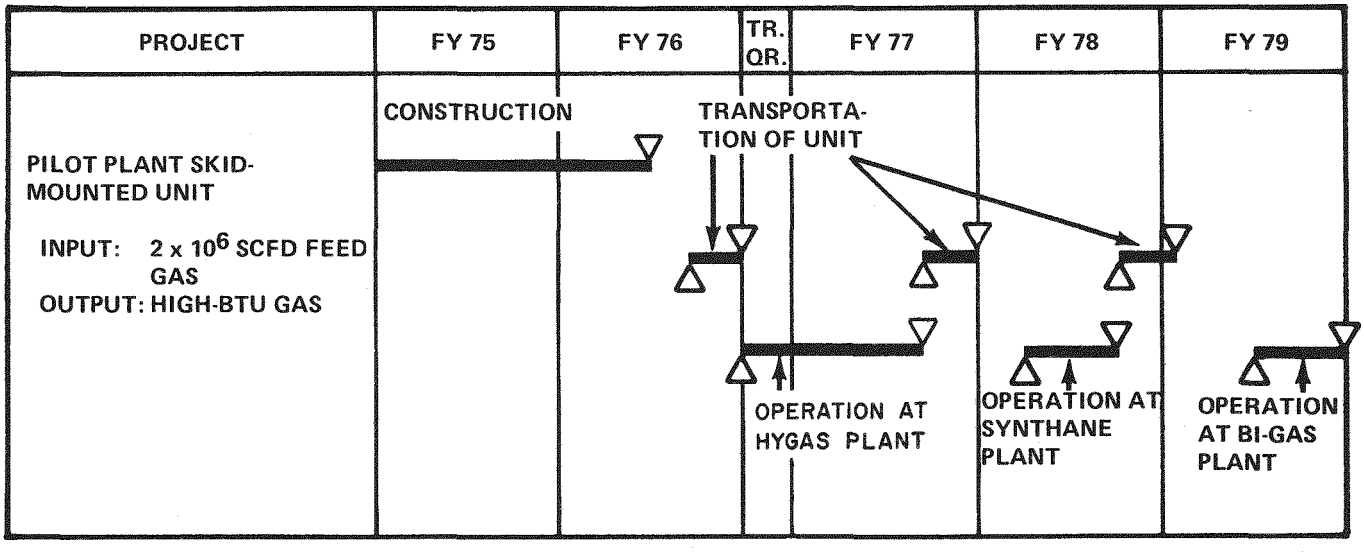


Figure VII-1. LIQUID PHASE MENTHANATION PRORAM SCHEDULE

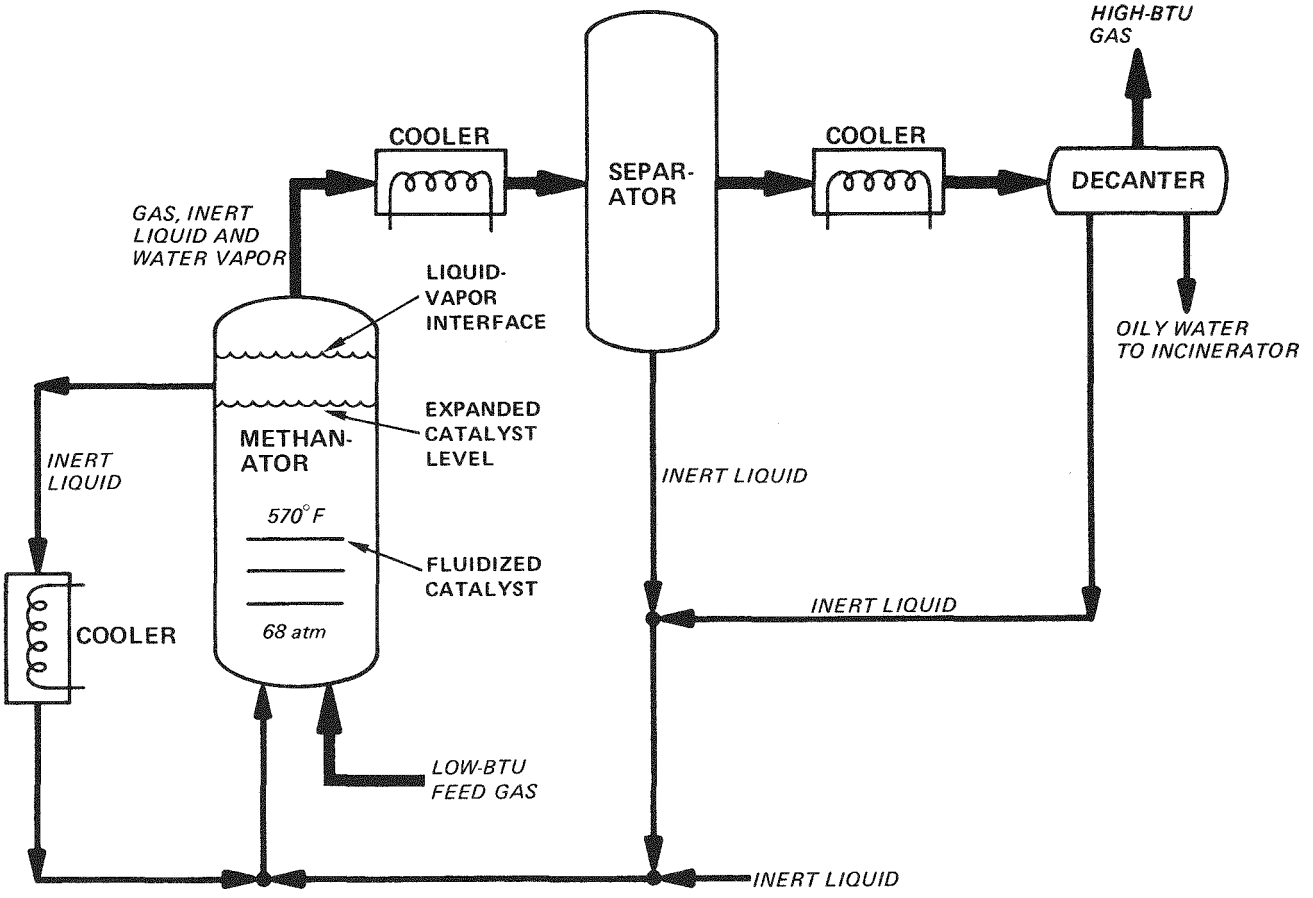


Figure VII-2. LIQUID PHASE METHANATION PROCESS SCHEMATIC

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

The product gas exiting the top of the reactor contains 95 to 99.5 percent methane, 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, along with minute quantities of ethane, propane, hydrogen, and carbon dioxide. Most of the inert liquid condenses in the primary cooler and the remainder condenses in the secondary cooler along with the water. The inert liquid and water are separated, the inert liquid is recycled to the methanator, and oily water is sent to the incinerator. The reaction is nearly complete in one pass, and the product is high-Btu synthetic natural gas.

There are several advantages to the liquid phase methanation process:

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

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

HISTORY OF THE PROJECT

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

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

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

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

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

Davy Powergas, Inc., Houston, Texas, is responsible 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.

The pilot plant was completed in the third quarter of 1976. Laboratory research has dealt with combined shift-methanation rates and catalyst life studies. A polishing reactor was also installed in 1975 to study ways of increasing methane yield. The process development unit was also reactivated so that liquid phase methanation/shift operations could be further studied.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

The Liquid Phase Methanation (LPM) pilot plant was shipped to the IGT HYGAS plant in Chicago, Illinois. It was reassembled and shakedown operations begun. By the end of the quarter, all systems had been checked out.

Three catalyst tests were conducted during the quarter on the PDU. The test results of the run on CRG-A tablets compared favorably with those from prior runs. The second run was conducted on the extrudate form of the catalyst. The last of the series of planned PDU tests was made on an Englehand nickel catalyst.

Pilot Plant Activities

The LPM pilot plant was delivered to the IGT HYGAS plant in Chicago, Illinois the first week in October. The control room and the four pilot plant skid sections were moved into place and anchored to the site in November. Most of the major mechanical, electrical, and instrument installations were completed by the end of the quarter and shakedown operations initiated.

Prior to reassembly, however, major vessels were opened and inspected for corrosion and proper placement of internals. Since rusting was found to be minimal, no chemical cleaning was done.

When electric power was brought to the control room after reassembly, all pumps on the skids were bumped to check rotation and electrical hookups. The nuclear level detector and its lift mechanism were thoroughly examined for practicality of operation.

A revised experimental program for pilot plant operation was prepared and transmitted to ERDA and AGA. The program detailed the experiments to be performed with the synthesis gas stream from the IGT reformer.

A schedule for shakedown operations was worked out and transmitted to ERDA. The following operations were included:

- Nitrogen pressurization and leak testing.
- Cold oil flow tests.
- Gas feed tests.
- Preparation for experimental program.

Leak testing of the various segments began on December 6, and by the end of the month, all systems up to, and including, the reactor checked out. The leak testing was still incomplete by the end of the quarter.

Catalyst Evaluation Tests

The bench-scale unit was run to test the use of a feed gas similar to that produced by the HYGAS reformer and to check the validity of the reaction model under conditions expected in the LPM pilot plant with this gas. Feed gas was alternated between the 3:1 hydrogen to carbon monoxide ratio gas and the simulated reformer gas. Each time the feed gas was switched to the simulated reformer gas, the catalyst activity doubled. This was the expected result according to the LPM reaction model.

The first run of the quarter in the PDU was designed to test CRG-A tablets (3/32-inch in diameter and 3/32-inch long). The run was completed after 92 hours. The catalyst rate constant remained at 1.5-1.75 $\times 10^{-6}$ gm moles/atm-gm. cat-sec., which is comparable to prior experience.

A second PDU run was begun with CRG-A extrudates (commercial preparation) using a 2:1 hydrogen to carbon monoxide ratio feed gas and Witco 40 Mineral Oil. The run lasted 68 hours at 500 psig. The catalyst activity leveled out after 45 hours with a rate constant of 3.0×10^{-6} gm moles/atm-gm. cat.-sec. During the course of the run, the Witco 40 Mineral Oil was replaced with Freezene, a Witco product with a lower pour point (—35° F.) As no adverse effects were noticed, this oil will be used when freeze-up of the Witco 40 would be likely due to cold weather.

The last of the planned series of runs for the PDU was on an Engelhand nickel catalyst. Freezene 100 mineral oil was used as the process liquid, along with a 2:1 hydrogen to carbon monoxide feed gas. The initial activity level was calculated to be 1.5×10^{-6} gm moles/atm-gm. cat.-sec. Over a period of three to four days, the ativity equilibrated at a value of $0.9 - 1.0 \times 10^{-6}$.

VIII. EVALUATION OF HIGH-BTU GASIFICATION PROJECTS

C. F. BRAUN AND COMPANY
ALHAMBRA, CALIFORNIA

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

INTRODUCTION

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

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

PROGRAM DESCRIPTION

Braun's tasks fall into two categories: technical evaluations and development of conceptual designs for commercial plants for each of the candidate high-Btu processes.

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

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

Other technical support activities include investigating all major equipment problems and recommending changes or redesign, conducting practicability and feasibility studies necessary to prevent unproductive research, monitoring construction activities and operations, consulting on pilot plant problems, reviewing performance data, and analyzing process operation difficulties.

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

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

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

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

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

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

During the quarter, Braun engineers visited the HYGAS, carbon dioxide acceptor, BI-GAS, and Synthane pilot plants to observe the operations. Information acquired will be used to evaluate these processes and to develop optimum methods for use in the conceptual designs.

