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U.S. DEPARTMENT OF ENERGY
Division of Coal Conversion

QUARTERLY REPORT

July-September 1978
DOE/ET-0067/3
Publication Date: May 1979

COAL

GAZIFICATION

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COAL GASIFICATION

MASTER

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FOREWORD

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EXECUTIVE SUMMARY

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

DOE's program for the conversion of coal to 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 Interior. Both high- and low-Btu gasification processes are being developed. High-Btu gas can be distributed economically to consumers in the same pipeline systems now used to carry natural gas. Low-Btu gas, the cheapest of the gaseous fuels produced from coal, can be used economically only on site, either for electric power generation or by industrial and petrochemical 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. Coals have widely differing chemical and physical properties depending on where they are mined, and are difficult to process. Therefore, to develop the most suitable techniques for gasifying coal, DOE, 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, each of 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 because some require high pressures, and because all produce corrosive and chemically-active gases, resistant alloys and new pressure vessels must be developed to obtain reliable performance.

A number of the processes for converting coal to high-Btu gas have reached the pilot plant stage. Laboratory research is also continuing in order to develop data for verifying the feasibility of each specific process and for supporting the operation of each plant. Responsibility for designing, constructing, and operating these pilot plants is assigned to: Rockwell International Corporation, for the Short Residence Time Hydrogasification, 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.

Rockwell International is the contractor for DOE on the project *Advanced Development of a Short Residence Time Hydrogasifier*. The contract to Rockwell for a three-year program to advance the development of the SRT process was awarded in September.

Operations at the pilot plant of the *BI-GAS Process for the Generation of Pipeline Gas* resumed this quarter. New instrumentation, installed for the purpose of indicating proper flows of char, provided reliable char flow/no flow indications. All damage to the pilot plant from the February 1978 fire has been repaired. In addition to several pilot plant runs this quarter, combined bench-scale PEDU studies were conducted to develop a fluidized bed methanation process for upgrading coal-derived synthesis gas.

During the quarter, the pilot plant of the *HYGAS Process for Producing Pipeline Gas by Hydrogasification* was given its annual maintenance turnaround. In addition, repair work made necessary by a fire at the Chem Systems' Liquid Phase Methanation Unit was completed. Pilot plant test 79, a highly successful run using Illinois No. 6 mine coal, was completed. Late in the quarter, the high-pressure test 75 was started. Data are being transferred to Procon, Inc., for its design of a HYGAS demonstration Plant.

After 24 months of operation of a pilot plant, the *Steam-Iron System for the Production of Hydrogen* facility is being shut down. Twenty test runs were completed during the two-year test period, with the last three runs being completed this quarter. These later tests were run at higher temperatures than were the previous tests, to study the expected higher production rates of hydrogen. Operations will now be discontinued for an indefinite period of time.

Eleven pilot plant runs were made this quarter at the government-owned pilot plant testing the *Synthane High Pressure Fluidized Bed Coal Gasification Process*. The first long-term integrated operation of the pre-treater and gasifier was achieved, this on the difficult-to-treat Illinois No. 6 seam coal. In September, an explosion in the plant's high-pressure boiler caused considerable damage, and no further operations are planned until the boiler can be repaired.

Because of the damage resulting from the June 22 fire at the pilot plant of the *Liquid Phase Methanation Process*, it was decided by DOE to temporarily discontinue operations of the pilot plant. Other phases of the LPM project may continue.

The Department of Energy and the Gas Research Institute is sponsoring a *Technical Evaluation of High-BTU Gasification Processes*, which is being conducted by C.F. Braun and Company. Braun engineers observed operations at the HYGAS, Steam-Iron, Synthane, and LPM pilot plants during this quarter. Braun's responsibilities in connection with the Metals Properties Council terminated this quarter. Several reports are in preparation.

LOW-BTU GASIFICATION

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

In order that operational status of low-Btu gasifiers be developed as soon as possible, the Department of Energy issued a Request for Proposal (RFP) for development of *Gasifiers in Industry*. A cooperative agreement was signed for six selected projects using commercially available technology. Acurex-Aerotherm Corp. is responsible for installing a Wellman-Galusha single stage, fixed bed gasifier in the Glen-Gery brick plant. Irvin Industrial Development, Inc. will be using two single stage Wellman-Galusha gasifiers to provide space heating, process steam, and direct and indirect fired applications to a 172-acre industrial park. A new 65-acre development in Pike County, Kentucky will be supplied with fuel from two Wellman-Galusha

gasifiers. General Refractories Co. will use one Woodall-Duckman two-stage gasifier to fuel two tunnel kilns and twelve periodic kilns. Land O'Lakes Creamery will use a Wellman-Incandescent gasifier to provide fuel for use in boilers and space heaters for the spray drying of milk whey. The University of Minnesota will use a Stoic two-stage gasifier to provide steam for heating the Duluth, Minnesota campus.

Hydrocarbon Research Inc. is responsible for the *Development of a Fast Fluidized Bed Gasifier* that brings gas at high velocity into contact with solids in turbulence. Construction of the seven ton-per-day plant continued during the quarter. A test plan was formulated for initial operation of the gasifier.

The design, procurement, and construction tasks relating to the one-ton-per-hour process development unit for the *Molten Salt Gasification Process* have been completed by Atomics International. Startup of the PDU commenced late in the quarter.

An *Advanced Coal Gasification System for Electric Power Generation* is being investigated by Westinghouse Electric Corporation, under DOE sponsorship. Recently-completed modifications to the 12 ton-per-day PDU at Waltz Mill allowed the first integrated operations of the devolatilizer and the gasifier. Also during this quarter, a conceptual design of a three-meter scale-up model was prepared.

Combustion Engineering completed Runs 3 and 4 in the recently-completed five ton-per-day process development unit (PDU) for demonstration of *Low BTU Gasification of Coal for Electricity Generation*. While the initial runs in this entrained flow gasifier appear successful, modifications to the PDU are planned which will result in less booster fan vibration, better measurement of gas and solids flow, and improved slag tapping.

Under 100 percent DOE sponsorship, Bituminous Coal Research, Inc. is developing the TRI-GAS Process for Production of Low-BTU Fuel Gas. During this quarter, fourteen tests were run in the 100 pound-per-hour multiple fluidized bed process equipment development unit (PEDU), treating Illinois No. 6 seam coal.

The Commonwealth Research Industry, funded by DOE and industry, will develop a *Gasification Combined Cycle Test Facility* to develop and evaluate coal gasification systems as sources of suitable fuel for a combustor/combined cycle system. Various gasification processes and equipment will be tested. During this quarter, clearance for pre-construction had not been received, hence, field move-in by early 1979 appears to be doubtful.

Data continues to be collected for the *Coal Conversion Systems Technical Data Book*, which is being prepared under DOE sponsorship by the Institute of Gas Technology. It will provide a simple source of up-to-date technical information necessary for the design and operation of coal conversion facilities. The first issue of the data handbook was published in loose-leaf form (in 1978) so that it can be revised, expanded, and updated. During this quarter, data collection continued on the subject categories of properties of process materials, conversion fundamentals, design procedures, supporting processes, and materials of construction.

Systems, Science, and Software is developing a general *Computer Model of Coal Gasification Reactors*. Computational studies of combustion and gasification with the fluidized-bed code were continued this quarter, as was the development of the entrained flow code.

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I. ADVANCED DEVELOPMENT OF A SHORT RESIDENCE TIME HYDROGASIFIER

ROCKWELL INTERNATIONAL CORPORATION
CANOGA PARK, CALIFORNIA

Plant Site: Canoga Park, California
Contract No.: ET-78-C-01-3125
Contract Funding: \$18,053,000
(100% DOE)

INTRODUCTION

Rockwell was awarded a contract for a three-year program in September 1978 to advance the development of the Rockydyne single-stage short residence time (SRT) hydrogasifier to demonstration plant status. The program builds and expands on the foundation already established under predecessor Contract No. EX-77-C-01-2518.

A four ton-per-hour (coal feedrate) reactor facility will be designed, constructed and operated at conditions applicable to a commercial SNG process with both a subbituminous coal and a highly-caking bituminous coal as feedstocks. Scaling of reactant injection elements from the $\frac{1}{4}$ ton-per-hour element, investigated under the previous contract, to a commercial scale of a four ton-per-hour element will be investigated and the technique of clustering elements of one size to feed a larger size reactor will be demonstrated.

Additional testing will be concerned with establishing economic reactor operating conditions and with building a viable process data base to support the next step toward commercialization with minimum risks. The four ton-per-hour hydrogasifier system will be capable of extended duration runs of up to 30 days.

In conjunction with an A&E firm subcontractor, a preliminary design will be generated of a full-scale commercial SNG plant utilizing hydrogasifiers of the type developed in the program.

PROCESS DESCRIPTION

Raw coal (up to eight-inch size) is crushed at a rate of 15 tons-per-hour to less than $1\frac{1}{2}$ inch size. The crushed coal is mechanically conveyed to a hopper from which it is fed to a mill where it is pulverized and dried to produce seven tons of coal per hour sized for less than 90 weight percent passage through 200 mesh and to contain less than three weight percent moisture. The dried, pulverized coal is pneumatically transported to a cyclone separator from which the coal is gravity-fed to a 40-ton capacity storage silo via a screener to remove particles larger than $1/16$ inch. A 470 cubic foot capacity lockhopper is used to transfer the coal from the silo to the high-pressure reactor feeder in six-ton batch quantities at a rate of 40 tons-per-hour.

The reactor is a continuous feed device that hydrogenates the pulverized coal at elevated pressures and temperatures. The reaction is terminated by quenching the product gas and char to 600°F in two heat exchangers located downstream of the reactor. Gaseous hydrogen and deionized water are used, respectively, as the cooling media in the upper and lower quench heat exchangers. The deionized water is pressurized to 500 psig and operated at 420°F minimum temperature to prevent moisture condensation on the product gas/char side of the cooler. (Moisture condensation could cause plugging of heat exchanger passages by buildup and agglomeration of char particles.)

The char removal consists of a 200 cubic foot capacity char receiver, a 200-cubic-foot capacity char lock-hopper, a 400-cubic-foot capacity char surge hopper, a char slurrolizer, a slurry storage tank, two product gas cyclones with solids collectors, and two vent gas cyclones with solids collectors.

The char receiver and product gas cyclones provide the primary means for separating the product gas from the char solids. The collected char is removed intermittently by dense phase flow to the char lockhopper. The vent gases are directed to the product gas scrubber.

HISTORY OF THE PROJECT

Rockwell International Corporation (RI) initially translated the reactor concept into a practical high-throughput continuous-flow, engineering-scale experimental reactor in a partial liquefaction R&D program. Experimental development in that program has been carried out in two hydroconversion test facilities: a ¼ ton-per-hour system capable of operation for 10 minutes, and a one ton-per-hour system in which runs up to one-hour duration have been made. Although maximization of liquid product yields was emphasized, a few tests at nearly zero-liquid conditions served as a prelude to development of the reactor as a hydro-gasifier. This was undertaken in 1977 under Contract EX-77-C-01-2518 which extended from March 1977 through August 1978. The prime contractor was the Rocketdyne Division of Rockwell International Corporation and Cities Service Research and Development Company (CSR D) was a major subcontractor.

The experimental studies comprised: ¼ ton-per-hour, short-duration (10 minutes) reactor tests in the RI ¼ ton-per-hour hydroconversion facility; ¼ ton-per-hour, long-duration (½-hours) reactor tests in the RI one ton-per-hour hydroconversion facility; and two- to four-pounds per-hour reactor tests in the CSR D bench-scale laboratory facility.

Because the bench-scale equipment could be activated sooner and was less expensive to operate than the ¼ ton-per-hour unit, its function was to provide experimental guidance for the selection of test conditions for the relatively fewer ¼ ton-per-hour tests.

