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MORGANTOWN ENERGY TECHNOLOGY CENTER

TOPICAL REPORT

SURFACE COAL GASIFICATION

This overview report, prepared by Morgantown Energy Technology Center staff, describes the historical development and current status of the Surface Coal Gasification Program.

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UNITED STATES DEPARTMENT OF ENERGY
Morgantown Energy Technology Center
Morgantown, West Virginia 26505

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1.0 INTRODUCTION

1.1 Program Perspective

The United State Department of Energy program for Surface Coal Gasification has evolved over several years of R&D activities beginning with the Office of Coal Research and followed by a thrust from the Energy Research and Development Administration to build demonstration plants and a growing realization that the United States technology base, economics, and domestic manufacturing infra-structure requires stimulation to meet the targeted 1992 alternate-fuels goals that were established during the Administration of President Carter. Also, 1979-80 gasification technology commercialization activities have been initiated through PL96-126, Alternative Fuels Awards, and the formation of a Synthetic Fuels Corporation (SFC) through PL96-294.

In this setting, the U.S. DOE Fossil Energy's pilot-plant program has assumed a dual role: (1) developing advanced processes and (2) expanding the technology base necessary to support potential demonstration-plant problem areas, optimization, and commercialization.

1.2 Program Objectives

The successful commercial application of surface gasification of coal could enable the United States to use from its vast deposits of coal to produce a wide variety of energy products and chemical feedstocks, thus aiding this country's move toward energy independence. As shown in Figure 1-1, the technology base is well developed and extremely flexible for converting coal into alternate products suitable for the demands of a broad and heterogeneous market and a wide array of users/owners.

The surface coal gasification pilot-plant activity currently consists of the following subactivities:

- High-Btu Gasification.
- Low-' and Medium-Btu Gasification.

Successful completion of projects in the Surface Coal Gasification Program will develop and demonstrate the means to convert the full range of U.S. coal into clean synthetic gaseous and liquid fuels, which can substitute for petroleum-refinery products and chemicals. The gaseous fuels include high-Btu gas having a heating value of approximately 950 Btu/scf and low- and medium-Btu gases having heating values that range from approximately 80 to 350 Btu/scf.

The three primary objectives of the Surface Coal Gasification Pilot-Plant Program are:

- Develop a technology data base that enhances private-sector commercialization and DOE demonstration-plant startup, operation, and optimization.
- Evaluate the technological and economic status of second- and third-generation processes and assess their suitability for meeting U.S. market needs and environmental requirements using domestic coals (caking as well as non-caking) to produce synthetic natural gas, gaseous fuels for power generation or as an industrial fuel, or as a synthesis gas intermediate for chemical feedstocks.
- Establish the availability through development and/or demonstration of clean-up equipment, components, and systems suitable for use in coal gasification processes.

To meet these objectives, several pilot-plant and process-development operations are being conducted under the Surface-Gasification Program. Four of these operations are described in this report:

- Combustion Engineering Low-Btu Entrained-Bed Gasifier.
- Bi-Gas High-Btu Entrained-Bed Gasifier.
- Westinghouse Ash-Agglomerating Fluid-Bed Gasifier.
- Cities Services/Rockwell Short-Residence Time High-Btu Hydrogasifier.

Gasification technology-crosscut conclusions and results of technical problems and issues common to the four pilot plants are also discussed in detail. Further topical reports will cover all DOE pilot plants and, thus, will reflect a broader, more comprehensive crosscut addressed to technology base and commercialization needs.