Three visits were made to the HYGAS plant before it was shut down for repairs. Heat and material balances were prepared by Braun at Conoco's request on Run 39 of the carbon dioxide acceptor pilot plant. Braun also monitored the first attempt to add coal to the gasifier at the BI-GAS plant. Two visits were made to the Synthane plant at the beginning of the quarter, and subsequent operations were monitored by telephone.

Reports were drafted on the comparison of acid gas removal processes and cost comparisons for fixed-bed methanation processes. The report on the single-step total sulfur recovery was submitted to ERDA-AGA for review.

A comparative study of the steam-iron process for hydrogen production and a more conventional process such as Koppers-Totzek was begun. The final report dealing with the commercial design for Western coal was compiled and sent to be printed.

Technical Evaluations

High-Btu Gasification Processes

Three visits were made to the HYGAS pilot plant during the quarter for observation of Run 57, Run 58, and for a post-run debriefing on Run 58. The plant was shut down in December for repairs. Problems were encountered in the coal feed systems, in the oxygen feed control unit, and the light-oil recovery system.

Observations were made of Runs 39, 40, 40B, and 41A at the carbon dioxide acceptor pilot plant. The progress of Run 41B was followed by telephone. Heat and material balances were prepared on Run 39, the first test run that successfully gasified Glenharold lignite. Runs 40A and 40B were made on Texas lignite. This feedstock contained a substantial amount of impurities which accummulated in the gasifier bed, thus limiting the acceptor circulation rate. Runs 40B, 41A and 41B were terminated by boot upsets.

Two visits were made to the BI-GAS plant during the quarter. The first attempt to add coal to the gasifier was monitored in December. Coal was fed to Stage II of the gasifier for the first time on December 16. Feed was maintained for 36 hours. Natural gas burned in Stage 1 provided the heat requirements of the gasifier. The coal grinding and spray drying sections of the plant were also in operation. The coal feed was stopped because of problems with the waste water pond. The level of the pond was near flood stage and the solids content of the water was near the acceptable limit for waste water.

Two visits were made to the Synthane plant at the beginning of the quarter, with subsequent operations monitored by telephone. Formation of clinkers and other hard accretions in the gasifier limited operations by interferring with char removal. A 37-hour run in December was the best to date, but this run had to be terminated because of erosion of a back pressure valve. Changes will be made to reduce tar production and prevent deposit formation in the cyclone and its dip leg.

Process Specifics

During December, the first draft of the report on the comparison of acid gas removal processes was completed. The results of the Selexol versus hot carbonate studies were included in this report. The review of the initial report on shift conversion was also started during the quarter.

The cost comparisons for fixed-bed methanation processes were completed and the draft report was begun. Design work for resizing the liquid phase methanation reactors from four 25-percent reactors to two 50-percent reactors was completed.

In the area of effluent treatment, the report on the single-step total sulfur recovery was submitted to ERDA-AGA for approval and review by the project advisors. The evaluation of proposed processes for Western coal flue gas cleanup continued. An economic study was begun to determine the optimum temperature to which flue gas should be cooled for both Western and Eastern coals.

Design work for the plant size study has been completed. Operating costs estimates were completed for 50- and 125-billion-Btu-per-day plants. The capital cost curves were completed for both single- and two-train plants. Preliminary gas cost versus plant size curves were completed and transmitted to ERDA-AGA.

A preliminary design was begun to determine if hydrogen produced by the steam-iron process can be competitive with hydrogen produced from a more conventional process such as Koppers-Totzek. The updating of mechanical development reports continued during the quarter. Work is also being conducted to formulate development programs for subcontract awards to qualified vendors. Three reports were submitted to ERDA-AGA, for their review of the findings and recommendations for each problem area.

Conceptual Design of Commercial Plants

The final report of commercial designs for Western coal was compiled and sent to the Government Printing Office for printing. Work continued on the draft report of commercial designs for Eastern coal.

IX. MOLTEN SALT GASIFICATION PROCESS

ATOMICS INTERNATIONAL DIVISION
ROCKWELL INTERNATIONAL CORPORATION
CANOGA PARK, CALIFORNIA

Plant Site: Santa Susana, California

Contract No.: E(49-18)-2342

Total Funding: $9,729,990
(100% ERDA)

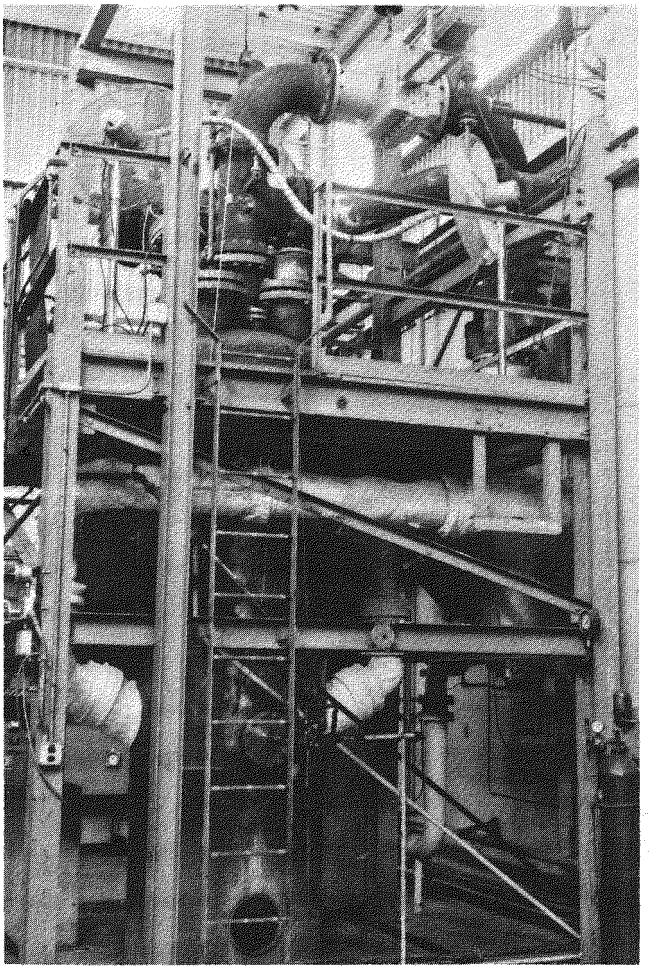
INTRODUCTION

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

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. The program schedule is shown in Figure IX-1.

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

- Air and solids feed system design and operating parameters



- Melt withdrawal and quench system design requirements
- Entrainment of particulates in the product gas and purification requirements
- Optimum sodium carbonate regeneration process flow scheme

PROCESS DESCRIPTION

In the molten salt gasification process, coal is gasi-

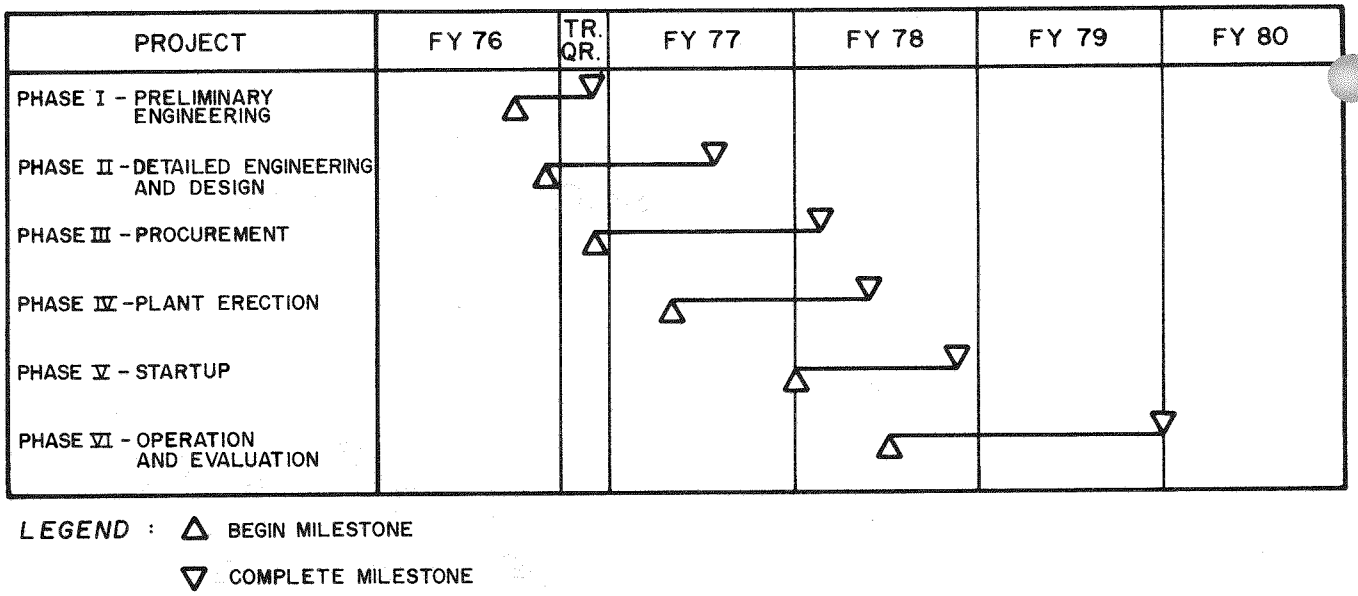


Figure IX-1. MOLTEN SALT GASIFICATION PROGRAM SCHEDULE

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

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

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

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

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

- The process allows the use of a complete range of coal particle sizes, from $\sim$¼ 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 ($<\sim$¼ 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 a