A total of 42 short-duration ¼ ton-per-hour tests was made. A summary of the short duration testing is given in Table I-1. Several conclusions may be drawn from these data, e.g.,

- 1) Under approximately comparable reactor conditions, overall carbon conversions were lower for subbituminous than for bituminous coals.
- 2) Conversely, the lower ranked peat exhibited appreciably higher overall conversions than did bituminous coals.
- 3) Reactor conditions yielding high values of overall carbon conversion also tended to give high carbon conversions to gases.
- 4) Conditions were established at which carbon conversion was to all gaseous products for subbituminous, bituminous, and peat coals.

COAL SOURCE AND TYPE	No. OF RUNS	RANGES OF VARIABLES TESTED				
		Pr. pig	Tr. of	RESID. msec	CARBON CONVERSIONS, %	
					OVERALL	TO GASES
MONTANA ROSEBUD SUBBITUMINOUS	17	1000 TO 1500	1416 TO 1900	600 TO 4100	27.8 TO 49.8	22.5 TO ~49.8
KENTUCKY hv A BITUMINOUS	9	1000 TO 1500	1624 TO 1908	480 TO 5500	47.3 TO 67.2	40 TO ~57.2
ILLINOIS No. 6 hv C BITUMINOUS	4	1000 TO 1500	1468 TO 1982	1000 TO 1470	48.0 TO 70.7	37.2 TO 70.6
MINNESOTA PEAT	12	500 TO 1500	1534 TO 1850	500 TO 3700	73.4 TO ~87.3	63.5 TO 87.3

Table I-1. SUMMARY OF SHORT-DURATION ¼ TON-PER-HOUR REACTOR TESTING

The main contribution of the tests in the one ton-per-hour facility was the experience gained concerning exposure of the reactor for longer periods, and achievement of more precise values for conversion and elemental balance.

PROGRESS DURING JULY-SEPTEMBER 1978

As the contract was initiated in September, no progress report was available.

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

BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

Plant Site: Homer City, Pennsylvania
Contract No.: EF-77-C-01-1207
Contract Funding: \$66,000,000
DOE: \$44,000,000
AGA: \$22,000,000

INTRODUCTION

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

The principal objective of the program "Gas Generator Research and Development" is the development of the BI-GAS process for gasifying coal to produce

high-BTU pipeline gas. 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

PROCESS DESCRIPTION

The BI-GAS process is a two-stage, high-pressure, oxygen-blown system reacting 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 is mixed with water and the coal/water slurry is fed to a cyclone. The coarser coal particles accompany the cyclone underflow slurry, which is sent to a wet grinding mill for further coal particle size reduction. The percent solids in the final coal water slurry is further concentrated in a thickener and centrifuge. Coal solids are repulped and mixed with flux to the desired concentration, and fed to the downstream high pressure feed system.

A high pressure slurry pump picks up the blended slurry and transports it under pressure to a steam pre-heater. The hot slurry is then contacted with hot recycle gas in a spray dryer for nearly instantaneous vaporiza-

tion of the 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 recycle gas from the methanator. The coal is separated from the hot recycle gas in the cyclone and flows by gravity to the gasifier.

The coal enters the gasifier through injector nozzles near the throat separating the stages. Steam is introduced through a separate annulus in the injector. The two streams combine and join the hot synthesis gas rising from Stage 1. A mixing temperature of about 2,200°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 1,700°F, and are quenched to 800°F by atomized water prior to separation in a cyclone. The synthesis gas (containing carbon monoxide, carbon dioxide, hydrogen, water, hydrogen sulfide, and methane) passes through a scrubber for additional cooling and cleaning. The clean gas, along with the desired amount of moisture, is sent to a carbon monoxide shift converter to establish the proper ratio of carbon monoxide and hydrogen required in the methanation process.

Figure II-2. BI-GAS PROCESS SCHEMATIC

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 accumulation of slag in the Stage II and the slag quench section, production of naphthalene, and unsatisfactory viewing of slag tapping during BI-GAS Pilot Plant operations.
- The generation of excess coal fines during grinding of coal feed, especially with Rosebud Mine coal.
- Instrumentation relating to char flow control.

HISTORY OF THE PROJECT

This project was started in December 1963. BCR's first experiments confirmed the basic assumption that a high yield of methane could be obtained directly from coal by reaction with steam at elevated temperatures and pressures. BCR next conducted continuous flow experiments in an externally heated reactor processing five pounds of coal per hour. The experimental data

were extrapolated to design a process development unit that would simulate the conditions of Stage 2 of the BI-GAS process. The unit was internally fired and could process 100 pounds of coal per hour. Experiments were designed to determine the optimum residence time, coal rank, and processing conditions (pressure, temperature, and hydrogen partial pressure) that would produce the greatest yield of methane. North Dakota lignite, Wyoming subbituminous C coal, and Pennsylvania high volatile A bituminous coal were used in the experiments. During these experiments, BCR found that the physical design of the Stage 2 process development unit influenced methane yield. Therefore, a cold flow model of Stage 1 and the bottom of Stage 2 was developed to investigate methods for improving the flow patterns in Stage 2 and to establish design criteria for the slagging section of the gasifier.

BCR developed the basic design criteria for a fully-integrated pilot plant capable of processing five tons of coal per hour and producing 100,000 standard cubic feet of clean pipeline-quality gas per hour. Stearns-Roger was awarded the contract for constructing the \$34 million facility on July 11, 1972. The pilot plant management contract was subsequently awarded to Phillips Petroleum Company in November 1974. The gasification vessel to be used in the pilot plant was designed and built by Babcock and Wilcox, a Stearns-Roger subcontractor. The pilot plant was completed in 1976 and start up operations began. Formal acceptance of the plant from Stearns-Roger Construction Co. was made by Phillips Petroleum Company on September 15. By the end of the year the flash drying system and gasifier system were operated successfully. Baseline conditions were established and maintained until the objectives had been achieved. The most successful test to date in the pilot plant was completed in November 1977 when a 24-hour, steady state operating period was achieved while collecting three complete sets of laboratory samples.

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

In February 1978, a ruptured line resulted in gasifier depressurization and fire. By June, all fire damage had been repaired. Plant safety studies indicated the need for monitoring of char flow in order to detect any loss of char flow to Stage I of the gasifier to avoid development of potentially hazardous conditions within the

gasifier. BI-GAS Pilot Plant test operations continued through the third quarter of 1978.

PROGRESS DURING JULY-SEPTEMBER 1978

Combined bench scale and PEDU studies continued during this quarter to develop a fluidized-bed methanation process for upgrading the coal-derived synthesis gas produced by the BI-GAS gasifier. Results of PEDU Test No. 30 became available and indicate that it is possible to operate under conditions of combined shift and methanation for extended periods of time without experiencing catalyst deactivation through carbon formation.

Phillips Petroleum Company is responsible for management and operation of the BI-GAS Pilot Plant. During this quarter, additional char eductor tests were conducted to evaluate responses on the new instruments for measuring pressure increases and pressure drops. It appeared that valid char flow/no-flow indications were possible. Authorization to proceed with start-up

of the BI-GAS Pilot Plant was received July 28 for Test 65. This test was short lived, but provided information about behavior of the char feed system. Gasifier Tests G-5A and G-5B were conducted during August. In these tests, ground limestone was fed with the coal to act as a slag fluxing agent. Slag formation and slag tapping problems were encountered. During September Tests G-5C and G-6 were conducted. In Test G-5C, limestone was fed with Rosebud coal. A char burner pipe plugged, causing shutdown. In Test G-6, no limestone was fed, hoping to eliminate the deposits previously found in the Stage II gasifier. No deposits were found in Stage II of the gasifier after this test.

An experimental coal grinding program continued this quarter, with the objective of reducing the amount of fines generated when grinding Rosebud coal.

Life tests on various catalysts were continued, but no PEDU tests were conducted during August or September. It had been decided to extend the life tests further to obtain additional steady-state data at 900°F (and possibly 950°F) before a decision is made regarding preparation of a PEDU-scale sample of any of the newer catalysts being examined.

III. PIPELINE GAS BY HYDROGASIFICATION (HYGAS PROCESS)

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

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

INTRODUCTION

HY-GAS is a process for the direct hydrogenation of coal hydrocarbons, in the presence of coal and steam, followed by steam-oxygen gasification of remaining char. The HYGAS process is being developed by the Institute of Gas Technology (IGT) as part of the joint program of DOE and the Gas Research Institute (GRI). DOE is providing two-thirds of the funds and GRI, one-third.

The objective of this contract is to operate the HYGAS pilot plant facility with a mildly caking Illinois Bituminous Coal in order to develop an improved data base for the design of a conceptual commercial/demonstration plant based on the HYGAS process. The overall program plan is shown in Figure III-1.

PROCESS PILOT PLANT DESCRIPTION

Several processing steps are required to convert coal to high-Btu gas with the HYGAS process. A diagram of the process is provided in Figure III-2. Coal preparation involves crushing the coal to -14 mesh. Caking coal is pretreated in a fluidized bed at temperatures between 750°F and 850°F at atmospheric pressure to destroy caking tendencies and produce a free-flowing coal. Noncaking coal is fed directly to the slurry tank.

The coal is slurried in this tank with an aromatic recycle oil to form a thick slurry. This slurry is then pumped to 1,000 psig and injected into the top section of the gasifier (slurry dryer) which contains a fluidized bed of hot coal particles. Oil is vaporized and removed, together with the hot gases passing upward from the lower stages of the gasifier.* Vaporized oil is recovered for reuse by quenching the effluent from the gasifier.

Dry coal particles, at approximately 600°F from the slurry drying section, flow by gravity through a dipleg into a lift pipe. This lift pipe serves as the first stage of hydrogasification. In this stage, the heated coal comes in contact with a hot gas from the lower sections of the reactor. This gas contains methane, carbon oxides, hydrogen, and steam. The hydrogen chemically reacts with the more reactive part of the incoming coal, forming additional methane. Approximately one-third of the methane in the final product gas is produced in this step.

In the second stage hydrogasification section, the partially converted coal from the first stage mixes with the rising hydrogen-rich gas at about 1,400-1,700°F. Part of the hydrogen and steam react chemically with the coal, forming methane and carbon oxides. Approximately one-third of the methane in the final product gas is produced in this step. Hot residual char is then

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

PROJECT	TR. QR.	FY 77	FY 78	FY 79
INTEGRATED PILOT PLANT OPERATION INPUT: 75 TONS/DAY COAL OUTPUT: 1.5×10^6 SCFD HIGH BTU GAS				
	△		▽ △ ○	▽ ○

LEGEND: △ BEGIN MILESTONE ▽ COMPLETE MILESTONE ○ DECISION MILESTONE
 Figure III-1. HYGAS PROGRAM SCHEDULE

Figure III-2. HYGAS PROCESS SCHEMATIC

transferred to the third stage. Here the steam and oxygen react with the char in a fluidized bed to produce a mixture of gases rich in hydrogen. This mixture is passed upward into the hydrogasification sections. Ash is removed from the bottom of the steam-oxygen zone.

The raw product gas leaving the top of the reactor at about 600°F is cooled and rinsed in a water quench, purified, and passed to a methanator. The mol ratio of hydrogen to carbon monoxide in the purified gas entering the methanator is adjusted to about three to one. The purified gas passes through a nickel catalyst at 800-900°F and is transformed to pipeline quality gas with an average heating value of 930 to 950 Btu per standard cubic foot.

HISTORY OF THE PROJECT

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

During 1975, eleven test runs were made in the HYGAS pilot plant. The longest run (Test 37) was made in July, demonstrating the feasibility of using lignite. Fifteen days of self-sustained operation were achieved with over 1,000 tons of lignite processed. The entire plant was on stream for 92 percent of the time, or 333 hours. Various individual steady-state periods were achieved which totalled 160 hours. The heat and material balances were within ± 5 percent of closure. Subsequent to Test 37 with lignite, IGT was authorized to start testing with highly caking Illinois No. 6 bituminous coal.