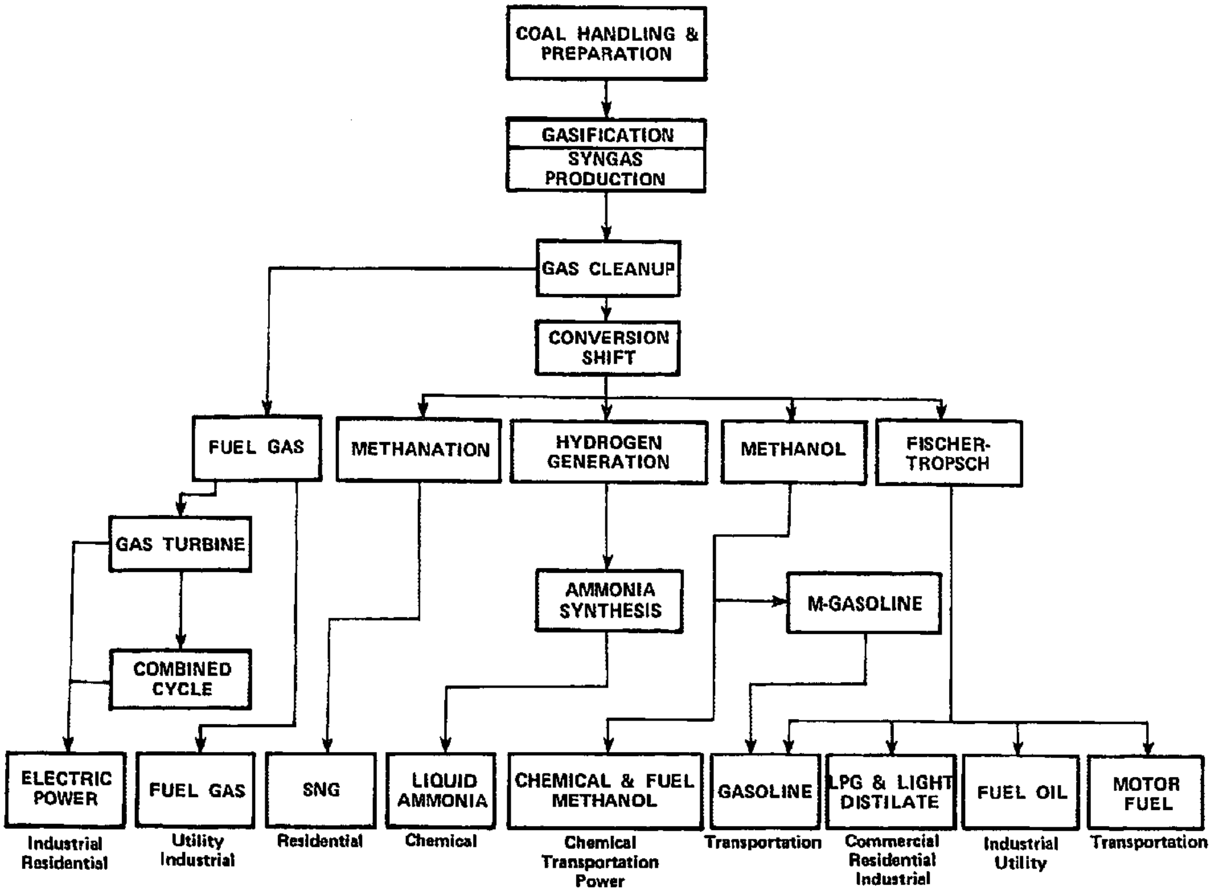


Figure 1-1. Flexibility of Coal Gasification

2.0 COMBUSTION ENGINEERING LOW-BTU ENTRAINED-BED GASIFIER

2.1 Project History

In 1972, Combustion Engineering began developing an entrainment-type coal gasifier to produce low-Btu gas for use in electric-power generation.[1] A three-phase coal gasification program under joint funding by the Office of Coal Research, Electric Power Research Institute (EPRI), and Combustion Engineering, Inc. (C-E), was initiated on October 1974. The three phases were:

- Design a 5-ton/hr Process Development Unit (PDU) and execute R&D study tasks related to the needs of both the PDU and commercial-scale plants.
- Fabricate, construct, and shakedown the PDU (which is located in Windsor, Connecticut).
- Operate the PDU on a range of U.S. coals and conduct a conceptual design study and cost estimate for a large commerical plant.

Approximately one-third of the financing has been provided by the industrial partners, EPRI and C-E, with the remainder of the funds being provided by the Federal Government.

2.2 Project Goals

The objectives of the Combustion Engineering Air-Blown Atmospheric Entrained-Bed Gasification Project (C-E AEG) are: (1) to demonstrate the capability and suitability of the process and equipment to produce a low-Btu gas of predictable composition, heat content, and cleanliness from a range of selected coals; (2) to provide the design information for scale-up of the equipment to commercial-size plants using a selected coal; and (3) to demonstrate that the Process Development Unit (PDU) can be operated in an environmentally acceptable manner.

2.3 Process Descriptions

The C-E AEG gasifier, which is designed for atmospheric pressure operation, is of vertical cylindrical construction (see Figure 2-1). A combustion section, consisting of tangentially oriented combustor nozzles, is at the bottom of the structure. Directly above is the diffuser section to prevent combustor gas from circulating back to the combustor. The upper section of the structure is the reductor where additional coal is fed into the gasifier and devolatilization and reduction reactions take place. Hot gases from the combustor section entrain, combust, and gasify the feed coal as it passes vertically through the unit. Slagged ash is withdrawn from the bottom of the combustor. Water-cooled, refractory-lined walls enclose the combustion and gasification sections.