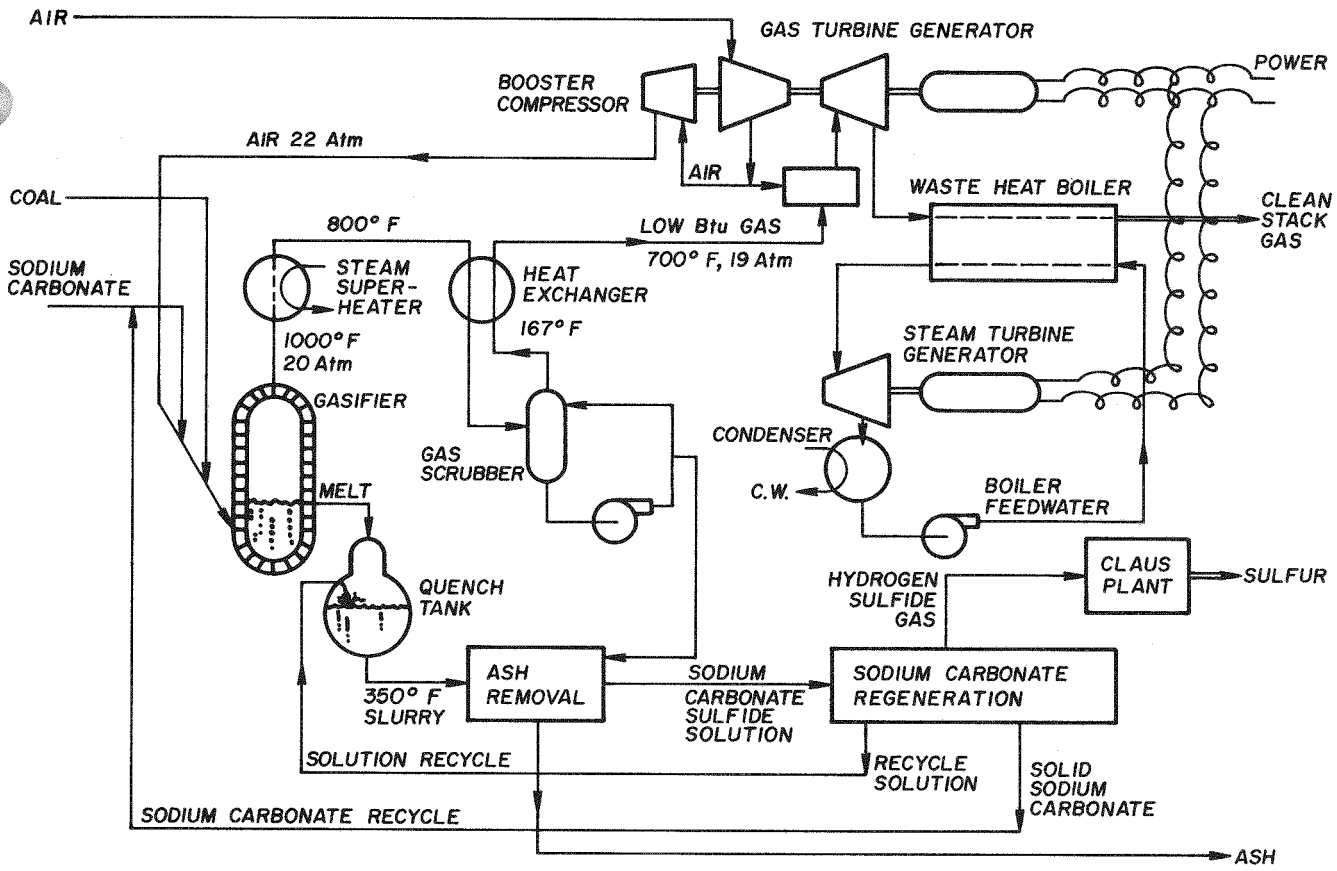


Figure IX-2. MOLTEN SALT GASIFICATION PROCESS SCHEMATIC

retained in the melt, minimizing the requirements for product gas cleanup.

- The sulfur of the coal is recovered in elemental form, minimizing storage, handling, and marketing problems.
- The molten salt gasifier operates in a stable manner over a wide range of air and coal feed rates, indicating the potential for good load following capability.
- The overall process has a high thermodynamic efficiency.
- The process shows a good potential for the economic generation of electric power.

HISTORY OF THE PROJECT

Before December 1974 (when ERDA and industry began co-sponsoring the previous project), Atomics International did extensive experimental work to develop the molten salt combustion and gasification process. Tests were initially conducted in a laboratory-scale unit and then in a bench-scale combustor. The purpose of the experimentation was to determine combustion rates, conditions for obtaining different ratios of carbon monoxide to carbon dioxide, ash-melt interaction, ash capacity of melt, chemical reaction of sodium carbonate with ash, and suitable metal to withstand corrosion. The tests revealed that the combustion rates achieved for various feedstocks such as char, coal, coke, etc., with wide ranges of fixed carbon, volatile matter, sulfur, and ash contents were much greater than with conventional burning. In addition, the tests showed that the process was environmentally acceptable as well. Atomics International concluded that the molten salt process was sound and that a pilot plant should be constructed and operate 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 field laboratory in Santa Susana, California. It was further decided that a one-ton-per-hour plant would be constructed rather than the original five-ton-per-hour facility. During the first quarter of 1976, the proposal to construct the one-ton-per-hour plant was reviewed by ERDA and the development contract for the five-ton-per-hour facility was terminated.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

It was decided during October that Atomics International (AI) would conduct all the detailed design work for the process development unit (PDU). This decision was the result of a review with ERDA representatives of alternative design approaches. During the quarter the gasifier enclosure structure was redesigned and simplified, the site layout prepared, and the soil survey completed. An application to construct the PDU was submitted to the District Director of the Air Pollution Control District in December.

Specification preparation for identified long-lead-time procurement items for the PDU was completed. Reports were completed covering the thermal analysis performed in support of the gasifier design and the stress design of the pressure vessels.

Process Development Unit

Overall Plant Design

The evaluation of the previous approach of subcontracting part of the design package for the process development unit (PDU) indicated that significant cost and schedule overruns would occur. Consequently, after alternative design approaches were reviewed with ERDA representatives in October, a decision was made to conduct the entire detailed design effort within Atomics International.

The delay in initiating the facility detailed design work, as well as insufficient time allocation for subcontractor bidding, approval, and negotiation in the original schedule, necessitated preparation of a new schedule. Figure IX-1 reflects the new schedule.

PDU detailed design work began on November 1. The gasifier enclosure structure was redesigned and simplified as a result of the 25 percent design review. A 25 percent review of the detailed site layout was also performed. The soil survey of the PDU site was completed and the report received.

At a November meeting with the Ventura City Planning Commission and Air Pollution Control District (APCD) representatives, AI was informed of a new APCD rule adopted in September which significantly reduces the allowable amount of pollutants released from a new source. The new standards necessitated a revision of the process material balance and a resizing of the affected plant components. The application for authority to construct the PDU was submitted to the District Director of he APCD in December.

Process and Systems

Specification preparation for identified long-lead process equipment items was completed and purchasing began during the quarter. A schedule based on anticipated delivery and construction need dates was prepared for the procurement of all remaining major equipment.

The review of the main combustion air compression system was completed and a proposed subcontract submitted to ERDA.

Instrumentation and Controls

During the quarter, the piping and instrumentation diagram and the instrument index were approved and released. The procurement list for all process instrumentation and control items to be purchased by AI was compiled.

Additional instrumentation and control items will be obtained as surplus from other ERDA programs, by equipment vendors as subsystem parts, or supplied by the construction subcontractors.

Components

A report covering all the thermal analyses performed in support of the gasifier design was completed and released. A stress report covering the design of the pressure vessels was also completed.

The engineering specifications and drawings for all long-lead gasifier/quench system components were completed. Bids for the gasifier, melt withdrawal chamber, and quench tank were received and a vendor selected.

X. ADVANCED COAL GASIFICATION SYSTEM FOR ELECTRIC POWER GENERATION

WESTINGHOUSE ELECTRIC CORPORATION
LESTER, PENNSYLVANIA

PDU Site: Waltz Mill, Pennsylvania

Contract No.: E(49-18)-1514

Total Funding: $26,000,000 (through calendar year 1976)
ERDA: $22,000,000
Industry: $ 4,000,000

INTRODUCTION

The advanced coal gasification system for electric power generation is being developed by Westinghouse Electric Corporation. ERDA is providing the major portion of the funds through the pilot development unit. Industrial contributions to 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 advanced coal gasification system for electric power generation is provided in Figure X-2. Production of low-Btu gas by this process requires completion of three operations: coal preparation, devolatilization-desulfurization, and gasification-combustion. In the coal preparation section, the coal is crushed to −6 +600-mesh, dried, and transported to a reactor vessel for devolatilization-desulfurization

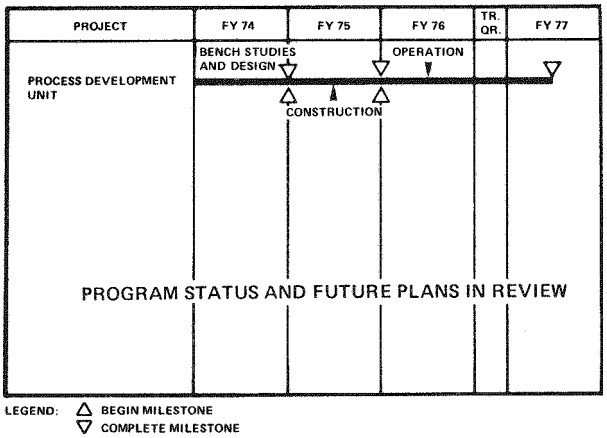


Figure X-1. ADVANCED COAL GASIFICATION PROGRAM SCHEDULE

and partial hydrogasification. A central draft tube is used primarily for recirculating solids. Recycled solids required to dilute the feed coal and temper the hot inlet gases flow downward in the fluidized bed surrounding the draft tube. The fluidizing agent is a portion of the gases entering the unit. Recirculating solids have flow rates up to 100 times the coal feed rate to prevent the agglomeration of the feed coal as it devolatilizes and passes through the plastic or sticky phase. Dense, dry char collects in the fluidized-bed at the top of the draft tube and is withdrawn at this point. Dolomite or Calcium oxide (sorbent) is added to the fluidized-bed to absorb the sulfur present as hydrogen sulfide in the fuel gas. Spent sorbent is withdrawn from the bottom of the reactor and regenerated. Heat for devolatilization is supplied primarily by the high-temperature fuel gas produced in the gasifier-combustor. After separation of fines and ash, product gas is cooled and scrubbed with water for final purification.

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

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

- Uses a variety of coals, including caking and high-ash coals, without costly pretreatment.
- Utilizes a wide range of coal particle sizes without extraction of fines.
- Operates at high thermal efficiency.
- Reduces heat losses by conducting desulfurization at an elevated temperature.

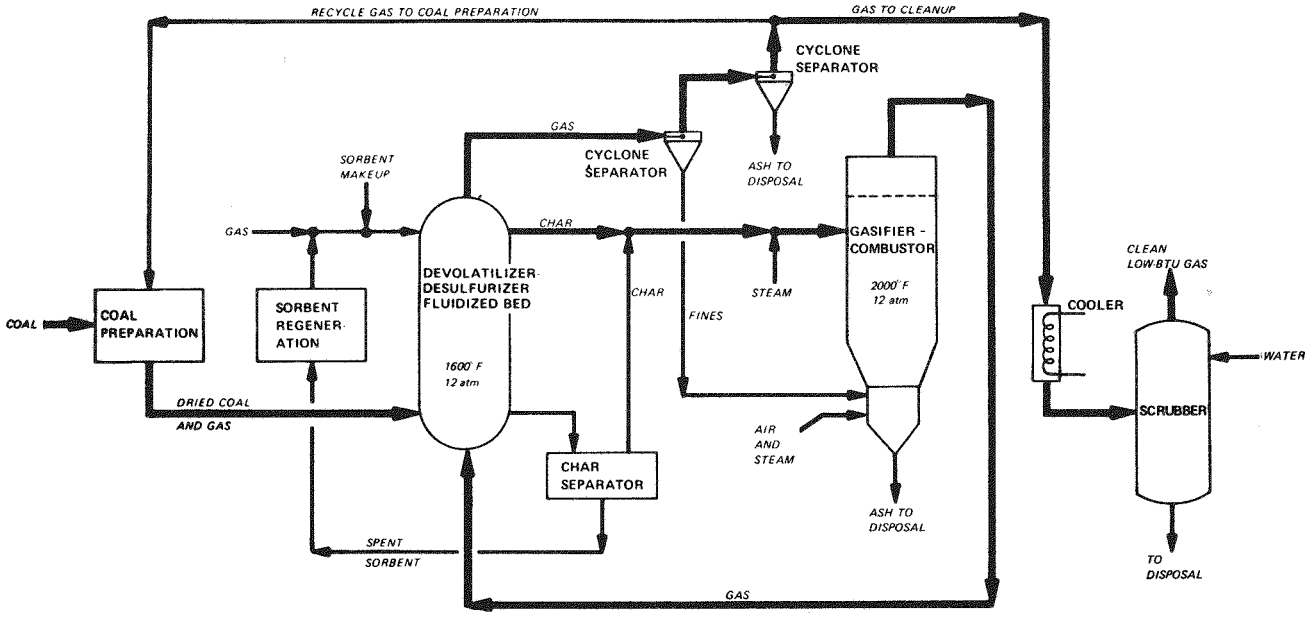


Figure X-2. SCHEMATIC OF ADVANCED COAL GASIFICATION SYSTEM FOR ELECTRIC POWER GENERATION

- 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 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 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.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

During the quarter, an analysis of devolatilizer test data for all the tests conducted in the past year was performed to determine the effects of various parameters on the growth or attrition of particles in the devolatilization process. Analyses of Tests TP-009 and TP-010 were also completed.