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

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

The liquid phase methanation pilot unit (see Chapter V) was received at the HYGAS plant in October, and all systems had been checked out by the end of December 1976.

Tests were conducted in 1976 in the HYGAS pilot plant with pretreated Illinois No. 6 bituminous coal (highly caking) as well as with Rosebud subbituminous coal. Tests during 1977 used Peabody No. 10 mine coal.

Of major technical and economic importance to this process is the production of the hydrogen-rich gas required for hydrogasification. During the early part of 1974, shakedown runs and batch tests of the two-megawatt electrothermal gasifier for producing hydrogen-rich gas were completed. Although this technique was demonstrated to be technically feasible, it was found to be too costly due to the large quantity of electric power required. Therefore, experimentation using this technique was discontinued. A steam-oxygen unit, which gasifies char, was constructed and installed in the base of the HYGAS pilot plant hydrogasification reactor during 1974 and is presently being used to date.

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.

A fire occurred in June in Chem Systems' Liquid Phase Methanation Unit, with resultant damage to wiring and instrumentation. The fire did not affect the HYGAS pilot plant.

PROGRESS DURING JULY-SEPTEMBER 1978

Pilot Plant Experimental Operations

During July, the HYGAS plant was shutdown and the plant operating personnel took their annual two-week vacation the first two weeks of the month. Annual plant turnaround activities, including maintenance, repairs, and clean-up were carried out, as were modifications in preparation for the next series of tests. Repair work made necessary by the fire at the Chem System's Liquid Phase Methanation Unit was carried out smoothly and effectively and was completed in time to allow the initiation of Test 74 early in August.

The entire HYGAS pilot plant was inspected following the reactor's good performance with caking bituminous coal from the Illinois No. 6, Peabody No. 10 Mine during Test 74. The best steady-state period

was 40 hours with a char conversion of 78 percent. Immediately afterward, the reactor and related piping and vessels were pressure tested as a preliminary procedure for Test 75 high-pressure (900 psig) operations. Routine maintenance and turnaround activities were completed, and lightoff for Test 75 occurred at 0130 hours on September 24. The plant effluent processing section was in good condition following Test 74.

One of the major activities under this task has been the transfer of data of Procon, Inc., for its design of a HYGAS demonstration plant. During this reporting period, data were supplied for oil make and phenolics.

Cold Flow Model

A cold-flow model of the upper stage of the gasification reactor is being constructed. This stage of the system is the only section of the unit that is not a direct mechanical transfer of technology from the pilot plant reactor. The model is being constructed to determine the gas-solids behavior, on a large scale and at elevated pressure, in systems similar to the proposed demonstration plant design.

The procurement status of the various elements of this model is:

Compressor: received and set in place. Wiring in progress.

Instrumentation: received and partially installed.

Building Foundation: completed.

Building Structural Steel: nearly completed. Cannot be finished until the last vessel is delivered.

Vessels: The test and cyclone receiver vessels have been received and erected. Delivery of the solids receiver vessel is now projected to be October 30.

Cyclone: The cyclone has been received and installed.

Pipeline Filters: received and installed.

Control Valves: received.

Test Methanation and Catalyst

The IGT fixed-bed methanation unit was prepared for fire-damage assessment.

Engineering Services

The study of pretreatment minimization of Illinois No. 6, Peabody No. 10 Mine bituminous coal continued during this quarter, using a small scale unit.

IV. STEAM-IRON SYSTEM FOR PRODUCTION OF HYDROGEN

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Plant Site: Chicago, Illinois
Contract No.: EF-77-C-01-2435
Contract Funding: \$13,502,647
DOE: \$9,335,432
AGA: \$4,167,215

INTRODUCTION

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

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

PROCESS DESCRIPTION

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

In the pilot plant, a char-water slurry containing from 35 to 50 percent char is heated in a direct fired

furnace to produce a lean-phase mixture of char and steam. The steam lifts the char to the preheater bed at the top of the producer vessel. There it is fluidized with air and steam, thereby combusting approximately ten percent of the feed char and raising the temperature from 600°F to approximately 1,750°F.

The preheated char then enters the producer bed where it is gasified at approximately 2,000°F with air and steam to yield a reducing gas. Spent char is cooled with additional steam and discharged from the producer vessel at about 1,000°F. The 2,000°F reducing gas is then fed to the reducer bed of the steam-iron reactor.

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

Four fluidized beds are used in the steam-iron process to obtain full countercurrent operation. The reducing

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

LEGEND : △ BEGIN MILESTONE ○ DECISION MILESTONE
 ▽ COMPLETE MILESTONE

FIGURE IV-1. STEAM-IRON SYSTEM PROJECT SCHEDULE

Figure IV-2. STEAM-IRON PILOT PLANT SCHEMATIC

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

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

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

HISTORY OF THE PROJECT

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

The pilot plant was completed in 1976, concluding the tasks under contract E(49-18)-1518. Subsequent operations were continued under a new contract. The first iron ore solids circulation tests were made late in 1976. The first producer feed test was successfully completed in March 1977. Integrated operation of the producer and steam-iron reactor was achieved for a short period for the first time in October 1977. Test work

was concluded on September 30, 1978. Twenty test runs were completed during the 24-month test period.

PROGRESS DURING JULY-SEPTEMBER 1978

Tests 18, 19, and 20 were completed this quarter. Test 18 covered 16 days. Smooth circulation of iron ore was demonstrated at pressures ranging from 400 to 500 psig.

The testing of the Steam-Iron Process was to be discontinued after September 30, 1978, the final two tests were to be made at higher temperatures, in order to obtain higher hydrogen production rates. In previous tests, temperatures were intentionally limited to less than $1,100^\circ\text{F}$ in the steam-iron reactor to protect the carbon-steel lift-line shell. Since the chemistry of the steam-iron process is very sensitive to temperatures between $1,000^\circ$ and $1,500^\circ\text{F}$, the production of hydrogen was limited to low rates, at the low test temperatures. All lift-line slip joints were modified during August. The new metal joints, backed by fiber insulation, greatly reduce the heat loss from the line and allow operation at higher temperatures on the process side without overheating the carbon-steel pressure-shell.

In Test 19, the reactor pressure was increased to 500 psig during hydrogen production and obtained the highest hydrogen concentrations, to date, in the product gas. Test 20 was the longest hydrogen-producing period, to date. It ended on September 30, the end of the contract period. Operation of the steam-iron plant will be discontinued for an indefinite period of time.

During the 24 months of operating the steam-iron pilot plant facility, many significant accomplishments were achieved:

- An intensive development program was completed. A total of 355 days of operation was accumulated.
- The technical feasibility of continuously recirculating a stream of iron solids at high pressure and temperature was demonstrated. A total of 1,393 hours of ore circulation were logged at rates up to 71 tons-per-hour. Circulation during the last few tests was smooth and easily controlled.
- A method of introducing dry coal to a high-pressure, fluidized-bed system was developed, using high-pressure mud pumps and a slurry vaporizer. Slurry concentrations up to 50 weight percent were processed through the system over a period of 944 hours.
- The technical feasibility of the combined Steam-Iron Process for hydrogen production was indi-

cated. A total of 342 hours of hydrogen production was obtained.

- The producer reactor was operated at design conditions. Char feed rates up to 2.0 tons-per-hour were maintained at reactor pressures of 500 psig and bed temperatures of 1,800°F.
- Hydrogen production was increased to 5,000 SCF per hour. No technical barrier in reaching design hydrogen production (44,000 SCF per hour) as temperatures are increased to design levels in the steam-iron reactor is apparent. Additional operating time will be required to reach design temperatures.
- Hydrogen purity reached 90 percent and 95 percent on a nitrogen-free basis in Tests 17 and 19, respectively. (Nitrogen was introduced through instrument purges and aeration of seal legs.) The high purity was obtained without introducing any stripping gas into the reducer/oxidizer seal leg.
- Iron ore attrition rates were very low and consistent with the design data. No ore was added during each of the five continuous days of hydrogen production in Tests 17 and 20. During those periods no significant decrease in bed levels was noted.
- A reactor pressure control valve system was developed using oilfield choke valves.
- A number of solids control valve designs capable of operating in a fluidized bed of solids were developed and successfully tested.

- A high-pressure, high-temperature slip joint was developed and successfully tested in 16 and 20-inch-diameter service.

Important operating achievements during the 24-month operating period are summarized in Table I.

Table IV-1. OPERATING ACHIEVEMENTS REALIZED DURING 24-MONTH OPERATING PERIOD OF THE STEAM-IRON PROCESS FOR HYDROGEN PRODUCTION

Total Number of Test Days	355
Hours of Ore Circulation	1,393
Hours of Char Feed	944
Hours of Hydrogen Production	342
Char Feed, tons	864
Average Char Feed Rate, tons/Hr.	0.92 (50% of Design)
Maximum Char Feed Rate, tons/hr.	2.00 (110% of Design)
Char Gasified in Producer, %	2-70 (Design conversion: 70%)
Reactor Pressure, psig	100-500 (Design operating pressure: 1000 psig)
Producer Bed Temperature, °F	1200-1750 (Normal operating temperature: 1800°F)
Steam-Iron Bed Temperature, °F	700-1300 (Normal Operating temperature: 1500°F)
Ore Circulation Rates, tons/hr.	6-71 (Normal circulation rate: 45 tons/hr.)
Maximum Hydrogen Production, SCF/hr.	5000 (Production rate at 500 psig: 22,000 SCF/hr.)

V. SYNTHANE PROCESS

THE LUMMUS COMPANY
BLOOMFIELD, NEW JERSEY

Plant Site: Allegheny County,
Pennsylvania

Contract No.: EY-76-C-02-0003-0000

Contract Funding: \$41,500,000
(100% DOE)

INTRODUCTION

SYNTHANE is a coal gasification process which combines pretreatment and fluid bed gasification of coal at high pressure, utilizing steam and oxygen additives. The SYNTHANE process was developed by the Bureau of Mines and is now the responsibility of DOE. The government-owned SYNTHANE pilot plant is being operated by The Lummus Company. The objective of this contract is to obtain definitive process information, sufficient for commercial design purposes, on the conversion of coal to gas of pipeline quality. The overall program plan for the development of the SYNTHANE process is shown in Figure V-1.

PROCESS DESCRIPTION

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

Coal, crushed to -20-mesh, is dried, pressurized to approximately 40 atm, and is transferred into the fluidized-bed pretreater by means of high pressure steam and

Figure V-1. SYNTHANE PROGRAM SCHEDULE

Figure V-2. SYNTHANE PROCESS SCHEMATIC

oxygen. Pretreatment provides a mild oxidation of the coal particle surface so that caking coals will not agglomerate in the gasifier. The coal overflows from the pretreater into the gasifier fluidized bed through an injection pipe. Steam and oxygen enter the gasifier just below the fluidizing gas distributor. The gasification reaction occurs within the fluidized bed. Char flows downward into a bed fluidized and cooled with steam, and is removed with transport steam, slurried in water, and depressured through let down valves. In a commercial plant, this char can then be burned to produce process steam. The product gas, containing methane, hydrogen, carbon monoxide, carbon dioxide, ethane, and impurities, is passed through a venturi scrubber and a water scrubber to remove carry-over ash, char, and tars. The concentration of hydrogen and carbon monoxide in the gas is adjusted to a three-to-one ratio in a shift converter. The acid gases are absorbed in a hot-potassium carbonate (Benfield) 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 methanation systems will be tested in the pilot plant. Each system can methanate about $\frac{1}{8}$ of the puri-

fied gas. Both systems were developed at PERC and use a Raney nickel catalyst.

One system operates isothermally with no recycle in a Tube Wall Reactor (TWR) in which the inside wall of the tube is coated with the catalyst and the heat of reaction is transferred to boiling Dowtherm on the outside of the tube wall. The other system is a Hot Gas Recycle (HGR) Reactor in which temperature is controlled by using a cooled recycle side stream of product gas. High pressure drop is avoided by coating parallel plates with catalyst, a low pressure drop configuration. The low level of CO that leaves the methanation as the catalyst deactivates will be converted in an adiabatic final methanator filled with pelleted nickel methanation catalyst. Initially, Girdler modified G-87 RS will be used.