Feed coal is pulverized to 70 percent through 200 mesh and dried to about 1 percent moisture (by weight) in a C-E ball mill pulverizer* (see Figure 2-2). Four auger-type gravimetric feeders are employed to meter the input of pulverized coal to the gasifier's combustor and reductor zones. Preheated air carries the metered coal into the gasifier. The combustor zone is fired with a near stoichiometric quantity of air, and the resulting hot gases rise into the reductor zone while the molten slag formed in the combustor is removed from the bottom and water quenched.

Hot gases rising from the combustor meet the freshly injected coal in the upper section of the diffuser. Feed coal is devolatilized, and the volatiles are cracked in the high-temperature lower section of the reductor. As the gases rise through the remainder of the gasifier, they are cooled to 1800°F by endothermic-reduction reactions.

Gases exiting the top of the reductor pass through a waste-heat recovery unit, where the temperature is reduced by tubular heat-transfer surfaces. The cooled gas then flows sequentially to a spray dryer, a cyclone, and a scrubber for removal of the entrained char and the particulate matter. The collected char and ash are then recycled to the combustor. Product gases are passed into a Stretford unit to remove the H_2S, producing a clean, low-Btu fuel gas.[2] The composition of the raw gas and the clean product gas are shown in Table 2-1.

*Product names are used for identification only and endorsement by the U.S. DOE is not implied.