In the gasifier section of the process development unit (PDU), initial shakedown tests (TP-001/006) as well as hot test TP-011-1 were completed. Compilation of data for both tests continued.

The primary PDU support activities were directed to support of the combustor-gasifier operation. The semi-circular model was operated to simulate the combustor-gasifier.

Devolatilizer Tests

An analysis of devolatilizer test data for all tests conducted in the past year was performed during the quarter to determine effects of various parameters on the growth or attrition of particles in the devolatilization process. A dimensionless particle-size parameter (char particle/coal particle size) was plotted versus freeboard velocity, coal rank, temperature, residence time, and a solids loading parameter (coal feed/gas flow rate). Two significant correlations found were that particle size was a strong function of freeboard velocity and a moderately strong function of coal rank. In both cases, the particle size of char in the reactor was found to increase with increasing velocity and rank. An additional correlation study revealed that the char product to overhead fines ratio decreased with freeboard velocity, while the ratio of char plus overhead products to coal feed rate remained essentially constant at all freeboard velocities. The latter correlation indicated that about 65 percent of the coal was collected as char products. These correlations indicated that there was little net growth of particles in the devolatilizer, but the bed particle size increased with velocity, based on the fluid mechanical separation of fines as velocity increased.

An analysis of solids taken from test run TP-009-2 during the period of dolomite feed to the reactor showed that some separation of char and dolomite was achieved. Some smearing of the dolomite surface with tars occurred, and very little sulfur was absorbed by the dolomite.

Gasifier Process Development Unit

In preparation for initial shakedown tests of the

gasifier, local and state agency reviews were conducted, and permits and approvals were granted as follows:

- Pennsylvania Department of Environmental Resources—inspected the site and granted a one-year operating permit.
- Pennsylvania Department of Labor and Industry —inspected pressure vessels and steam boilers for coding requirements and issued pertinent permits.
- Factory Mutual Insurance—granted approval for operation and design of the startup propane burner for the gasifier.
- Westinghouse A.R.D.—amended the operating license to provide for operation of the K-Ray nuclear densitometer on the gasifier test system.

Tests TP-001/-006 shakedown tests were completed in the gasifier system of the PDU during November. The first gasifier hot test, TP-011-1 was completed in December. Compilation of the data from both tests continued after the end of the quarter.

Test TP-011-1 used coke breeze from a Pittsburgh seam coal as the char feedstock. Despite the hardware problems encountered, the following objectives of the test were achieved:

- The gasifier was started at a cold condition, and steady-state operation was achieved.
- The char was ignited with hot air at 1000° F, and the reactor temperature was controlled with steam.
- Char, devolatilizer fines, and recycled gasifier fines were fed on a continuous, controlled basis, while ash product was discharged from the bottom of the unit.
- Baseline data was provided for fluidized-bed operation in the ash agglomeration combustor and in the gasifier for all transport lines.
- A shakedown of the equipment problems that could be corrected by procedural changes or by the repair, replacement, or redesign of PDU hardware was provided.
- Operator training was provided for all crews.

Support Studies

After experimental tests to study the effect of the expanded section on slugging were completed in October, the semi-circular column was modified to the gasifier-combustor configuration. Tests in the semi-circular model in November studied the effect of air tube position on the solid exchange rate between the gasifier and the combustor and the jet penetration. Seventeen test series were completed during December. The effect of changing gas flows from the air jet, the char-ash separator, and the conical distributor for different positions of the jet nozzle continued to be studied to determine the impact on solid circulation, jet penetration, and slugging bed height.

After the calibration runs of the fluidized-bed laboratory test unit were completed in October, a gasification test run was conducted with Minnehaha char. Further experiments on char-steam and char-carbon dioxide reactions continued during the rest of the quarter.

Construction of the bench-scale ash agglomeration combustor approached completion. Work continued in the areas of sorbent behavior and reactor analysis.

XI. LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT

Plant Site: Windsor, Connecticut

Contract No.: E(49-18)-1545

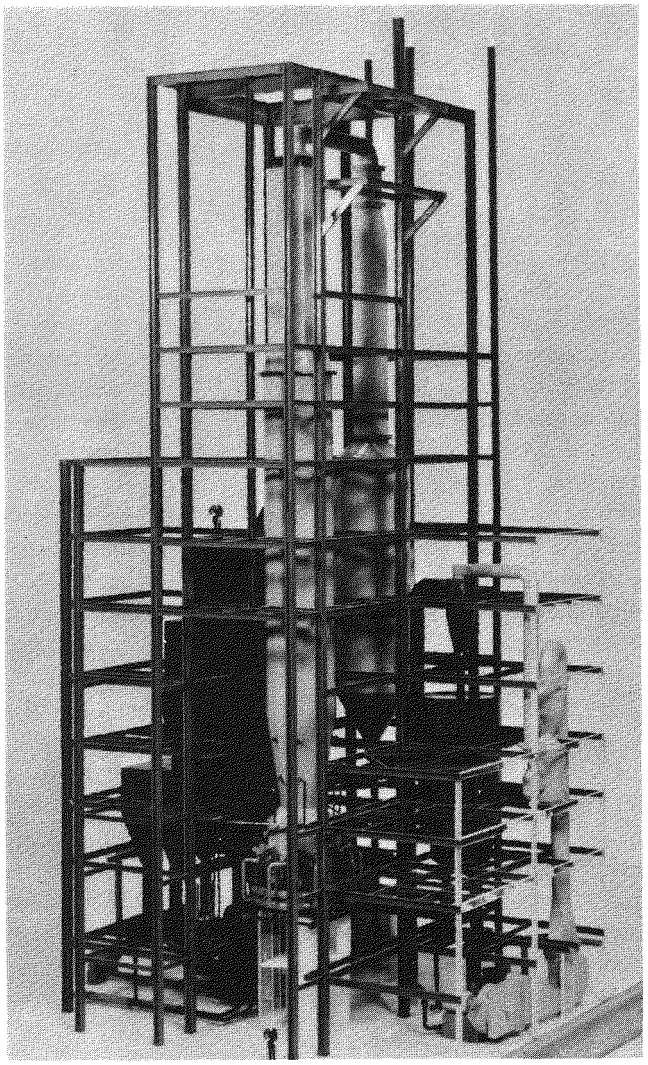
Total Funding: $20,609,084
ERDA: $13,739,389
Industry: $ 6,869,695

INTRODUCTION

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

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

Combustion Engineering also has a continuing research program to refine the process and verify its technical and economic feasibility. The schedule for development of this low-Btu gasification process is provided in Figure XI-1.



PROCESS DESCRIPTION

The Combustion Engineering gasification process is

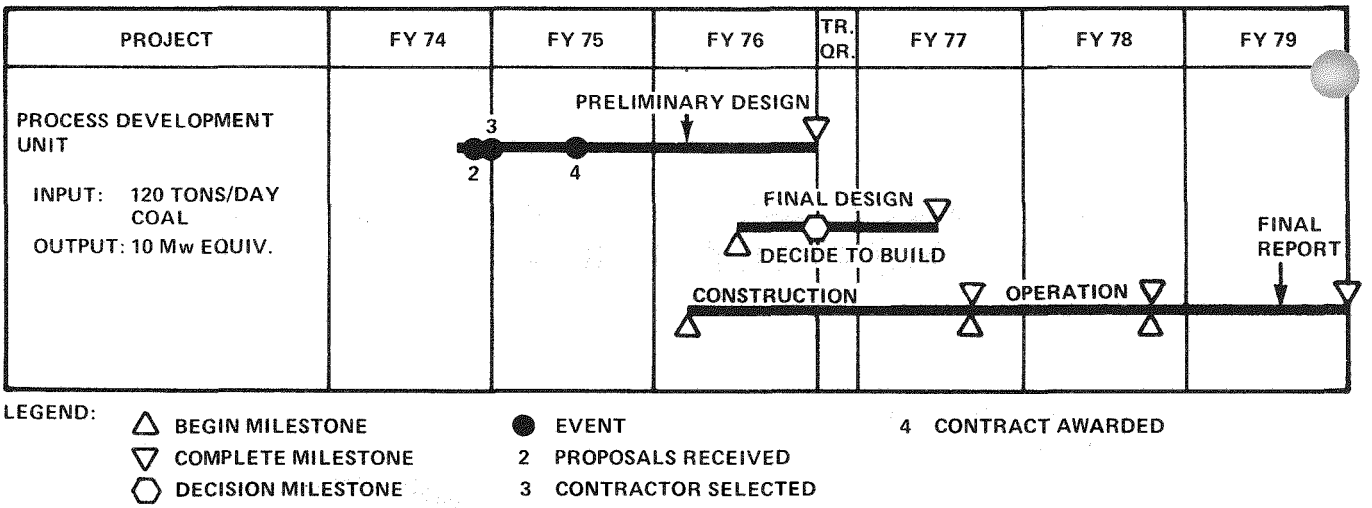


Figure XI-1. LOW-BTU GASIFICATION PROGRAM SCHEDULE

based on an air-blown, atmospheric-pressure, entrained-bed gasifier. A schematic of the process is provided in Figure XI-2. In the process, a portion of the pulverized coal and recycled char are fed to the combustion section of the gasifier and burned to supply the heat necessary for the endothermal gasification reaction. In the combustion section, nearly all of the ash in the system is converted to molten slag, which is then drawn off the bottom of the gasifier. The remainder of the pulverized coal is fed to the reduction portion of the gasifier where it is reacted with steam and hot gases entering the reduction zone from the combustor. The gasification process takes place in the entrainment portion of the reactor where the coal is devolatilized and reacts with the hot gases to produce the desired product gas. This 1600° F product gas is then cooled to 300° F. At this point, the gas contains solid particles and hydrogen sulfide that must be removed. Solids are removed and recycled by means of a spray drier, cyclone separators, and venturi scrubbers. Hydrogen sulfide is removed and elemental sulfur produced by the Stretford process. The clean low-Btu gas (127 Btu per standard cubic foot) can then be delivered to the burners of power boilers, gas turbines, or combinations of the two in a combined-cycle power generator.

Operating conditions will have a variety of effects on the cost and quality of the gas produced in this system. For example, oxygen could be substituted for air in the gasifier combustor, thereby increasing the heating value of the product gas from 127 to 285 Btu per standard cubic 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.