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

- Caking coals can be used directly as can a wide range of other coals, including lignite.
- Hydrocarbons released during pretreatment are retained within the system, thereby maximizing the efficiency of coal conversion to gas.
- More than half of the methane is produced directly in the gasifier. By maximizing methane production in the gasifier, oxygen requirements are reduced. Therefore, the investment for an oxygen plant is lower and the sizes of all process vessels down-

stream 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.
- Little tar and oil are produced when using the deep bed method of coal feeding.

Some of the disadvantages of the process are:

- Char is produced which must be utilized for steam production in an environmentally acceptable manner.
- Without deep bed coal injection, some tars and oils are produced which must be disposed of or utilized.
- More economical coal feeding methods than the currently used lock hopper system must be developed.

HISTORY OF THE PROJECT

The Synthane process was developed by the Bureau of Mines at the Pittsburgh Energy Research Center, Bruceton, Pennsylvania. Development work started with scattered research in several areas.

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

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

Construction of the Synthane pilot plant was completed in March 1975, and all areas and systems were transferred from the construction contractor to ERDA (DOE, as of October 1977). Through 1975, work concentrated on installation of auxiliary equipment and the repair and modification of the plant due to equipment and design changes. During the first quarter of 1976,

these repairs and changes were completed, and initial testing began. Gas was first produced from Rosebud Coal on July 7, 1976. The gasifier was modified at the beginning of 1977 to provide a deep bed injection of coal feed. Subsequent operations were designed to improve gasifier operability. Studies of Western sub-bituminous coals were completed in August 1977 with a successful run that provided ten steady-state periods.

In 1978, studies were conducted on Illinois No. 6 coal, which is a caking coal. Successful pretreatment and gasification of this coal were accomplished by mid-year.

PROGRESS DURING JULY-SEPTEMBER 1978

Eleven pilot plant runs were made this quarter on Illinois No. 6 coal. A new secondary steam-oxygen distributor worked well, reducing oxygen consumption by about 25 percent. During one of the runs in August, the gasifier had three long steady periods that lasted from 25 to 48 hours. This represented the first long-term integrated operation of the pretreater and gasifier. By increasing bed densities, better control was gained over bed height. Coarser crushing of coal, with fewer coal fines, allowed higher bed densities to be achieved and reduced tendencies to agglomerate in the pretreater.

An explosion in the high pressure boiler occurred as the boiler was being restarted after an instrument air failure on September 21. The boiler tubes were bent out six inches on one wall and the sheet metal was ripped open on the front and back of the boiler firebox. A fuel oil fire damaged the instruments and electrical wiring in front of the boiler. No further operations are planned until the boiler is repaired about mid-January 1979.

Current plant operating problems include:

- Uneven coal feed to the pretreater and the gasifier causes the temperatures to fluctuate. Better control must be achieved before high coal conversion can be reached with higher temperature.
- Fine char carryover from the gasifier to the gas scrubbing system produces a foam that causes the circulating pumps to cavitate.
- Clinker formation in the gasifier.
- Agglomeration in the pretreater. Increased temperatures and finer coal feed have reduced agglomeration in the pretreater.

The current plans are to repair the high pressure boiler and to modify the gasifier to reduce clinker formation.

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VI. LIQUID PHASE METHANATION PROCESS

CHEM SYSTEMS, INC.

HACKENSACK, NEW JERSEY

Plant Site: Hackensack, New Jersey

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

Contract Funding: \$2,355,730
DOE: \$1,435,530
AGA: \$ 920,200

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

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

INTRODUCTION:

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 method.
- 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 VI-1.

LEGEND:

- BEGIN MILESTONE
 COMPLETE MILESTONE

Figure VI-1. LIQUID PHASE METHANATION PROGRAM SCHEDULE

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 VI-2.

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

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

In this process, inert liquid is pumped upward through the reactor (which operates at 20 to 68 atm and 570°-650° F) at a velocity sufficient to both fluidize the catalyst and remove the reaction heat. At the same time, the low-Btu feed gas (carbon monoxide and hydrogen) is passed upward through the reactor where it is converted to methane in the presence of the fluidized catalyst. The heat of the exothermic reaction is absorbed by the inert liquid as sensible heat. The liquid is then circulated through a heat exchanger to maintain the desired temperature, and the cooled inert liquid stream is recycled to the reactor.

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

The reactor effluent gases are cooled. Any water produced in the reaction is condensed along with the process liquid that was vaporized in the reactor. The liquids are phase separated. The process liquid is recycled back to the reactor. Part of the water can also be recycled back to the reactor as required with the remainder being sent to the plant's condensate system. The cooled gases can then be sent to a small trim methanator for final conversion of carbon monoxide and hydrogen to methane. Carbon dioxide may be removed either prior to or after the final methanation step. The final methanator is a fixed bed unit where complete reaction occurs adiabatically in a single pass through the reactor. The effluent gases from this polishing reactor are cooled by preheating feed gas and then against cooling water or air. The product SNG (HHV > 950 Btu/SCF) is dried and compressed (if required) to pipeline gas pressure.

There are several advantages to the liquid phase methanation process:

Figure VI-2. LIQUID PHASE METHANATION PROCESS SCHEMATIC

- 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 activity is maintained and the necessity of overdesigning the reactor to accommodate declining catalyst activity levels is eliminated.
- The methanation reaction is nearly complete in a single pass, eliminating the need for recycle or multiple reactors.
- Higher conversion per pass is achieved because the axial diffusivity of the reactants is relatively low compared to a gas-solid fluidized bed.

HISTORY OF THE PROJECT

In addition to an extensive literature search of both the methanation reaction and the fluidization of solids, Chem Systems initially conducted studies on the thermal

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

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

Development of the liquid phase methanation process has continued on three levels: bench-scale unit, process development unit, and pilot plant. The bench-

scale unit has been used for experiments with process liquids and catalysts and for the development of a reaction model correlating the physical and chemical aspects of the liquid phase methanation reaction process. The model was also used for developing data for designing the larger units. The process development unit was used to:

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

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

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

All tasks under contract E(49-18)-1505 were completed during 1976 and work under contract EX-76-C-01-2036 was initiated. The Liquid Phase Methanation (LPM) pilot plant was completed and shipped to the IGT HYGAS plant in Chicago, Illinois. It was reassembled and shakedown operations were completed at the beginning of 1977. The pilot plant received HYGAS product for the first time in April 1977 for a short period. A longer run of 70 hours was completed with HYGAS product in August. Additional runs were made on HYGAS product and on methane reformer gas until mid-1978, when a major fire occurred at the inboard filter during filter change. An investigation of the cause of the fire commenced immediately.

PROGRESS DURING JULY-SEPTEMBER 1978

As a result of the fire at the LPM Pilot Plant on June 22, 1978, a preliminary estimate was made of the cost to repair the unit. The major uncertainty was whether any metallurgical damage occurred to the filters, heat exchangers and associated piping in the burn

area. A testing program will be initiated in the near future and a more accurate assessment of the repair cost will then be made.

At the pilot plant, the fire investigation committee, composed of CSI, IGT and DOE personnel, dismantled the suspect filter inlet and discharge block valves. A large solids deposit was found in one of the discharge valves and small nickel deposits were found adhering to the polished surface of all the valves. Subsequent hydrostatic testing proved that these deposits on the polished surfaces were sufficient to have caused the leak which resulted in the fire.

A meeting was held at the DOE offices in Washington on July 13 to discuss LPM project planning for the next fiscal year. It was tentatively decided by DOE to temporarily discontinue operations at the LPM Pilot Plant although other phases of the LPM project will continue.

Therefore, at the pilot plant, work continued on securing the pilot plant for short-term shutdown of four to six months. The reactor bottom head was opened and all remaining catalyst was removed. The reactor internals were found to be in place and 1.3 drums out of 4.0 drums of catalyst charged were cleaned out of the pilot plant. The bottom of the reactor-separator was opened on July 31 including the lines to the main circulating oil pumps and more catalyst was found. All activities at the pilot plant will cease until directed otherwise by DOE.

During August, the reactor bottom head and the bottom of the reactor-separator were reassembled after removing all catalyst from these areas. The lines to the main circulating oil pumps were also reinstalled as were the lines around the main circulating oil filters. Catalyst was removed from the circulating oil cooler and the unit was reassembled. All vessels were dried with nitrogen.

The used INCO catalyst was shipped back to the manufacturer. Files in the LPM control room were shipped to the Fairfield Research Center for temporary storage.

On August 7, the fire investigation committee issued its report on the fire at the LPM Pilot Plant on June 22, 1978.

On September 27, a team from Argonne National Laboratories made a visual inspection of the vessels damaged in the fire at the LPM Pilot Plant on June 22, 1978. A report will be issued covering the results of this metallurgical inspection and recommendations

for further testing. Based on these findings, the estimate of cost to repair the pilot plant will be revised.

No other activities went on during September at the pilot plant.

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VII. EVALUATION OF HIGH-BTU GASIFICATION PROJECTS

C. F. BRAUN AND COMPANY
ALHAMBRA, CALIFORNIA

Project Site: Alhambra, California
Contract No.: EX-76-C-01-2240
Contract Funding: \$5,729,518
DOE: \$3,819,679
GRI: \$1,909,839

INTRODUCTION

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

Specifically, the evaluation contractor carries out evaluation activities in the areas of general program activities, factored estimates, process studies, and mechanical development. General program activities cover pilot plant surveillance, progress report evaluation, review and evaluation of pilot plant data, environmental coordination with other agencies, materials of construction program evaluation, and proposal evaluations. Factored estimates involve preparation of commercial concept designs and gas cost calculations for the processes in the program, using Western and Eastern coal feeds. Process studies involve all the unit operations conducted in converting coal to pipeline gas. The purpose of these studies is to select the best technology in each type of process operation for comparative economic evaluation of the processes in the joint program. Mechanical development involves identification of equipment that will be required in commercial-scale gasification plants that is not currently being manufactured because of the pioneer nature of the process or because the size or capacity exceeds that of similar items commercially manufactured. The second portion of the development involves investigation of the capa-

bility and interest of vendors of specific equipment items to undertake development contracts to produce needed equipment.

The technical evaluations are being performed on the following pilot plants:

- HYGAS Steam-Oxygen
- HYGAS Steam-Iron
- Synthane
- BI-GAS

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

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

practical means of performing the operations in a demonstration or commercial facility include:

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

In the area of conceptual designs, Braun is responsible for the development of conceptual commercial process designs for the purpose of making economic comparisons of the processes in the combined DOE-GRI program.

PROGRESS DURING JULY-SEPTEMBER 1978

Braun engineers observed operations at the HYGAS, Steam-Iron, Synthane, and LPM pilot units during the quarter.

Reports being prepared include:

- FE-2240-31 Factored Estimates for Eastern Coal Commercial Concepts. A camera-ready copy was transmitted to DOE for printing by the Government.
- FE-2240-51 Sulfur Removal from Flue Gas. The report was published on September 21, 1978.
- FE-2240-40 Considerations in Sizing Coal Gasification Plants. Comments were received and the report was forwarded to DOE for approval to publish on September 19, 1978.
- FE-2240-99 Rev. 2 Coal Gasification Program Reports on Work by CF Braun & Company. DOE approval was received by telephone and the report was published on September 29, 1978.
- FE-2240-100 Rev. 1 Coal Gasification Commercial Concepts Gas Cost Guidelines, DOE approval was received by telephone and the report was published on August 14, 1978.
- FE-2240-96 Fixed Bed Methanation Processes. DOE approval was received by telephone and the report was published on August 25, 1978.