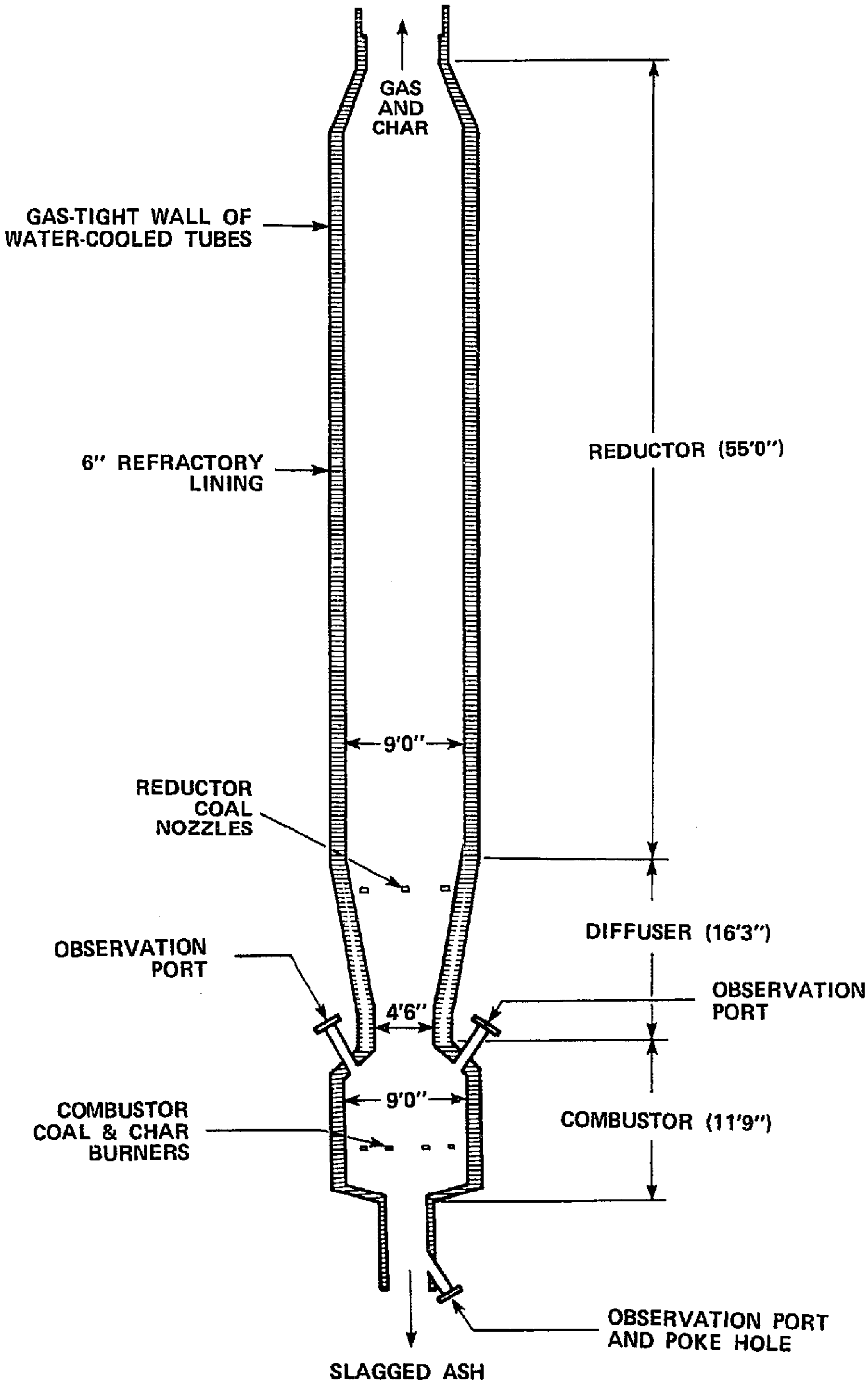
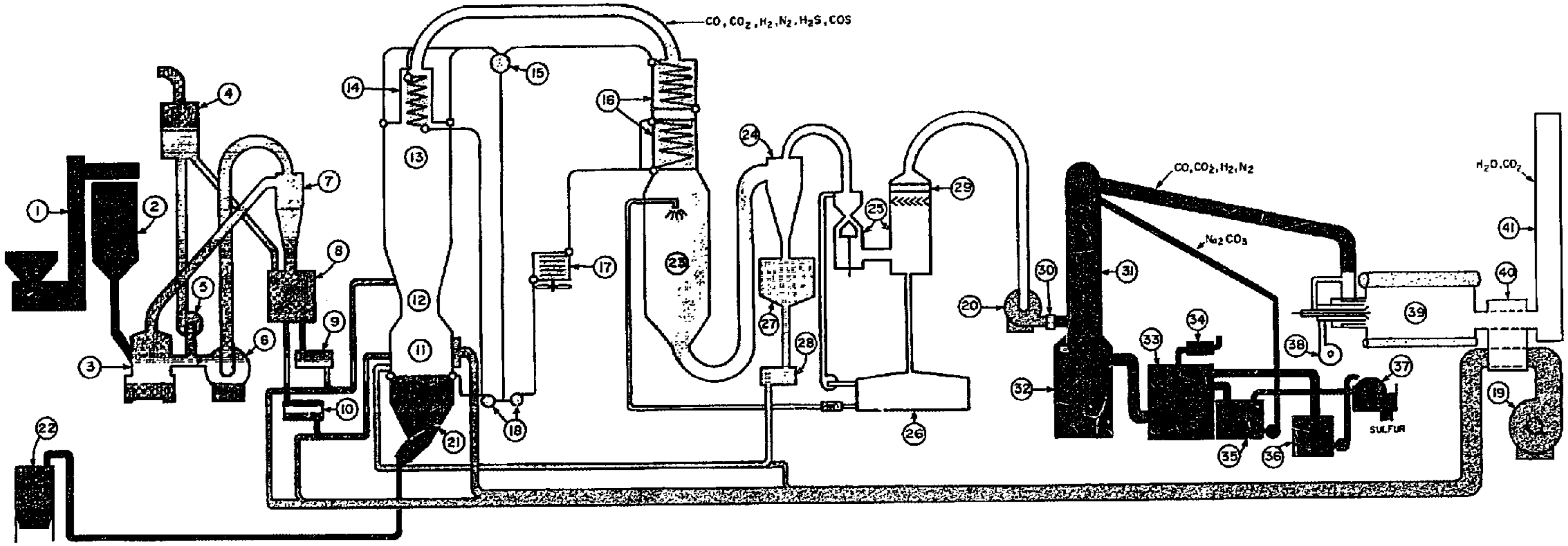


Figure 2-1. Combustion Engineering PDU Gasifier Schematic



AREA 100

1. Coal Unloading Equipment (Fairfield Engineering)
2. Coal-Storage Silo

AREA 200

3. Pulverizer (Combustion Engineering)
4. Bag Filters (Industrial Clean Air Inc.)
5. Vent Fan
6. Recirculation Fan
7. Pulverized-Coal Cyclone
8. Pulverized-Coal Storage Bin
9. Reductor Pulverized-Coal Feeder (Acrison)
10. Combustor Pulverized-Coal Feeder (Acrison)

AREA 300

11. Gasifier Combustor
12. Gasifier Diffuser
13. Gasifier Reductor

14. Primary Cooler
15. Mixing Sphere
16. Secondary Coolers
17. Water Cooler (MRM-Ecodyne)
18. Circulating Pumps (Ingersoll-Rand)