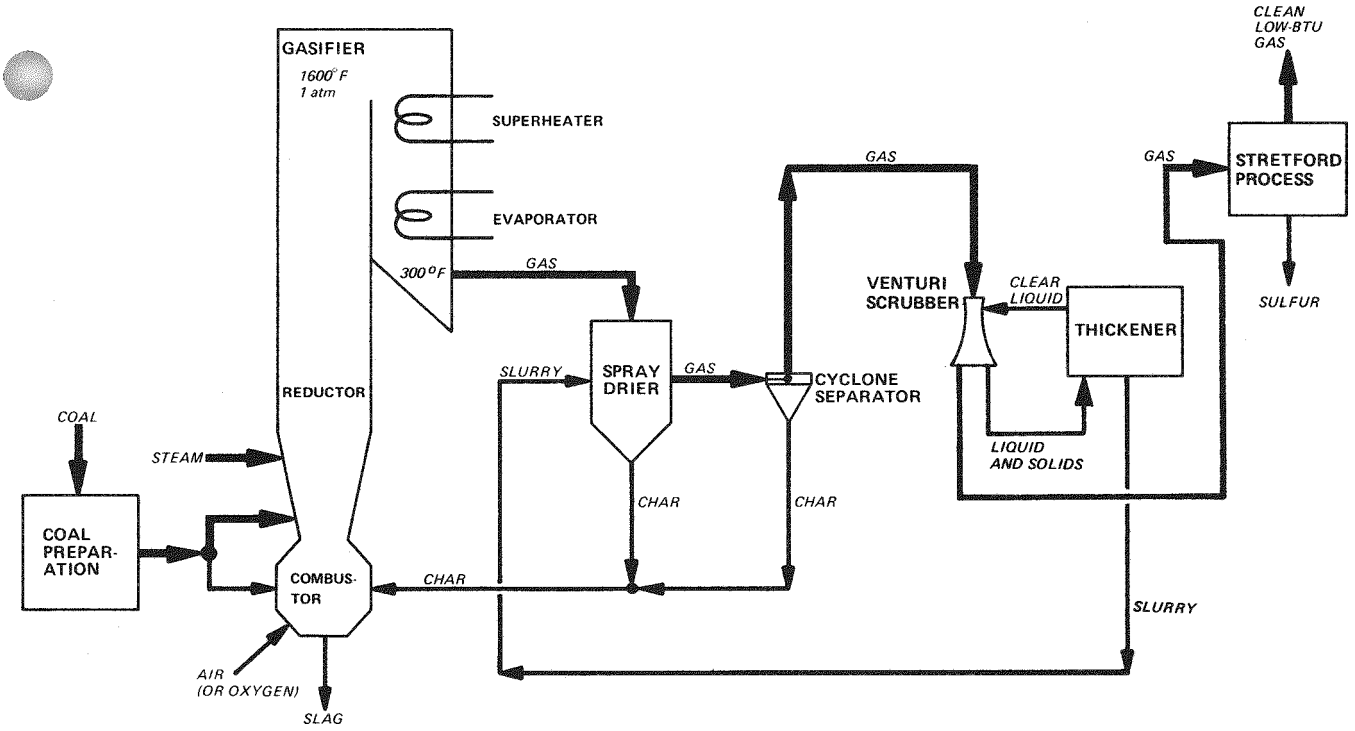


Figure XI-2. SCHEMATIC OF LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

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

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

Design of the process development unit began in 1974. The unit, to be located at Windsor, Connecticut, will have a capacity of five tons of coal per hour. The objectives of this phase include (1) development of component and process concepts and details necessary for the design and operation of gasification systems of this type and (2) completion of the engineering required for construction of the unit. Detailed engineering has been completed and construction is scheduled to be completed in early 1977. Operations are expected to continue until mid-1978.

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

By the end of the quarter, an estimated 38 percent of the entire plant construction was complete. The site preparation, prefabricated buildings, and the structural steel and grating work were completed. Major equipment continued to be delivered to the site and equipment erection was 43 percent complete.

With the exceptions of the slag and refractory compatibility evaluations, and the study of electric plant applications, all research and development work was completed and preparation of the final task report review was continuing. Atmospheric disintegration testing began and the series of dynamic slag-refractory tests was completed.

PROCESS DEVELOPMENT UNIT

An estimated 38 percent of the entire plant con-

struction was complete as of the end of the quarter. The site preparation, prefabricated buildings, and structural steel and grating work were completed. The concrete work and the coal and underground work were 98 percent complete. Equipment erection was 43 percent complete and the structure winterization is expected to be finished in January.

Major process development equipment received at the site included: gasifier combustion waterwalls, spray dryer, thickener, hydrogen sulfide absorber, FD fan inlet silencer, slag handling system control panel, cooling tower, and the air-water cooler.

Instrumentation and controls remained critical path items to the scheduled PDU startup date. A fabrication schedule for the digital control system and the control room console was completed in December. C-E Controls was to begin assembly on an accelerated basis of the consoles and related PDU control room equipment in January. It was anticipated that the C-E control equipment would be nearly complete by May 1977.

In preperation for shakedown testing of the PDU, work continued on the construction and startup schedule. The hiring schedule for the PDU operators and technicians was revised, incorporating more complete subcontractor specification information and training plans. The controls specialist for the PDU was selected from the field service startup department. The operator's instruction manual was prepared and work began on a detailed training program and schedule.

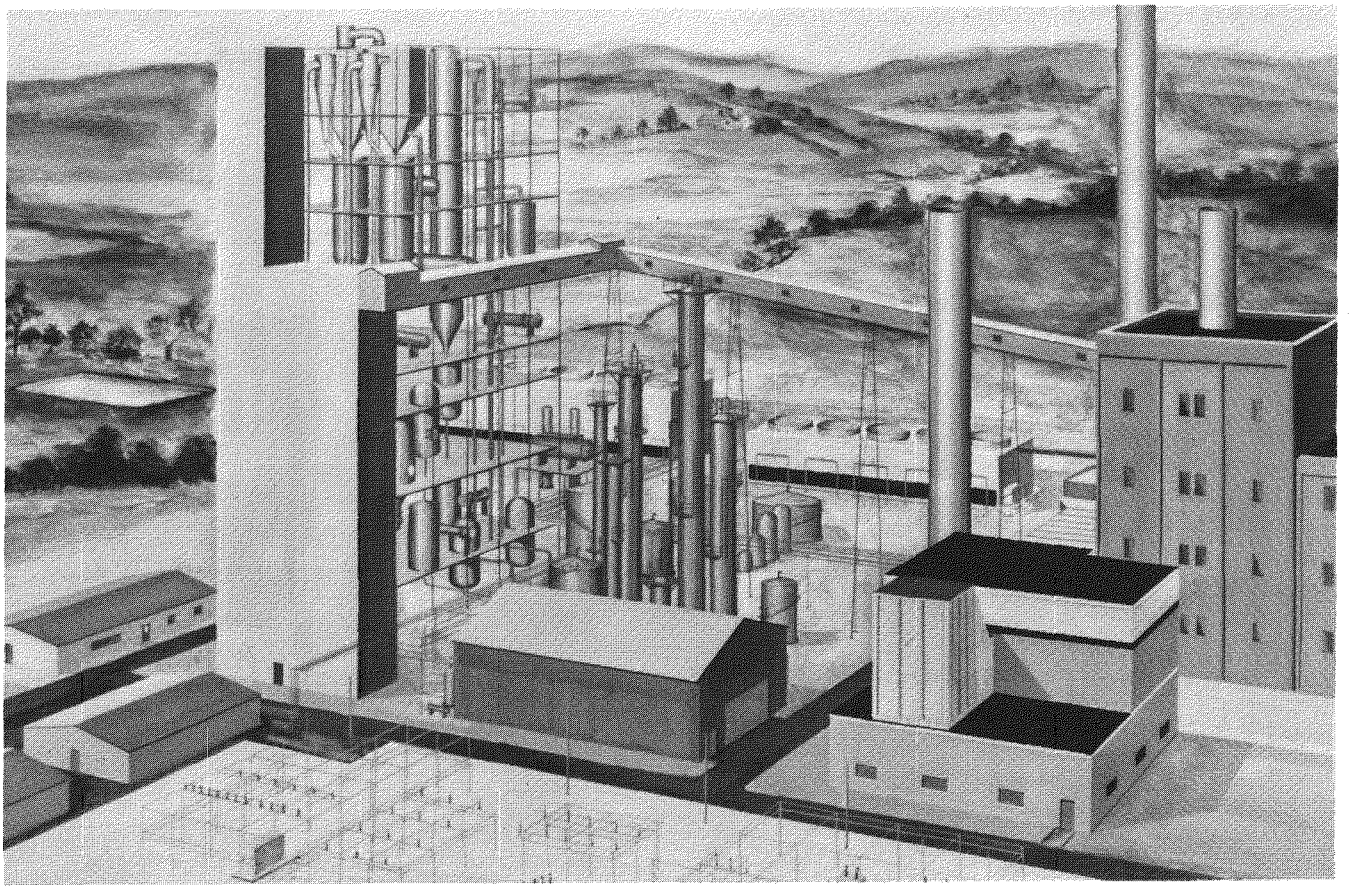
Supporting Studies

With the exceptions of the slag and refractory compatibility evaluations, and the study of electric plant applications, all research and development work were completed and final task reports were being reviewed.

The furnace installation for performing atmospheric disintegration testing of refractories planned for the PDU was finished and testing began in November. Five gas atmosphere tests were conducted to evaluate the performance of two refractories, 90 Ram PC and 90 Ram HS, which will be used in the long-slagging zone of the gasifier.

Porosity and average pore size analysis for candidate refractories were completed. The refractory characteristics within the heat-affected zone controls the rate at which the slag will penetrate the refractory.

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



FOSTER WHEELER ENERGY CORPORATION
LIVINGSTON, NEW JERSEY

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

INTRODUCTION

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

PROCESS DESCRIPTION

A schematic of the projected coal gasification combined-cycle system is provided in Figure XII-2. In this

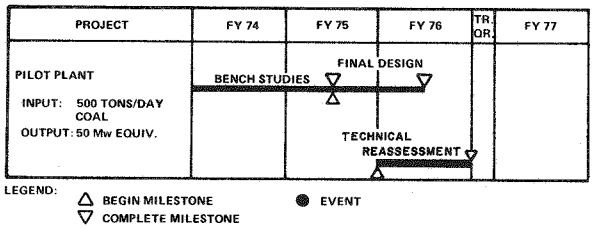


Figure XII-1. COAL GASIFICATION COMBINED-CYCLE SYSTEM PROGRAM SCHEDULE

process, coal is dried, pulverized so that 70 percent will pass through 200-mesh, and fed to the upper section (Zone II) of the gasifier via lock hoppers. The coal is gasified by steam and the hot gases rising from the lower section of the gasifier (Zone I). The low-Btu product gas leaving the gasifier passes through a refractory-lined cyclone separator to remove char. The char is cooled to approximately 800° F and injected into Zone I by superheated steam. The char reacts with the steam and air at 2800° F and is completely gasified. The ash becomes molten slag and flows from the bottom of the gasifier where it is quenched in water and withdrawn. A fluxing agent (limestone) is used to maintain proper viscosity of the slag. The hot reaction gases and carry-over char from Zone I rise into Zone II of the gasifier, thus completing the cycle.