- FE-2240-98 Factored Estimates for Lignite Commercial Concepts. The report was approved for publication and a camera-ready copy for printing by the government was forwarded to DOE on August 29, 1978.
- FE-2240-13 Problems Associated with Controlling Sulfur Emissions from High-BTU Coal Gasification Plants. DOE approval was received by telephone and the report was published on August 31, 1978.
- FE-2240-50 Sulfur Recovery in a Coal Gasification Plant. DOE approval was received by telephone and the report was published on August 31, 1978.
- FE-2240-56N A Comparison of Steam-Iron and Koppers-Totzek Processes for Commercial Hydrogen from Char. DOE advised by telephone that the report will be placed on file at DOE, but will not be published by Braun. The letter N is added to the report number to avoid duplication with the Braun Progress Report for the month of July 1976.
- FE-2240-97 Combined Shift Methanation Processes. A revised draft of this report was issued on August 10, 1978 to the GRI Project Advisors for review and comment. Resolution of comments will be needed by mid-September in order to complete publication by the end of September.

Additional copies of the following reports were forwarded to DOE for final reviews.

- FE-2240-13 Problems Associated with Controlling Sulfur Emissions from High-BTU Coal Gasification Plants
- FE-2240-52 Fixed Bed Methanation Processes
- FE-2240-31 Factored Estimates for Eastern Coal Commercial Concepts
- FE-2240-55 Factored Estimates for Lignite Commercial Concepts
- FE-2240-50 Sulfur Recovery in a Coal Gasification Plant
- FE-2240-51 Sulfur Removal from Flue Gas

The scheduled work under this contract has been completed. Several reports (including the final report) remain to be published, awaiting approval by DOE.

VIII. DEVELOPMENT OF FAST FLUID BED GASIFIER

HYDROCARBON RESEARCH, INC.
LAWRENCEVILLE, NEW JERSEY

Plant Site: HRI R&D Center,
Lawrenceville, New Jersey

Contract No.: E(49-18)-2361

Contract Funding: \$4,019,043

INTRODUCTION

Under DOE sponsorship, HRI, Inc. is to develop the fast fluid bed gasification concept conceived at the City University of New York (CUNY). A multi-phased program is proposed. The objective of the first phase (Phase I) of the program is to determine operating parameters, feasibility, and viability of a fast fluidized bed gasifier. The several specific tasks which constitutes Phase I of the program are:

Task 1 Develop an optimum process design for experimental evaluation of the fast fluidized bed gasification process. This work will consist of:

- Preparing a process design flow sheet detailing expected material and heat balances for the atmospheric and 150 psig fast fluid bed unit fed initially with non-caking bituminous coal. The process will be designed to utilize coal feeding and conversion product disposal facilities available at HRI.
- Identifying equipment availability for the construction of this process unit.
- Preparing a plan to procure the equipment, outline plant precommissioning tests, and laboratory tests to be conducted at CCNY to meet the project requirements.

Task 2 Construct and commission a seven ton-per-day plant and initiate laboratory tests at CUNY. This work will include testing cold flow operability of the installed components

and conducting cold flow model design at CUNY.

Task 3 Operate the seven ton-per-day fast fluid bed plant to determine coal conversion rates and products, process heat and material balances, and the feasibility of treating caking coals without pretreatment.

Task 4 Prepare proposal for Phase II, which will address evaluating of specific coal feeding and ash removal systems plus the design, construction, and operation of a pilot development unit and/or a pilot plant to produce low BTU gas.

No program schedule diagram is available, but the time allotted for completion of the various tasks is as follows:

Task 1	14 weeks
Task 2	86 weeks
Task 3	31 weeks
Task 4	4 weeks

The performance period commenced July 1, 1976 and will end by December 30, 1979.

PROCESS DESCRIPTION

Fast fluidization is a technique for bringing gas at high velocity into contact with solids characterized by

extreme turbulence. Finely-divided coal is gasified in a greatly-expanded fluidized bed in the presence of air (or oxygen) and steam. Gas velocities as great as 20 feet per second are utilized. Pressures to 150 psig may be achieved. Low-BTU gas is produced.

Advantages expected of this conceptual process include:

- High coal feed capacity
- Superior gas-to-solid contacting
- No coal pretreatment required
- Good turndown capability
- Uniform reaction temperature throughout fluid bed
- High-temperature operation

HISTORY OF THE PROJECT

Process design studies commenced in 1976, with supporting work at CUNY and HRI. By January 1978,

testing of coarse solids flow characteristics began at CUNY, utilizing a six-inch test system. By mid-1978, orders had been placed for most major equipment and instrumentation, with the gasifier being installed in June.

PROGRESS DURING JULY-SEPTEMBER 1978

During this quarter, work continued on installation of major piping, installation of instruments, preparations for winter operations, and installation of major control panels. A test plan was formulated for the initial operation of the gasifier.

Process piping is 80 percent complete. Piping and tubing associated with instrumentation is 70 percent complete. The anthracite coal to be used during initial gasifier operations has been ordered.

IX. GASIFIERS IN INDUSTRY

ACUREX-AEROTHERM CORP.

Plant Site: York, Pennsylvania
Cost: \$1,554,000

IRVIN INDUSTRIAL DEVELOPMENT, INC.

Plant Site: Georgetown, Kentucky
Cost: \$5,600,000

PIKE COUNTY, KENTUCKY

Plant Site: Pikeville, Kentucky
Cost: \$5,800,000

GENERAL REFRACTORIES CO.

Plant Site: Hitchens, Kentucky
Cost: \$4,300,000

LAND O'LAKES CREAMERY

Plant Site: Perham, Minnesota
Cost: \$6,500,000

UNIVERSITY OF MINNESOTA

Plant Site: Duluth, Minnesota
Cost: \$5,486,000

INTRODUCTION

Although a number of low Btu gasification systems are commercially available today, only three operating users exist in the United States. Published technical, economic, and environmental data from these installations, as well as from ones in other parts of the world, are very limited.

On March 30, 1976, a Program Opportunity Notice (PON FE-4) titled "Integration and Evaluation of Low-Btu Coal Gasification Technology in Operational Environments" was issued. This procurement solicited proposals from industrial, commercial, and local government/institutional interests for design, construction, integration, and one to three years of operation of a low-Btu gasification system.

The objectives of the program are to:

- Demonstrate low-Btu gasification technology by integrating and evaluating coal gasification systems in varied applications and operating environments.
- Accumulate and analyze technical data on component and system operating parameters which will assist in the design and development of advanced

state-of-the-art prototype coal gasification systems.

- Decrease the consumption of natural gas and fuel oil in the near-term through application of state-of-the-art systems until advanced, second generation coal gasification systems are available.

DOE will share up to 50 percent of the total cost of the programs. In exchange, all technical, economic, and environmental data acquired from the design through operation of the gasification system will be available to the public. A cooperative agreement rather than a contract is the instrument used for negotiating the agreements between DOE and the participants.

The gasifier is to be a state-of-the-art technology and commercially available in order that operational status can be reached as early as possible. The coal feed limit is set at eight tons per hour in order to be usable by many small plants.

PROGRAM DESCRIPTION

The six proposals selected included four commercially available fixed-bed gasifiers: the Wellman-

Galusha (with and without agitator); a Stoic; a Wellman-Incandescent; and a Woodall-Duckham. Coal types range from anthracite to low sulfur (less than 0.8 percent) Wyoming, Utah and Kentucky bituminous to medium sulfur (up to 1.25 percent) Kentucky bituminous. Gas cleanup requirements range from hot raw gas for a brick kiln; a de-tarred/particulate-cleaned gas for boiler feed and spray drying of milk whey; to an industrial park application requiring complete gas cleanup including desulfurization. Five projects are currently underway.

Acurex-Aerotherm Corporation

A Wellman-Galusha, single stage, fixed bed gasifier was installed at the Glen-Gery brick plant in order to fire several zones of a brick kiln. Paralleling a gasifier now in use, the gasifier can convert one ton of anthracite coal per hour. A cyclone removes particulates from the product gas. The gasifier is fully instrumented for both economic and environmental evaluation. The project schedule and process schematic are shown in Figure IX-1.

Figure IX-1. ACUREX-AEROTHERM PROJECT SCHEDULE AND PROCESS SCHEMATIC.

Irvin Industrial Development, Inc.

Low-Btu gas for space heating, process steam, and direct and indirect fired applications will be provided to a 172-acre industrial park by single-stage Wellman-Galusha gasifiers with agitators. Each gasifier will burn 1.5 tons per hour of Eastern Kentucky coal with 0.8 to two percent sulfur. Four cleaning devices will be used: cyclones for dust collecting; spray towers for oil and tar removal; electrostatic precipitators for particulate removal, and a Holmes-Stretford clean-up system for sulfur extraction. The project schedule and process schematic are shown in Figure IX-2.

Pike County, Kentucky

Two Wellman-Galusha 6.5-foot diameter gasifiers with multiple cyclones for dust removal will provide fuel for hot water heating and chilling units for cooling in a new 65-acre development. The community will include 500 multi-dwelling housing units, a two-bay fire station, a 120-bed medical facility, a day-care facility for 80 children, a 750-student school, a 10,000-square-foot shopping center, and an industrial park. The project schedule and process schematic are shown in Figure IX-3.

Figure IX-2. IRVIN INDUSTRIES PROJECT SCHEDULE AND PROCESS SCHEMATIC

Figure IX-3. PIKE COUNTY PROJECT SCHEDULE AND PROCESS SCHEMATIC

General Refractories Company

Fuel for two tunnel kilns and twelve periodic kilns with an average demand of 895×10^6 Btu per day will be provided by one Woodall-Duckham, two-stage, 10-foot diameter gasifier. Low-sulfur coal from a company-owned mine will be fed to the gasifiers at the rate of 2 tons per hour. Cyclones will remove tar from the upper streams and dust from the lower. The project schedule and process schematic are shown in Figure IX-4.

Land O'Lakes Creamery

A two-stage, 8.5-foot diameter Wellman-Incandescent gasifier will provide fuel to use in boilers and space heaters and for spray-drying of milk whey. Utah coal with less than one percent sulfur will be fed to the gasifier at the rate of three tons per hour. System capacity will be 40 million Btu per hour with 14 million BTU used for the spray-drying. The project schedule and process schematic are shown in Figure IX-5.

1st Year 2nd Year 3rd Year 4th Year 5th Year

Scheduled to Run 1 to 3 Years

Scheduled to Run 1 to 3 Years

This schematic diagram illustrates a coal gasification process. Bituminous coal is fed into a hopper and then a feeder into a vertical gasifier. Air and steam are introduced at the bottom of the gasifier, creating a combustion zone. The gasifier is equipped with a fines bin and an ash pan at its base. Gases from the gasifier pass through a cyclone dust collector and a tar drum before entering a cyclone tar collector. The gas then flows through gas conditioning equipment, which includes a burner and a spray dryer (part of a spray drying operation). The conditioned gas is then sent to a steam distribution system. The process also includes a boiler and an induced draft fan, which are connected to a stack that releases gas into the atmosphere.

Preliminary engineering was begun on the General

Figure IX-6. UNIVERSITY OF MINNESOTA PROJECT SCHEDULE AND PROCESS SCHEMATIC

project engineering continued. By late 1978, construction was nearing completion.

Land O'Lakes, Inc.

Land O'Lakes, Inc. encountered problems in going ahead with the project and has withdrawn its authorization to Applied Technology Corporation to go ahead with the project.

PROGRESS DURING JULY-SEPTEMBER 1978

Acurex-Aerotherm Corporation

Project activities during this quarter consisted of gasifier operation and acquisition of operating cost data. Coal feed rates to the Wellman-Galusha single-stage gasifier varied from 22 to 24 tons-per-day, which is full load. Both ash depth and air inlet saturation temperature were test variables investigated. No operational problems occurred.