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

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

One of the advantages of the system is that the entrained gasifier used has an inherent capability to handle agglomerating coals at high throughput. In addition, the reaction temperatures in the gasifier are high enough so that no tars or heavy hydrocrabons are produced. The environmental performance of the total system is expected to be excellent. Station heat rates for

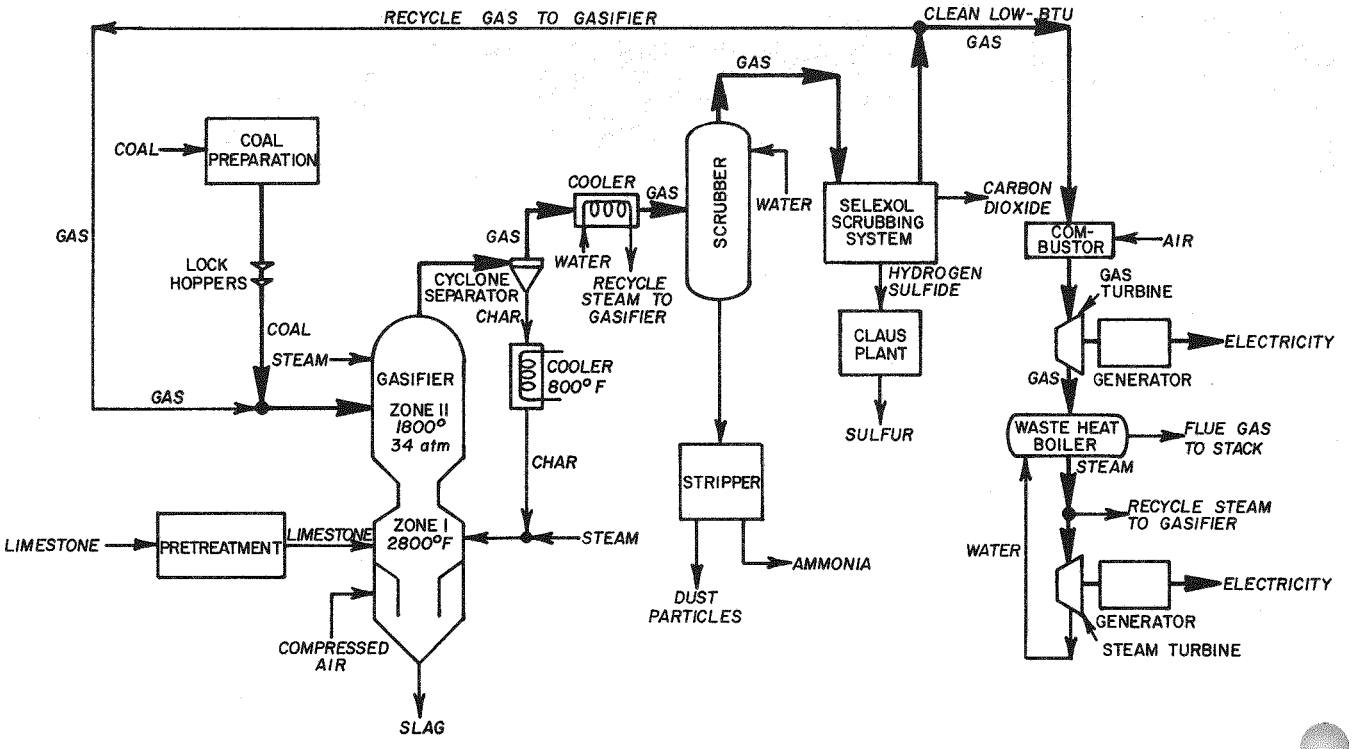


Figure XII-2. COAL GASIFICATION COMBINED-CYCLE SYSTEM SCHEMATIC

the system, employing gas turbines currently being developed by U.S. manufacturers, are expected to be ter than those obtainable from conventional power generation systems.

HISTORY OF THE PROJECT

Initial studies of the process, started in August 1972 and completed in March 1974, confirmed the technical feasibility of the process and established the process design basis. Under the current contract, signed on January 14, 1975, Foster Wheeler is responsible for the detailed design and engineering of a pilot plant with a capacity of 20 tons of coal per hour. General Electric Company, a subcontractor to Foster Wheeler, is providing assistance with the design of the gas turbine and waste heat boiler. The pilot plant is to be constructed at Northern States Power Company, Lawrence Generating Station, Sioux Falls, South Dakota. The design philosophy for the pilot plant is to concentrate the technology development efforts on the gasifier and its related equipment. Commercially proved equipment and processes will be used, where possible, throughout the remainder of the system to minimize overall development problems.

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

PROGRESS DURING OCTOBER-DECEMBER 1976

Throughout the reporting period, Foster Wheeler, in conjunction with the other industry team members, continued to develop the pilot plant design. The work effort was consistent with the intermediate steps scheduled for the period, and none of the various team members reported any particularly unusual delays or interruptions that would prevent the project from maintaining the established schedule. In the absence of any such reports of delays or problems, it was concluded that the corresponding schedule milestones would be met.

More specifically, such points as the conceptual design efforts dealing with commercial plants, as listed in the last quarterly report, remained under investigation. Additionally, the team assigned to review the draft of the Pilot Plant Design Report continued their examination of all of the process and mechanical design information completed to date. Both the System Transient Analysis and the Cold Flow Model test results and changes discussed in the last quarterly report remained under investigation and were being evaluated in greater detail.

No problems were reported during this period which seemed to be insurmountable and no particular changes in the program are anticipated at this time.

XIII. LOW-BTU FUEL GAS

BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

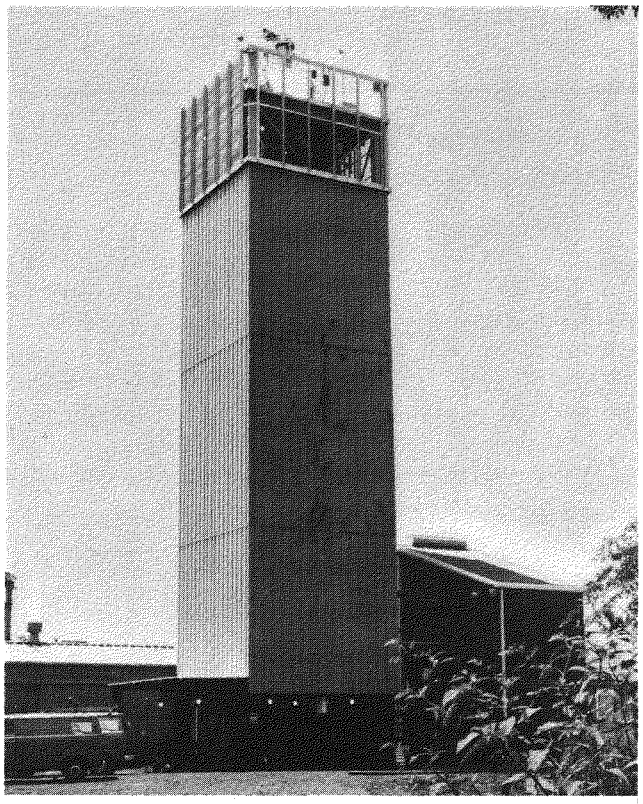
Plant Site: Monroeville, Pennsylvania
Contract No.: E(49-18)-1527
Total Funding: $2,665,000
(100% ERDA)

INTRODUCTION

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

PROCESS DESCRIPTION

The BCR low-Btu research effort is based on a three-stage fluidized-bed gasification process. Because BCR has applied for a patent for the process, no specific process information will be available until the U.S. Patent Office rules on its patentability. Generally, however, Stage 1 of the three-stage system receives the raw coal and functions as the pretreatment step in which the coal is devolatilized. Several pretreatment media have been investigated and have shown to be effective.



In this scheme, Stage 3 flue gas is used as the fluidizing medium for Stage 1. The coal then flows by gravity to Stage 2, the major gasification stage in which the devolatilized coal is gasified with air and either steam or carbon dioxide to generate the desired product gas. In addition, Stage 1 flue gas is fed to Stage 2 where the entrained tars and oils are gasified. Stage 3 operates at the highest temperature and serves to maximize carbon utilization. The ash discharged from Stage 3 will contain only a minimum amount of carbon. Hot flue gas from Stags 3 flows to Stage 1, thus completing the cycle.

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; that is, no wastes or by-products such as tars and oils are produced. The end

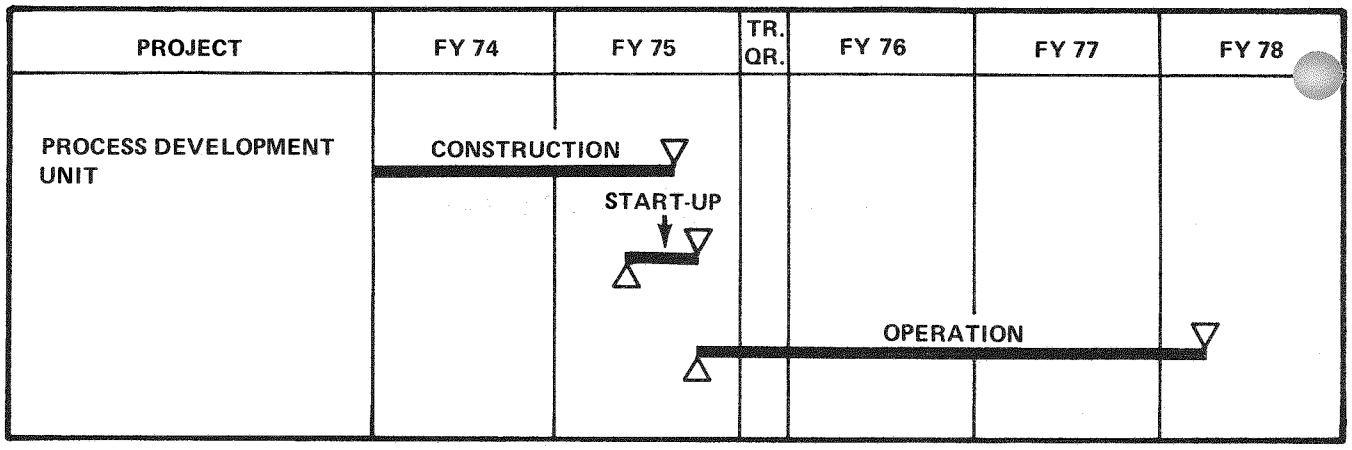


Figure XIII-1. LOW-BTU FUEL GAS PROGRAM SCHEDULE

use of the gasification product dictates the operating conditions as well as the gasifying medium. For example, gasifying with air and steam will yield a low-Btu fuel gas, gasifying with oxygen and steam will yield a higher-Btu gas, and gasifying with carbon dioxide will yield a gas rich in carbon monoxide that could serve as fuel for power generation by magnetohydrodynamics.

HISTORY OF THE PROJECT

Initial development of the low-Btu fuel gas process involved laboratory investigations to obtain kinetic data for various chars, or devolatilized coal, that would be produced in the first step of a multiple fluidized-bed gasification process. A small fluidized-bed batch reactor system was then used to verify proposed rate equations, determine the reaction rate between steam or carbon dioxide and char that could be achieved in a reactor of reasonable size, 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.

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. A data-acquisition system has been installed to sample selected test points, convert the data to engineering units, and store the values on magnetic tape.

Concurrent with the construction effort, BCR is conducting laboratory research in an effort to further refine the low-Btu fuel gas process. During 1975, laboratory research included using a cold flow model of the gasifier bed to study bed fluidization. Fluidization was improved when a 45-degree conical, rather than flat, distributor was installed in conjunction with special nozzles that direct the fluidizing gas 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 1976

Summary

Devolatilization/pretreatment tests completed du[illegible]g

the quarter used Illinois No. 6 seam coal as the feed to Stage 1. Devolatilization tests were conducted in the ge 1 reactor at temperatures greater than the softening temperature of the feed coal and in Test No. 14, no agglomerates were formed.

During Test No. 15 some agglomeration did occur at the coal feed nozzle. A new nozzle was designed and installed to overcome this problem. Agglomeration also occurred when bed temperatures were increased too rapidly and when a larger than normal char inventory was used.

The tests performed during the quarter also identified a control problem in the system. Consequently a new system to control bed height was developed, and a cold test was conducted to demonstrate the feasibility of the system. Modifications allowing three-stage operation of the process and equipment development unit were also completed.

Process Development Unit

Devolatilization Tests Nos. 14 and 15 were completed in October and consisted of batch pretreatment of the Illinois No. 6 coal feed to Stage 1. Temperatures above 775° F, the temperature at which the Illinois No. 6 coal began caking in the TGA tests, was chosen for Test No. 14 in order to determine whether the coal could be successfully devolatilized without the formation of agglomerates. Evidence of caking or plugging was not apparent during the test and inspection after completion of the test confirmed that caking had not occurred.

During Test No. 15, bed temperatures were increased by raising the oxygen content of the feed gas to 3.6 percent by volume, resulting in the bed temperature reaching 900° F. After 1¼ hours at that temperature, difficulty in feeding the coal was encountered. Gas temperature at the exit of Stage 1 reached 800° F, indicating that the refractory walls in the reactor were hot enough to have caused agglomeration at the point where the coal feed line entered the vessel. To eliminate this possibility, a water-cooled nozzle was designed to extend far enough into the vessel to allow the coal to drop directly into the bed without contacting the hot refractory walls.

Test No. 16 was conducted in the Stage 2 reactor using char from Test No. 14. The purpose of the test was to familiarize personnel with Stage 2 operation and to check out all the Stage 2 associated systems. During the test, no caking was noticed in the bed, thus indicating that the char had been successfully pretreated. The bed flowed smoothly from the reactor at the conclusion of the test.

Test No. 17 was run under conditions similar to Test No. 15, except that the bed temperature was raised from 750° to 900° F in 15 minutes instead of two hours, as for Test No. 15. From the data taken during Test No. 17, it was determined that agglomeration occurred in the bed shortly after the temperature reached 900° F.

In Test No. 18, 80 pounds of char produced in Test No. 17 was placed in the Stage 1 reactor. After a constant temperature of 1000° F was maintained in the bed for 1½ hours, the coal feed was started. After approximately one hour, difficulty was experienced in feeding the coal and withdrawing the char. Upon weighing the bed, it was found to have covered the feed line, thus causing the feeding problems.

In December, a system to control bed height and not bed weight was developed to prevent overfilling the reactor. The new control system is based on a pressure drop between a tap installed through the alternate withdrawal nozzle and the top of the reactor. The tap location can be adjusted to vary the bed height.

Devolatilization Test No. 20 was made in the Stage 1 reactor to try the new level control system, but was terminated when a plugged pressure tap resulted in an erroneous signal. A cold test made in the Stage 1 reactor to check out the new control system demonstrated the feasibility of the new system.

Laboratory Studies

Laboratory TGA tests made on chars from Tests Nos. 14 and 15 showed that the caking tendencies in an inert atmosphere had been completely destroyed by pretreatment of the coal.

XIV. DESULFURIZATION OF LOW-BTU PRODUCER GAS

AIR PRODUCTS AND CHEMICALS, INC.
MARCUS HOOK, PENNSYLVANIA

Plant Site: Morgantown, West Virginia
Contract No.: E(49-18)-2033
Total Funding: $467,200
(100% ERDA)

INTRODUCTION

Air Products and Chemicals, Inc. (APCI), under the sponsorship of ERDA, is conducting a research, development, and engineering support program to accelerate the development of a solid-absorbent system for desulfurizing hot, low-Btu producer gas. This system, being developed by ERDA at the Morgantown Energy Research Center (MERC), involves the use of a cyclic, fixed bed with iron oxide on fly ash as the absorbent, at producer gas temperatures and pressures. The specific objectives of the APCI support program are development of an iron oxide/fly ash absorbent, definition of process scale-up criteria, and process design of a commercial-size system.

PROGRAM DESCRIPTION

This support program began in July 1975 with an estimated duration of 16 months. It is composed of several tasks. Initially, APCI will identify practical sources of iron oxide, since experimental work to date has used Technical Grade iron oxide, an expensive and not readily available material. There are several sources which yield iron oxide in a reasonably concentrated form and offer large volume raw material potential at costs well below those of Technical Grade iron oxide. Iron oxide/fly ash absorbent samples will be prepared using different sources and levels (10, 15, 20, and 25 percent) of iron oxide. Kaolin and bentonite will be evaluated as possible binders. Pertinent physical properties such as bulk density, crushing strength, porosity, hydrogen sulfide absorption capacity, and pore size distribution will be measured.

Standard dynamic absorption tests will be conducted to determine the hydrogen sulfide absorption characteristics of the samples. These tests will be conducted in an existing ERDA 12-inch-diameter pressurized reactor with on-line gas chromatograph sampling. Sorbent performance will be characterized by a parameter defined as "breakthrough". This parameter is defined as the point at which a certain, designated hydrogen sulfide concentration is observed in the reactor offgas stream. For example, the ten percent breakthrough time is the on-stream time experienced by a sorbent when the offgas hydrogen sulfide concentration reaches ten percent of the concentration in the feed gas. Sorption efficiency is defined as the on-stream time required for a designated breakthrough percent divided by the perfect sorption time (the time required to saturate the bed with sulfur if all the entering hydrogen sulfide was retained in the bed). It should be noted that the perfect sorption time is dependent only on the quantity of hydrogen sulfide and is independent of the space velocity and the concentration of hydrogen sulfide. The results obtained with the samples will be compared with those obtained using an iron oxide/fly ash absorbent with 25 percent Technical Grade iron oxide. The results of this effort

will permit (1) selection of a readily available and relatively inexpensive source of iron oxide with absorption characteristics that are essentially equivalent to those of Technical Grade iron oxide and (2) determination of the effect that varying the iron oxide content will have on the physical and chemical properties of the absorbent.

To define the critical parameters to be used for scale-up of the process to commercial size, APCI will use an experimental process system that was developed under a previous ERDA contract. This system, referred to as the ERDA pressure unit, consists of a 12-inch-diameter isothermal reactor containing the iron oxide absorbent. The feed gas is a synthesized, low-Btu producer gas prepared by metering and mixing the constituent gases. The system will provide an experimental measurement of such parameters as reactor temperature, bed depth, absorbent characteristics (iron oxide content and pellet size), and hydrogen sulfide concentration. Results of the tests will be correlated and performance curves will be computed to fit the model to the results obtained so that the model describes absorption dynamics and accounts for all the process variable interactions.

After the accuracy of the model has been confirmed, the model will be modified to include the heat effects of both the gas and solid phases. Specifically, APCI will develop equations for heat effects within the particle and in the bed, develop heat transfer effects for a tubular heat exchange model, and combine these equations with the absorption rate equations. The resulting model will be used as a basis for developing performance curves for a reactor with a 36-inch diameter. Heat effects in commercial-scale equipment will be predicted through the use of computer simulation. Various heat removal schemes will also be evaluated.

To estimate optimum conditions for a commercial-size design, simplified economic and energy utilization algorithms will be developed. Operating constraints will be set and optimization will be achieved by computer search. To provide a basis for predicting coke formation and its effect on absorption, dynamic absorption runs will be conducted with tar added to producer gas. The coking rate as a function of tar content, temperature, and time, and also the effect of coke level on dynamic efficiency will be evaluated. The effects observed will be incorporated into the model. The loss of efficiency caused by coke formation and the addition of heat caused by coke combustion will be projected for commercial operations, and process optimization will be reevaluated.

PROGRESS DURING OCTOBER-DECEMBER 1976

During this reporting period, the experimental phases of the contract were completed and preparation of the final project report began. The report is expected to be completed during the first quarter of 1977.

XV. THE COAL CONVERSION SYSTEMS TECHNICAL DATA BOOK

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Contract No.: E(49-18)-2286
Total Funding: $840,000
(100% ERDA)

INTRODUCTION

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

PROGRAM DESCRIPTION

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

The outline of the data book is shown below:

Section I. *PROPERTIES OF PROCESS MATERIALS*
- A. Properties of Gasification Products
- B. Properties of Intermediates and Conversion Products
- C. Properties of Related Processing Materials

Section II. *SOLIDS STORAGE, PREPARATION, HANDLING AND PRETREATMENT*
- A. Coal Storage and Handling
- B. Coal Preparation
- C. Weighing and Metering of Solids Flow
- D. Feeding of Solids
- E. Chemical Treatment of Coal

Section III. *CONVERSION FUNDAMENTALS*
- A. Gasification
- B. Pyrolysis
- C. Liquefaction
- D. Fluidized-Bed Combustion
- E. Advanced Power Generation
- F. Chemical Equilibrium and Heats of Reaction

Section IV. *DESIGN PROCEDURES*
- A. Conversion Tables and Constants
- B. Fluidization
- C. Fluid Flow
- D. Heat Transfer
- E. Phase Separations
- F. Integrated Reactor Design

Section V. *SUPPORTING PROCESSES*
- A. Gas Treating
- B. Gas Purification
- C. Shift Conversion
- D. Methanation
- E. Environmental Control

Section VI. *MISCELLANEOUS PRODUCTS*
- A. Methanol
- B. Acetylene
- C. Ammonia
- D. Fischer-Tropsch Liquids

Section VII. *MATERIAL OF CONSTRUCTION*
- A. Refractories
- B. Ceramics
- C. Metals and Alloys
- D. Plastics

Section VIII. *EQUIPMENT SPECIFICATIONS*

Section IX. *PROCESS ECONOMICS*
- A. Cost Data
- B. Costing Procedures

Section X. *PROCESS FLOW SHEETS*
- A. Liquefaction
- B. High-Btu Gasification
- C. Low-Btu Gasification
- D. Fluidized-Bed Combustion
- E. Advanced Power Generation

PROGRESS DURING OCTOBER-DECEMBER 1976

Summary

In the investigation of process materials, the vapor-liquid equilibrium data of oils in water and that of water in oils was studied and reviewed. Various properties of coal and coal liquids were given along with data on the upgrading of coal liquids for use as power generation fuels.

Coal cleaning, pulverizing, and storage was described in the area of solids preparation. Conversion fundamentals dealt with coal pyrolysis, design procedures involved pressure drop correlations, and supporting processes dealt with trace element disposition.

Properties of Process Materials

Vapor-liquid equilibrium data included data on the solubility of oils in water and that of water in oils. Vapor-liquid equilibrium correlations were developed for the NH_3-CO_2-H_2S-H_2O system, using Russian data on dissociation of hydrogen sulfide and solubility of carbon dioxide in water at elevated temperatures and pressures. Available data on partial pressures of ammonia in the N_2-H_2S-H_2O system were also used to eliminate the effect of the sonic ammonium hydrosulfide on the solubility of ammonia.

Influence of mining techniques (conventional and continuous) on size consist and washability of coal was discussed, and the the occurrence of trace elements in coal tabulated.

The properties of coal liquids were given along with combustion characteristics of solvent refined coal and data on the upgrading of coal liquids for use as power generation fuels.

Solids Storage, Handling, Preparation Pretreatment, and Feeding

If the higher specific gravity increments are removed from crushed coal, the percentage of sulfur in the remainder is generally significantly lower than in the total original material, and the ash content is similarly reduced. Consequently, the sulfur reduction in coal accomplished by washing was given for coals from different regions. Pulverization and storage characteristics of SRC were also described.