Pike County Kentucky

During this quarter a search was initiated for a single source manufacturer/supplier with the expertise to supply a complete raw producer gas cleanup system. Bids were received for the energy center foundation and floor slab. The boiler manufacturer was instructed to determine the operating characteristics of the boilers under varying load conditions with various fuels; and to investigate if boiler temperatures are high enough to provide complete carcinogenic incineration of coal tar which may be burned as fuel.

General Refractories Company

All project work for the preliminary design has been completed except the final report. The preliminary design report was issued.

University of Minnesota

Construction of the gasification plant continued. Late in this quarter, construction was 92 percent complete, and all engineering was complete. Problems include delivery of remaining materials and resolution between the University and Foster Wheeler Energy Corporation for startup assistance.

Irvin Industrial Development Inc.

The project was delayed pending resolution of environmental issues. A draft environmental impact statement was prepared. The environmental hearing board held a public meeting on the DEIS at Georgetown, KY.

Land O'Lakes, Inc.

Negotiations with the original major contractor have been terminated and a new major contractor is being sought.

X. MOLTEN SALT GASIFICATION PROCESS

ATOMICS INTERNATIONAL DIVISION
ROCKWELL INTERNATIONAL CORPORATION
CANOGA PARK, CALIFORNIA

Plant Site: Santa Susana, California
Contract No.: EF-77-C-03-1429
Contract Funding: \$11,729,990
(100% DOE)

INTRODUCTION

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

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

PROCESS DESCRIPTION FOR GASIFICATION/COMBINED CYCLE POWER SYSTEM

In the molten salt gasification process, coal is gasified to produce electricity through gas and steam turbines. Three major steps are required: (1) molten salt coal gasification, (2) electric power generation, and (3) sodium carbonate regeneration. Figure X-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 1,800°F and 20 atm. The fuel gas produced has a heating value of approximately 150 Btu per standard cubic foot and is predominately carbon monoxide, hydrogen, and nitrogen. Because the melt retains the ash and sulfur from the coal, the melt must be continuously withdrawn from the furnace. The melt stream is subsequently regenerated.

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

In the regeneration section, the melt is withdrawn from the molten salt furnace into a quench tank where the salt is dissolved in water. The resulting slurry is then passed through a filter for removal of ash. The filtrate, 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, and recycled. The crystals are dried in a rotary kiln, and recycled to the molten salt furnace as regenerated sodium carbonate.

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

LEGEND : △ BEGIN MILESTONE
▽ COMPLETE MILESTONE

Figure X-1. MOLTEN SALT GASIFICATION PROGRAM SCHEDULE

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

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

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

HISTORY OF THE PROJECT

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

pilot plant should be constructed and operated to further explore and demonstrate its potential for commercialization.

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

- Effects of pressure on gasifier operation and performance.
- Air and solids feed system design and operating parameters.
- Melt withdrawal and quench system design requirement.
- Entrainment of particulates in the product gas and purification requirements.
- Optimum sodium carbonate regeneration process flow scheme.

In the previous project the preliminary design of a pilot plant was completed during the third quarter of 1975 and the plant cost estimated. Because these new costs were considerably higher than the original estimates, alternative approaches were evaluated in order to select a program which would enable the objectives to be met at a lower cost. Based on these studies, it was decided to move the pilot plant from Norwalk Harbor, Connecticut, to the Atomics International 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 and the development contract for the five-ton-per-hour facility was terminated.

Phase I, preliminary engineering, was completed in August 1976. It was decided that Atomic International would be responsible for the entire detailed design, and this work began in November 1976. Ground breaking for the process development unit occurred on March 8, 1977. By the end of 1977, detailed design, most of the procurement, and large part of the construction had been completed. By mid-1978, construction of the PDU was completed.

PROGRESS DURING JULY-SEPTEMBER 1978

The design, procurement and construction tasks relating to the one ton of coal per hour PDU have been com-

pleted. Startup of the PDU is proceeding. Penetration of heat from the preheat burner, which is located at the top of the gasifier vessel, to the lower portion of the vessel, has been slower than expected and it is antici-

pated that this will cause some delay in completion of all scheduled startup activities. The small plant improvement construction contract was awarded on schedule and completion is planned for early September.

XI. ADVANCED COAL GASIFICATION SYSTEM FOR ELECTRIC POWER GENERATION

WESTINGHOUSE ELECTRIC CORPORATION
MADISON, PENNSYLVANIA

PDU Site: Waltz Mill, Pennsylvania
Contract No.: EF-77-C-01-1514
Contract Funding: \$33,303,105 (through fiscal
year 1977)
DOE: \$29,303,105
Industry: \$ 4,000,000

INTRODUCTION

The advanced coal gasification system for electric power generation is being developed by Westinghouse Electric Corporation. DOE is providing the major portion of the funds through the process 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 and medium-Btu gas from coal for application to combined-cycle electric generation and industrial fuel utilization. Westinghouse is to:

- Conduct laboratory research to refine the advanced gasification process.
- Design and construct a process development unit with a capacity of 12 tons of coal per day.
- Operate the process development unit to establish the operating characteristics of the gasification sys-

tem. This will provide data for developing scale-up factors for the design and construction of a future 120-ton-per-day pilot plant.

The successful operation of the pilot plant will demonstrate the technical feasibility of the process, and provide data for determination of the 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 XI-1.

PROCESS DESCRIPTION

A schematic of the advanced coal gasification system for electric power generation is provided in Figure XI-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 mesh, dried, and transported to a reactor vessel for devolatilization and partial hydrogasification. A central draft tube is used primarily for recirculating solids. Recycled solids required to dilute the feed coal and

LEGEND: $\triangle$ BEGIN MILESTONE
 ∇ COMPLETE MILESTONE

Figure XI-1. ADVANCED COAL GASIFICATION PROGRAM SCHEDULE

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

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 160 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. 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 is burned with air in the lower leg of the gasifier at 1,900-2,000°F to provide the heat for gasification. Heat is transported from the combustor to the gasification zone by combustion gases flowing upward and by char circulating between the combustion and gasification zones. Ash from combustion of fines agglomerates on the ash from the char and segregates in the lower bed leg for removal.

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

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

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

HISTORY OF THE PROJECT

Initial development of the advanced coal gasification system involved laboratory research, including the design and construction of a process development unit (PDU). The PDU was mechanically completed in 1974, and a test program was initiated in 1975 to establish the oper-

ating characteristics of the system and provide data for developing scale-up factors for a pilot plant. Other laboratory research has involved:

- Fluidized-bed desulfurization with dolomite.
- Development of scale-up design correlations for fluidized beds.
- Combustion of coal-derived fuel in diffusion-flame gas turbine combustors.
- Identification and testing of apparatus for high-temperature gas stream particulate control.
- Development of a specification for the tolerance of a modern utility gas turbine to particulates, vaporized alkali metals, and other gaseous contaminants.

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

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

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

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

Efforts during the first half of 1976 were concentrated on tests in the process development unit devolatilizer subsystem. Following the conclusion of these test, much of the work effort shifted to completion of the gasifier PDU. Initial shakedown tests were completed late in 1976, and the first gasifier hot test was completed in December 1976.

During 1977, a series of shakedown tests, a reactor design test, and materials tests were performed to secure data and operational experience. The control of combustion in the unit was demonstrated; ash agglomeration and withdrawal were studied and successfully achieved; the reactor geometry was optimized to some extent; operating procedures were established; the ability to achieve high fines utilization and high carbon utilization was demonstrated; and operation was demonstrated with feedstocks with a wide range of characteristics in terms of composition, particle size, and reactivity. Design and procurement of hardware for integrated operation of the gasifier and devolatilizers reactors also continued throughout the year. Laboratory studies included support tasks for the current PDU combustor-gasifier test program, preparation for integrated operation, coal behavior studies, ash behavior studies, and reactor analysis.

By mid-1978, PDU modifications for integrated operations and the first oxygen-blown gasifier test with the expanded reactor configuration was initiated.

PROGRESS DURING JULY-SEPTEMBER 1978

The series of gasifier tests utilizing oxygen continued, with four tests being completed this quarter and a fifth test being initiated. These tests were designed to measure

the effects of steam flow and reactor temperature on the gasification of Pittsburgh seam coal using oxygen in the expanded gasifier configuration. The Pittsburgh seam coal was fed directly to the gasifier at 1,800°F (in test series TP-016) without the benefit of pretreatment or devolatilization.

PDU modifications for integrated operation of the devolatilizer and the gasifier and for operation with oxygen continued during this quarter. Preparation for a 30-day PDU test continued with the accumulation of a history and frequency record on PDU test anomalies for the period of March 1977 through September 1978. From this study a list has been compiled of possible critical problem areas. Resolution is expected to require definition of design changes and requirements for backup systems and spare parts ordering. It is believed that a 30-day downtime period immediately preceeding the 30-day test will be necessary to carry out maintenance and upgrading of PDU equipment. The test is tentatively planned for mid-1979.

The PDU at Waltz Mill is a 12 ton-per-day unit. A conceptual design of a three-meter scale-up model was prepared this quarter. Site selection for the scale-up model has been tentatively identified as adjacent to the utilities building at the Westinghouse ACCD location. Preliminary layout drawings have been prepared for a main building in which to house the test compressors. Expected high noise levels from the air compressor and chiller systems necessitates the two-building design. Cost estimates for the compressed air and chiller supply systems have been obtained.

XII. LOW-BTU GASIFICATION OF COAL FOR ELECTRICITY GENERATION

COMBUSTION ENGINEERING, INC.
WINDSOR, CONNECTICUT

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

INTRODUCTION

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

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

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

PROCESS DESCRIPTION

The Combustion Engineering gasification process is based on an air-blown, atmospheric-pressure, entrained-bed gasifier. A schematic of the process is provided in Figure XII-2. In the process, a portion of the pulverized coal and recycled char are fed to the combustion section of the gasifier and burned to supply the heat necessary for the endothermic gasification reaction. In the combustion section, nearly all of the ash in the system is converted to molten slag, which is then drawn off the bottom of the gasifier. The remainder of the pulverized coal is fed to the reduction portion of the gasifier where it is contacted with hot gases entering the reduction zone from the combustor. The gasification process takes place in the entrainment portion of the reactor where the coal is devolatilized and reacts with the hot gases to produce the desired product gas. This 1,700°F product gas is then cooled to 300°F. At this point, the gas contains solid particles and hydrogen sulfide that must be removed. Solids are removed and recycled by means of a spray drier, cyclone separators, and venturi scrubbers. Hydrogen sulfide is removed and elemental sulfur is produced by the Stretford process. The clean low-Btu gas (about 120 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 120 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 atm to ten atm the total plant cost would be reduced by eight percent. This savings results from the ten-fold reduction of gas volume and, hence, equipment size. Conversely, much of the process simplicity would be lost and additional development would be required for:

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

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

nomical for application to the majority of electric power plants.

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

By the end of 1975, the designs of many of the subsystems were nearly completed, and requests for quotations were issued for various components. About 30 percent of the major equipment for the PDU had either been approved for purchase or released for fabrication by the end of 1975. Plot plans and general equipment arrangements were completed, and preparation of the construction site for excavation and foundation installation was started. Some work had been done on establishing operating procedures and developing a test plan for evaluating the performance of the gasifier during steady state operation. Construction was completed in the Fall of 1977, and a dedication ceremony was held at the plant site on October 18, 1977.

Laboratory research included the investigation of the behavior of various refractories with slag and gas, and the development of a one-third scale plastic model for studying stream flow patterns. A mathematical analysis of the gasifier was carried out through the use of computer modeling of the unit. Plant metallurgical requirement studies and environmental studies were also conducted. Supporting studies consisted mainly of an analysis comparing the costs of producing electricity by various integrated gasification power plant systems. Two alternatives were selected for further study: a conventional steam plant with an atmospheric gasifier and a combined-cycle plant with a supplementary-fired boiler and atmospheric gasifier. In addition, specifications for an automated data-acquisition and reduction system were completed. The first PDU gasmaking run was completed in June 1978.