Conversion Fundamentals

Trace elements disposition in a Lurgi coal gasification plan was reported. Studies continued on the fundamentals of pyrolysis. Recent advances in pyrolysis processing have shown that significant increases in conversion, particularly to liquid products, could be achieved by control of the kinetic parameters as well as the chemical parameters (pyrolysis in the presence of hydrogen or hydrogen-transfer solvents). These concepts have been applied to only a few coals covering a relatively narrow range of composition. Insufficient data exists to discuss the interactive effects of the kinetic and compositional parameters, and particularly the controlling effect of composition of coal.

Correlation of data from preliminary studies strongly suggest that the primary factor determining the pyrolytic convertibility of a coal is the availability of hydrogen as reflected by the atomic carbon/hydrogen ratio.

Design Procedures

The comparison of selected pressure-drop correlations for dilute-phase, gas-solids vertical transport with the existing pressure-drop data on coal and related materials was completed during the quarter. Heat transfer correlations based on heat and momentum transport analogies and their applicability to slurry heat transport were discussed. In order to determine the pressure drop for solid-liquid flow through conduits, it is necessary to distinguish between different types of slurry-flow regimes that are characterized by the settling characteristics of solid particles. Classification of slurries based on flow regimes was studied and reviewed during the quarter; various pressure drop and critical velocity correlations will be presented next quarter.

Supporting Processes

The disposition of trace elements in coal combustion and their occurrence in water were reviewed.

XVI. COMPUTER MODELING OF COAL GASIFICATION REACTORS

SYSTEMS, SCIENCE, AND SOFTWARE
LaJOLLA, CALIFORNIA

Contract No.: E(49-18)-1770
Total Funding: $1,270,000
(100% ERDA)

INTRODUCTION

Under the terms of this ERDA contract, Systems, Science, and Software (S^3) 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 provide preliminary results relevant to coal gasification. A boundary layer formulation will be incorporated into the model and tested on configurations of various dimensions. A method to describe particle size distributions will be developed and integrated into the two-dimensional thermomechanical-chemical model, with heterogeneous chemistry coupled directly to the heat and mass transfer processes. The model will be

verified using pilot plant data and applied to specific problems of interest to ERDA. The computer model will then be developed further to include three-dimensional effects, internal heat transfer surfaces, and combustion chemistry, so that it can be applied to the broad spectrum of fluidized-bed and entrained-flow processes being considered for coal conversion and utilization.

PROGRESS DURING OCTOBER-DECEMBER 1976

A review of the fluidized-bed computer model was presented at the ERDA Fossil Energy Conference on Computerized Mathematical Modeling of Coal Conversion Processes on November 16. A paper entitled, "A Numerical Model of Gas Fluidized-Beds," summarizing some of the theoretical and numerical aspects of the model, was presented at the Annual Meeting in Chicago of the American Institute of Chemical Engineers.

A consultant, Professor Paul Libby of the University of California, San Diego, developed an analysis of the evolution of particle size distribution for dilute entrained flows, providing insight into the influence of turbulence upon the kinetics of single particles. He also presented model suggestions for the development of averaging techniques related to turbulent, particle-laden gases.

Professor C. Y. Wen of West Virginia University, a consultant, continued communications with S^3 staff members on coal chemistry related to steam-oxygen gasification. Staff members visited Professor Wen to examine models for heterogeneous gas-solid particle reactions.

During the quarter, the two-dimensional thermohydrodynamic code was used to study parametric influence upon non-reactive fluidized-bed flows. Reduction computer core requirements for the thermohydr namic model was completed, making it possible to perform calculations with an increased number of zones in the finite difference grid.

Work also continued on the formulation of the chemistry for steam-oxygen gasification processes. Source terms in the conservation of mass and energy equations for the combined chemistry-thermohydrodynamics code have been defined for the dominant heterogeneous oxidation or combustion reactions and for the related homogeneous oxidation and shift reactions.

The homogeneous reactor model (with the chemistry for the carbon dioxide acceptor process) was modified to treat nonisothermal processes and is, therefore, a more general representation of such homogeneous reactors. In order to treat the case of variable temperatures, the energy balance equation was solved simultaneously with the balance equations for the chemical species. The documentation of the homogeneous chemical reactor model was continued in the form of a topical report. The numerical methodology, as well as some of the chemistry in this computer program, should be applicable to homogeneous reactor models for other processes such as steam-oxygen gasification.

The formulation of the turbulence model for entrained flows continued during this quarter. Specific terms in the equations were formulated while the nature of other terms, such as turbulence influence upon the particle-gas drag relationship, were studied. The numerical code for the model system of equations continued to be developed. The code was tested on steady flows of viscous compressible gases and was extended to treat transient flows. Numerical procedures were evaluated for the integration of a system of equations which is mathematically similar to the system of equations for turbulent entrained flows.

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

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

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

INTRODUCTION

A six to seven-ton-per-day process development unit, operated by IGT under the HYGAS program, has demonstrated the operability of the ash-agglomerating process on coke feedstock. In 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.
- Provide design and cost estimates for both a commercial-scale atmospheric pressure gasifier and a pilot-scale pressurized gasifier.

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

- Modification and shakedown of the existing gasifier, including the addition of a thermal oxidizer.
- Operation of the process development unit for a sustained period of time.
- 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 XVII-1 provides a schedule for the ash-agglomerating gasification development.

PROCESS DESCRIPTION

The agglomerating ash 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 proces is shown in Figure XVII-2.

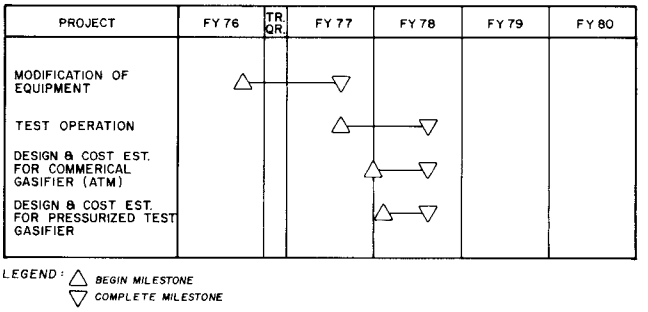


Figure XVII-1. ASH-AGGLOMERATING GASIFICATION PROJECT SCHEDULE

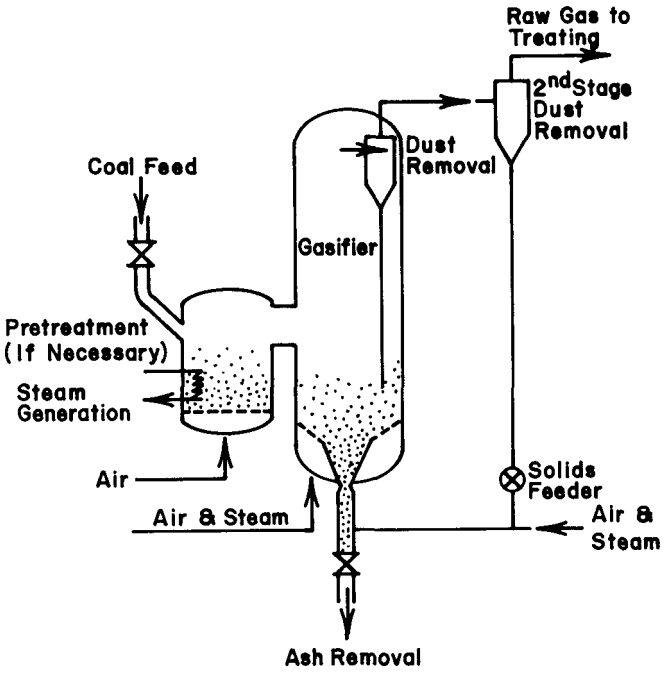


Figure XVII-2. FLOW DIAGRAM OF ASH-AGGLOMERATING GASIFICATION PROCESS

Coal is first crushed to –¼-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 gas through both internal and external cyclones. The raw low-Btu gas generated in the gasifier is subsequently combusted in a thermal oxidizer.

PROGRESS DURING OCTOBER-DECEMBER 1976

Modification of the ash-agglomerating gasifier equipment continued during the quarter. The L-valve auxiliary reactor feed system study was completed in October. Results of the study demonstrated that the flow of solids could be controlled over a 3-to-1 range and could be stopped when necessary. As a result of the test program, a two-foot-long horizontal section of L-valve will be installed as part of the modifications to the reactor feed system.

The 85-foot-high, 100-ton silo was fabricated and delivery is anticipated in January. The shop-fabricated four-foot-diameter cold model of the ash-agglomerating gasifier reactor was erected and reactor modifications were completed in November.

As of the end of the quarter, the rough plumbing, and concrete work had been completed. The structural steel was being fabricated and installation was scheduled for the second week of January. Cyclone and quencher fabrication was still in progress due to late delivery of the stainless steel. Work was proceeding on the alternate reactor feed system and the hot gas piping.

GLOSSARY

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

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

acid gas removal—the process of selectively removing hydrogen sulfide and carbon dioxide from a gas stream.

activated carbon—carbon obtained by carbonization in the absence of air, preferably in a vacuum; has the property of absorbing large quantities of gases, solvent vapors; used also for clarifying liquids.

adiabatic—any process where heat is neither given off nor absorbed.

adsorption—the process by which the surface of a solid or liquid attracts and holds any atom, molecule, or ion from a solution or gas with which it is in contact.

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

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

API—American Petroleum Institute.

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

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

ash—solid residue remaining after the combustion of coal.

ASTM—American Society for Testing Materials.

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

bench-scale unit—a small-scale laboratory unit for testing process concepts and operating parameters as a first step in the evaluation of a process.

binder—carbon products, tars, etc., used to impart cohesion to the body to be formed; a coal-extract binder may be used to prepare formed-coke pellets from non-coking coals.

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

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

bottoming cycle—the lower temperature thermodynamic power cycle of a combined-cycle system.

Btu—British thermal unit, the quantity of energy required to raise the temperature of one pound of water one degree Fahrenheit.

BTX—benzene, toluene, xylene; aromatic hydrocarbons.

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

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

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

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

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

catalyst—a substance that accelerates the rate of a chemical reaction without itself undergoing a permanent chemical change.

centrifuge—an apparatus rotating at high speed which utilizes the centrifugal force generated to separate materials of different densities, e.g., undissolved residue from coal solution in the SRC process.

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

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

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

coalification—metamorphosis of vegetable debris into coal.

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

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

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

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

combustor—a vessel in which combustion takes place.

coupon—a polished metal strip used to measure the rate of corrosion of the metal in a specific gaseous or liquid environment.

cracking—the partial decomposition of high-molecular-weight organic compounds into lower-molecular-weight compounds, generally as a result of high temperatures.

crude gas—impure gas produced in a gasifier.

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

cyclone separator—essentially a settling chamber to separate solid particles from a gas, in which gravitational acceleration is replaced by centrifugal acceleration.

degasification—a process for removing naturally occurring methane from coal seams.

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

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

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

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

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

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

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

diatomite—See Diatomaceous Earth.

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

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

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

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

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

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

effluent gas—gas given off from a process vessel.

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

endothermic reaction—a process in which heat is absorbed.

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

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

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

exothermic reaction—a process in which heat is liberated.

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

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

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

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

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

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

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

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

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

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

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

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

flue gas—gaseous combustion products.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

hydroclone—a small cyclone extractor for removal of suspend solids from a flowing liquid by means of the centrifuga

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

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

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

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

industrial gas—See Fuel Gas.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

raw gas—See Crude Gas.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

slurry—a suspension of pulverized solid in a liquid.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

water gas shift—the reaction between water vapor and carbon monoxide to produce hydrogen and carbon dioxide or the reverse:

$$CO + H_2O \rightleftarrows H_2 + CO_2.$$

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