PROGRESS DURING JULY-SEPTEMBER 1978

Summary

PDU gasmaking Runs No. 3 and No. 4 were completed during September and Run No. 5 was just getting underway as the month ended. Eighty gasmaking hours

were logged during Run 3. A total of 49.7×10^6 standard cubic feet of gas was produced which ranged from 58 to 74 BTU/scf in heating value. Run No. 4, which commenced less than a week after Run No. 3 ended, logged a total of 138 gasmaking hours. Gas produced during Run No. 4 totalled 87.5×10^6 standard cubic feet and varied between 45 and 73 BTU/scf in heating value.

All systems and subsystems of this PDU are in operation whenever the plant is operated in the gasmaking mode. The gas made by the gasifier is cleaned of particulate matter (char) and passed through the Stretford absorber to remove H_2S from the gas. The cleaned gas then is burned in the furnace of the plant's package boiler and the products of combustion discharged to atmosphere through the boiler's stack.

Process Development Unit

The PDU's gasmaking Run No. 3, which commenced on August 25, continued until the morning of September 3, 1978, at which time it was necessary to shut the plant down due to blockage of the combustor's slag tap hole by solidified slagged ash. Eighty (80) gasmaking hours were logged by the plant during Run No. 3. A total of 49.7×10^6 standard cubic feet of gas was produced during the run. Heating value of the gas produced varied in the range of 58 to 74 BTU/scf. Internal inspection of the major plant components following Run 3 failed to reveal any major problems except for the plug in the slag tap hole and loss of considerably more refractory from the floor, walls, and roof of the combustor and throat of the diffusor.

Operation during the middle and latter parts of Run No. 3 was characterized by repeated erratic performance of the coal and char feeders and progressive deterioration in the character of molten slag flow from the combustor's slag tap hole. Initially, slag flow was quite fluid and concentrated into one continuous molten stream. As the run progressed, the positive single stream of slag gradually degenerated into random small-stream flows

over the entire periphery of the tap hole. These small streams adhered to the slag neck wall and progressively built up to the point of completely blocking the tap hole.

PDU gasmaking Run No. 4 commenced on September 9, 1978, and continued until 6:30 p.m. on September 16, 1978, at which time complete blockage of the slag hole again shut the plant down.

One hundred and thirty-eight gasmaking hours were logged during Run No. 4. A total of 87.5×10^6 standard cubic feet of gas produced during the run. Heating value of the gas produced ranges from 45 to 73 BTU/scf. Internal inspection of the major plant components following Run No. 4 again failed to reveal any major problems, except for the plugged slag tap hole.

A decision was made to bring the plant back on-stream as soon as possible and attempt to reproduce the gasmaking runs of June 1978, when gas with a heating value of about 120 BTU/scf was produced. Preparations for gasmaking Run No. 5 on this basis would require only that the refractory dam and slag spout at the combustor's slag tap hole be rebuilt.

Rebuilding of the slag tap hole refractory was simple and straightforward, but undesirable booster fan vibration developed during leak testing of windboxes and ductwork during inspections following Run No. 4. Nearly a week was required to do the fan alignment and balancing job.

The realignment and balancing job finally was completed on September 29 and startup of the plant for Run No. 5 commenced on that date.

PDU gasmaking Run No. 5 commenced at the end of this quarter. Upon completion of this, major improvements will be made in plant components to improve reliability and accuracy of coal, char, and air measurements, to minimize booster fan vibration, to provide better regulation of Stretford solution, and to provide a reliable slag tapping operation.

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

BITUMINOUS COAL RESEARCH, INC.
MONROEVILLE, PENNSYLVANIA

Plant Site: Monroeville, Pennsylvania
Contract Nos.: EF-77-C-01-1527 (initial)
and ET-78-C-01-2798 (current)
Current Funding: \$2,690,000
(100% DOE)

INTRODUCTION

Bituminous Coal Research (BCR) is developing a multiple fluidized-bed coal gasification process for producing low-Btu fuel gas from caking and noncaking coals. The project is being sponsored by DOE. The low-Btu fuel gas product will be suitable primarily as boiler fuel gas for electricity generation, although alteration of operating conditions could yield medium-Btu gas suitable for other uses. The research task includes the

design, construction, and testing of a process development unit, and laboratory investigations. The schedule for development of the low-Btu fuel gas system is shown in Figure XIII-1.

PROCESS DESCRIPTION

The BCR low-Btu research effort is based on a three-stage fluidized-bed gasification process. Stage I of the

LEGEND:

- △ BEGIN MILESTONE
- ▽ COMPLETE MILESTONE

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

three-stage system receives the raw coal and functions as the pretreatment step in which the coal is devolatilized. Stage 3 flue gas is used as the fluidizing medium for Stage 1. The coal then flows by gravity to Stage 2, where devolatilized coal is gasified with air and steam to generate the desired product gas. Stage 1 flue gas is fed to Stage 2 where the entrained tars and oils are gasified. The remaining char from Stage 2 is consumed in Stage 3 by fluidized combustion. The ash discharged will contain only a minimum amount of carbon.

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

HISTORY OF THE PROJECT

Initial development of the low-Btu fuel gas process involved laboratory investigations to obtain kinetic data for various chars, or devolatilized coal, that would be produced in the first step of a multiple fluidized-bed gasification process. A small fluidized-bed batch reactor system was then used to verify proposed rate equations, determine the reaction rate between steam and char, and provide physical data such as minimum fluidizing velocity, attrition rate, elutriation losses, etc. The successful laboratory studies led to the design of a PEDU 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. Pretreatment testing of a Western non-caking coal (Montana Rosebud) was completed in the Stage 1 reactor. Correlations were developed for the properties of the product char as a function of Stage 1 operating temperature. Subsequently, testing of a mildly caking coal (Illinois No. 6) was conducted in the Stage 1 reactor beginning in mid-1976. A noncaking product char was obtained at pretreatment temperature of less than 800°F

and in the presence of oxygen. Further testing at 900°F to 1,000°F demonstrated the ability to devolatilize the coal while avoiding caking. The product char from this testing was free flowing and did not cake when subjected to laboratory testing at Stage 2 operating temperatures. A data-acquisition system was installed to sample selected test points, convert the data to engineering units, and store the values on magnetic tape.

Concurrent with process and equipment development unit (PEDU) operations, BCR is conducting laboratory research in an effort to further refine the low-Btu fuel gas process. During 1975, laboratory research included using a cold flow model of the gasifier bed to study bed fluidization. Fluidization was improved when a 45-degree conical, rather than flat, distributor was installed in conjunction with special nozzles that direct the fluidizing gas downward toward the distributor base and horizontally toward adjacent nozzles. Among other fluidization studies were those to observe the behavior of char in a fluidized bed, determine whether the purge flows on the pressure taps were necessary, and study the effect of purge flows on pressure drop in the unit. A computer model to predict the conversion in the fluidized-bed gasifier was also developed. The results showed the effects of mass diffusion and bubble diameter on conversion and product gas concentration.

PROGRESS DURING JULY-SEPTEMBER 1978

Summary

During this quarter, Illinois No. 6 seam coal was utilized in 14 tests in the Process and Equipment Development Unit (PEDU). The general objectives of these tests were to determine if the level control system would function properly in the Stage I fluidized-bed when mildly caking coal feed was used and to determine if the coal could be pre-treated at temperatures up to 880°F without causing agglomeration.

Discussion of Activities

Four tests were conducted in the 100 pound-per-hour PEDU during July to determine operability of the level control systems. It was concluded that the level control systems does function until agglomerates form. The tests indicated that a temperature of 875°F seems to be suitable for operation, while 840°F appears to be too cool to successfully pretreat Illinois No. 6 seam coal.

During August, three tests were run in the PEDU to determine the upper temperature limit for the Stage I pretreating fluidized-bed. Successful operation resulted at a bed temperature of 880°F. However, the Stage I preheater burned out during these tests.

During September, seven tests were completed in the TRI-GAS PEDU, all using Illinois No. 6 coal as feed to Stage I. The Stage I preheater burned out during these tests. A build up of a layer of a mixture of tars and fine char particles was noted at the top of the reactor. As a result of these problems, it was decided to suspend further testing in Stage I until the Stage I preheater is repaired and re-installed in the PEDU.

Several major modifications were made to the PEDU during the report period. These modifications were

aimed at obtaining a system capable of achieving optimum operation of the process. Each of the reactors will be modified to incorporate electric heating to balance heat losses; stage 3 changes have been completed.

Small-scale laboratory experiments and analytical studies were conducted to support the PEDU experimental program. Fluidization characteristics for typical coal and char feeds were determined in full-scale and small, cold-flow fluidization models. Devolatilization and gasification reactions were studied in small-scale differential and fluidized-bed reactors. Mathematical models of the TRI-GAS process were developed to help predict PEDU performance.

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XIV. GASIFICATION COMBINED CYCLE TEST FACILITY

COMMONWEALTH RESEARCH CORPORATION

Plant Site: Pekin, Illinois
Contract No.: EF-77-C-01-2352
Contract Funding: \$224,500,000
DOE: \$173,100,000
Industry: \$ 51,400,000

INTRODUCTION

Many directed studies have shown that the Combined Cycle Concept of Power Generation based upon low-Btu gas as the fuel source offers the greatest opportunity to (1) increase the efficiency at which thermal energy is transformed to electrical energy, (2) install additional generation capacity and adapt existing facilities that can perform in an environmentally acceptable manner both under current as well as projected standards, (3) increase the use of coal in the generation of electrical power. Indeed, it may be said that power generation utilizing combined cycles operating with low/medium-Btu gas from coal is the greatest single opportunity to provide substantial contributions to the energy supply through the increased use of coal.

The Gasification Combined Cycle Test Facility is a key project in the Gasification Development program. There are two principal objectives to be accomplished by this effort. The first of these objectives is to adapt low-Btu gasification processes for use in combined cycle power plants. This includes developing a suitable gas combustor as well as key control systems and demonstrating the integrated operation of these components in combination with the gasification system and turbine generator in a combined cycle test facility. The second but equally important objective is to develop and demonstrate the integration of future improved gasification and purification units with second generation higher inlet temperature combustion turbines. This facility will provide a site and resources for the evaluation of coal gasification combined cycle systems for power generation, low-Btu and medium-Btu gasifiers, hot and cold

clean-up systems for synthesis gases, components for advanced power generation turbines and fuel cells.

The project is being directed by Commonwealth Research Corporation (CRC) under the sponsorship of DOE, the State of Illinois, and an industry team composed of Commonwealth Edison (CE) and the Electric Power Research Institute (EPRI). Fluor Engineers and Construction, Inc. is performing the engineering and procurement. Fluor Constructors, Inc. will perform the construction. Lurgi Kohle and Mineralotechnik GmbH are providing the process design package for gasification and gas cleaning and American Lurgi is providing detailed engineering and procurement services for proprietary portions of this design. General Electric is currently pursuing a low-Btu combustor development program, to supply the combustor for the combine cycle operation. GE is also supplying a modified Frame 5-gas turbine with an output capability of 20 Mw. A brief milestone schedule for the project/Task I is shown in Figure XIV-1.

The current scope of the Program includes a 3 year operation plan. The primary goals in this operation plan are the following:

- Verify that the low-Btu gas produced from the following test coals can be reliably burned in the gas turbine.

The design coal Illinois #6
Illinois #5
Decker
Rosebud
Pittsburgh No. 8
Yet to be selected coal

LEGEND:

△ BEGIN MILESTONE

○ DECISION MILESTONE

▽ COMPLETE MILESTONE

Figure XIV-1. GASIFICATION COMBINED CYCLE TEST FACILITY PROGRAM SCHEDULE

- Establish the precise emission levels for each coal.
- Demonstrate the integrated operation of the unit component.
- Investigate the response characteristics of the plant to electrical system load variations.
- Obtain design data required for construction of a full size commercial facility.

PROCESS DESCRIPTION

The basic unit processes involved in Task I of the Powerton Program are gasification, desulfurization, tar-oil separation, gas turbine, and heat recovery steam generation. Supporting units are sulfur recovery, coal handling, thermal oxidation of by-products, and all the necessary utilities. A schematic of the gasification combined cycle test facility is provided in Figure XIV-2.

The gasification facilities will consist of two four-meter diameter Lurgi gasifiers. Although it is planned to operate both gasifiers at various capacities, one will satisfy the plant capacity of 24 tons of coal per hour. There is one gas quench and cooling train common to both gasifiers. Each gasifier will be a counterflow moving bed reactor. Coal will be fed to the top of the vessel and hot ash removed from the bottom. The counterflow design between coal and steam-air oxidant promotes natural zones for the basic gasification reactions, and allows utilization of the sensible heat of the gas for coal drying and preheating to achieve a high gasification efficiency.

The crude gas leaving the gasifier at approximately 800°F will contain dust, tar, oil, naptha, excess steam,

and various contaminants. This gas, after leaving the gasifier, will be quenched with water in a wash cooler. The saturated and cleaned gas will pass to gas coolers consisting of vertical tubular heat exchangers with water on the shell side. This water will be routed to a saturator arranged downstream of the desulfurization system, thereby transferring heat and water vapor from the crude gas to the clean product gas. This circulating water system will constitute a regenerative form of cooling and heating which will conserve the thermal energy in the product gas. The gas liquor condensed out of the gas in the various cooling steps will be routed to the tar-oil separation unit.

The desulfurization unit will consist of two scrubbers and a regenerator. Hot crude gas first will pass through a prewash scrubber for removal of cyanides and other water soluble contaminants. The prewashed crude gas then will flow through the second scrubber, where desulfurization will be effected by countercurrent contact with a solution of hot activated potassium carbonate. Regeneration of rich solution will be accomplished in a third vessel by stripping out absorbed hydrogen sulfide and carbon dioxide.

The stripped acid gas stream will be processed for removal of residual ammonia before it is fed to the sulfur recovery unit.

Tarry gas liquor from the various knockout vessels of the gas cooling train will be delivered to the tar separators. These vessels will be of special design to separate streams of tar, oil, and an aqueous liquor. The liquor will be recirculated to the process via an intermediate gas liquor receiver and a pressurizing pump. Excess gas liquor will be purged to the thermal oxidizer for disposal.

Figure XIV-2. GASIFICATION COMBINED CYCLE TEST FACILITY PROCESS SCHEMATIC

In the tar separator a mixture of tar and dust carried over from the gasifier will settle to the bottom of the vessel and be returned to the gasifier. A portion of this heavier tar will be purged from the system to the thermal oxidizer for disposal. Similarly, the lighter oil components will overflow from the tar separators to intermediate storage and to the thermal oxidizer for disposal.

Prior to combustion in the gas turbine, the low-Btu gas will be saturated with gas liquor that has been stripped of ammonia and then superheated to prevent any condensation. The product gas will be burned in a modified General Electric MS5001 gas turbine producing approximately 25 megawatts of power. Air for gasification will be extracted from the gas turbine compressor. A booster compressor delivers air to the gasifier at the required pressure. The turbine is designed to fire either low-Btu gas, distillate, or a combination of both fuels.

The exhaust gas from the turbine will flow through the heat recovery steam generator to generate process steam and then be vented to the atmosphere. In a true combined cycle plant, this steam production would be maximized and used to generate additional electric

power. Since the production of electricity from steam uses proven technology, steam generation in this demonstration plant is limited to the requirements for process and heating steam demand for the facility.

Steam will also be generated in the thermal oxidizer. However, the primary role of the thermal oxidizer is that of an incinerator for streams which are too small to collect for resale. In a full size plant, the tars, oils, and ammonia will be valuable products to be recovered and stored for resale.

Additional support facilities include ammonia removal, sulfur recovery by the Stretford process, coal handling, cooling water, plant and instrument air, flare water treating, and others.

HISTORY OF THE PROJECT

The Lurgi coal gasification process has long been used in plants in Europe and South Africa to produce

a clean burning fuel from coal. These plants have used coal gasification as a sulfur contaminant removal process with subsequent hydrogen sulfide removal to supply domestic gas systems with clean-burning gas.

Since the State of Illinois has large and wide spread coal deposits that presently may be unusable due to air emission restrictions, Commonwealth Edison has been exploring the potential of a gasification combined cycle facility since 1972. Along with EPRI, Fluor E & C, and Lurgi, CE began the initial work on the development of a system for the low-Btu gasification of coal for electricity generation. This involved economic evaluation of various coal gasification and energy conversion system for the production of electricity.

In March 1975, Lurgi and Fluor E&C were commissioned to proceed with the engineering and design of a Gasification Turbine Test Facility. Prior to this, the engineering and design efforts were devoted to a Clean Power Fuel Test Facility with work having been started by Fluor in April 1974. This involved a coal

gasification facility to produce a low-Btu gas for firing in conventional boilers and a future combined cycle system. In the fall of 1975, CE submitted a proposal outlining a program for a Gasification Turbine Test Facility, based upon the previous effort, to ERDA (now DOE) for funding. At that time, Fluor had begun the process design, layout drawings for the gasifier, arrangement drawings, model construction, and a preliminary overall plot plan. ERDA, along with the industrial partners, decided to fund the project. Full scale detailed engineering for the project was started in May 1977 geared toward construction beginning mid-1978.

PROGRESS DURING JULY-SEPTEMBER 1978

Clearances for preconstruction have not been approved by DOE. Field move-in for early 1979 appears to be doubtful, hence slippage in the project construction schedule will result.

XV. THE COAL CONVERSION SYSTEMS TECHNICAL DATA BOOK

INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

Contract No.: EX-76-C-01-2286

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

INTRODUCTION

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

PROGRAM DESCRIPTION

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

The outline of the data book is shown below:

- Section I: **PROPERTIES OF PROCESS MATERIALS**
 - A. Properties of Gasification Products
 - B. Properties of Intermediates and Conversion Products
 - C. Properties of Related Processing Materials
- Section II: **SOLIDS STORAGE, PREPARATION, HANDLING AND PRETREATMENT**
 - A. Coal Storage and Handling
 - B. Coal Preparation
 - C. Weighing and Metering of Solids Flow
 - D. Feeding of Solids
 - E. Chemical Treatment of Coal
- Section III: **CONVERSION FUNDAMENTALS**
 - A. Gasification
 - B. Pyrolysis
 - C. Liquefaction
 - D. Fluidized-Bed Combustion
 - E. Advanced Power Generation
 - F. Chemical Equilibrium and 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
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- C. Shift Conversion
- D. Methanation
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- A. Methanol
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Section VII: MATERIALS OF CONSTRUCTION

- A. Refractories
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Section IX: PROCESS ECONOMICS

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Section X: PROCESS FLOW SHEETS

- A. Liquefaction
- B. High-Btu Gasification
- C. Low-Btu Gasification
- D. Fluidized-Bed Combustion
- E. Advanced Power Generation

HISTORY OF THE PROJECT

The first edition of the Technical Data Book was prepared and distributed to Special Consultants for comments and suggestions at the end of 1977.

Main areas of investigation of the properties of process materials during 1977 were the analysis of equilibrium data, correlations for estimating the calorific value of coal, and the properties of coal liquids. Conversion fundamentals dealt with fluidized-bed combustion and pyrolysis data. Standpipe and slurry preheater design procedures were investigated. The performance of various materials of construction for coal conversion reactors were analyzed.

PROGRESS DURING JULY-SEPTEMBER 1978

Subjects investigated during the quarter included properties of process materials, conversion fundamentals, design procedures.

Properties of Process Materials

The data of Ginsberg, Otsuka and coworkers, and Frohlich concerning Vapor-Liquid Equilibrium in the $\text{NH}_3\text{-CO-H}_2\text{S-H}_2\text{O}$ System were reviewed.

Conversion Fundamentals

The report on pyrolysis was received from Resource Engineering, Inc., who were retained to attempt the following:

- to extend the correlation of the Fischer Assay data to include parameters other than chemical analysis, including petrographic analysis and internal surface area.
- to correlate Fischer Assay data with new rapid-rate pyrolysis processes.

Fixed-bed gasifier models developed at the University of West Virginia and the University of Delaware are being evaluated.

Design Procedures

Type I and Type II gas-solid transport pressure drop correlations are being investigated. Type I pressure drop correlations are those in which the ratio of total pressure drop is correlated to that due to gas alone. In Type II correlations, pressure drop is expressed as the summation of pressure drops due to momentum of each phase, static head, dry force, and wall friction.

Heat transfer coefficient for the slurry preheater were calculated for SRC-I runs at Tacoma, Washington, using Sieder-Tate and Crewe-Simons equations for comparison with experimental values.

Supporting Processes

Reports were received from a subcontractor with figures concerning the sulfur recovery, particulate removal, and wastewater treatment sections.

Materials of Construction

The sections of the annual report which concern laboratory and pilot plant corrosion data were revised.

Data are being compiled on mechanical properties of candidate metals and alloys for gasification.

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XVI. COMPUTER MODELING OF COAL GASIFICATION REACTORS

SYSTEMS, SCIENCE, AND SOFTWARE

LA JOLLA, CALIFORNIA

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

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

INTRODUCTION

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

PROGRAM DESCRIPTION

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

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

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

During the second and third years, the computer model will be expanded to apply to high-Btu gasification, low-Btu gasification, and entrained-flow processes. The computer programs developed during the first year will be combined, and the resulting prototype programs will be used to verify the accuracy of the formulations and 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 DOE. The computer model will then be developed further to include three-dimensional effects, internal heat transfer surfaces, and combustion chemistry, so that it can be applied to the broad spectrum of

fluidized-bed and entrained-flow processes being considered for coal conversion and utilization.

HISTORY OF THE PROJECT

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

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

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

During 1977, effort was concentrated on the development of a fluidized-bed model of steam-oxygen gasification and the completion of the three dimensional version of the entrained flow model. Test calculations of individual subroutines in that code were initiated.

PROGRESS DURING JULY-SEPTEMBER 1978

Calculations of combustion and gasification phenomena for the fluidized-bed coal gasification model continued this quarter. Preliminary two-dimensional bubbling calculations in a gasifier environment, simulating Synthane, were initiated. These calculations will culminate the present series of calculations with the fluidized-bed code.

For the entrained flow coal gasification model, a three-dimensional, time-depenent calculation of swirling vortex flow in a simplified combustor was completed. Further development of the entrained flow code was continued with the emphasis being incorporation of the chemistry subroutines into the multi-dimensional entrained flow model.

GLOSSARY

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

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

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

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

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

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

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

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

API — American Petroleum Institute.

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

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

ash — solid residue remaining after the combustion of coal.

ASTM — American Society for Testing Materials.

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

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

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

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

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

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

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

BTX — benzene, toluene, xylene; aromatic hydrocarbons.

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

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

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

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

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

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

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

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

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

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

coalification — metamorphosis of vegetable debris into coal.

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

coke breeze — the fine screenings from crushed coke usually passing a 1/2 inch or 3/4 inch screen opening.

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

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

combustor — a vessel in which combustion takes place.

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

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

crude gas — impure gas produced in a gasifier.

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

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

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

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

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

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

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

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

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

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

diatomite—See Diatomaceous Earth.

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

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

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

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

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

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

effluent gas—gas given off from a process vessel.

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

endothermic reaction—a process in which heat is absorbed.

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

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

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

exothermic reaction—a process in which heat is liberated.

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

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

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

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

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

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

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

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

Fischer-Tropsch process—method of hydrogenating mixtures of

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

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

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

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

flue gas—gaseous combustion products.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

industrial gas—see fuel gas.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

methanol—methyl alcohol, CH_3OH .

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

raw gas—see crude gas.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

slurry—a suspension of pulverized solid in a liquid.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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