19. Forced-Draft Fan
20. Induced-Draft Fan

AREA 400

21. Ash Hopper (United Conveyor Corp.)
22. Dewatering Bin (United Conveyor Corp.)

AREA 500

23. Sludge-Spray Dryer (Koch)
24. Char Cyclone Separator (Koch)
25. Wet Venturi Scrubber Chevron Separator (Koch)
26. Sludge Thickener (Envirex)

AREA 600

27. Char Receiving Bin
28. Char Feeder (Acrison)
29. Gas Reheater
30. Gas Cooler

AREA 700

31. H_2S Absorber (Stretford)
32. Reaction Tank
33. Oxidizer
34. Air Compressor (Gardner-Denver)
35. Solution Tank
36. Sulfur-Slurry Tank
37. Rotary Vacuum Filter (Emico)

AREA 800

38. Forced-Draft Fan
39. Incinerator Boiler (C-E Type "A")
40. Tubular Air Heater
41. Stack

Figure 2-2. Combustion Engineering PDU Equipment Schematic

Table 2-1. Combustion Engineering PDU Gas Composition

Constituent	Raw Gas, Vol. %	Clean Gas, Vol. %
CO	15.0	14.7
CO_2	9.5	7.5
H_2	7.0	6.8
H_2O	2.5	6.5
N_2	66.0	64.5
H_2S	40 ppm	0
COS	Trace	0

2.4 Current Status

2.4.1 Process Development Unit (PDU)– The PDU has accumulated approximately 4,000 hours of gas-producing operation since start-up in June 1978. However, problems encountered during the Phase III operation period have limited the ability of the PDU to achieve full-load operation. All operations to date have been in the range from 50 to 70 percent of design capacity. A major modification of replacing all refractories in the gasifier was accomplished during the second quarter of fiscal year 1980. With these new refractories, completion of the air-blown parametric test program on Pittsburgh seam coal was followed by a sustained operation run of the plant in the air-blown mode with Pittsburgh seam coal. As of July 1980, difficulties with the newly installed refractories were still preventing smooth operation of the PDU. C-E and EPRI refractory experts studied the problem and recommended replacing the washed-out Harbison-Walker (H-W) Ruby refractories with studded C-E 90 ram-type refractories. The C-E 90 ram-type refractories were tested during the Phase III test runs and showed promising results. The test program was resumed immediately following the completion of the installation of these ram-type refractories.

As part of the extended program, the PDU has been modified to allow the use of oxygen-enriched air to produce a richer product gas. The inclusion of oxygen-enriched air will permit increased operating latitude for commercial retrofit of boilers originally designed to burn natural gas or oil.

2.4.2 Mathematical Modeling–A mathematical model of the process operation was developed under Phase I (Task 10) to predict the performance of the gasifier under various input and operating variables. Refinement of the model is a continuing effort that is paralleling the operational phase of the PDU.

2.4.3 Laboratory Support–Support effort from other departments within the Power System Division of Combustion Engineering, Inc., is part of the integrated PDU testing plan.

2.4.4 Other Efforts–A carbonyl sulfide (COS) removal study sponsored by the Empire State Electric Energy Research Corporation (ESEERCO) commenced in the second quarter of FY 1980. The purpose of this 1-year project is to evaluate the COS hydrolysis chemical reaction in a packed catalytic reactor. A slipstream of gas from the PDU will be used to evaluate the catalyst activity in the packed catalytic reactor in an actual product-gas environment.

2.5 Projected Work

2.5.1 Process Development Unit (PDU)– Testing of three additional coals in both the air-blown mode and the oxygen-enriched air-blown mode will be the major PDU activity for FY 81. Pittsburgh seam coal, which has been used as the principal feedstock in air-blown testing, will be tested with enriched air first to establish a comparison baseline for the performance of the PDU under the enriched-air operation. Selection of additional coals for testing has not been finalized; however, after a decision is made, a parametric test-program schedule will be prepared for each coal to determine the operating characteristics, gas composition, and heating value that results from the variation of input and operating variables.

2.5.2 Mathematical Model–For each coal tested, the efforts of verifying the mathematical model developed in Phase I (Task 10) with the test results will be continued. The mathematical model, when fully verified, will be suitable for use in predicting the effect of input and operating variables on gasifier performance and definition for future scale-up purposes.

*2.5.3 **Demonstration Plant***—A conceptual design of a 150-MW demonstration plant that has been funded by DOE was started in FY 81. The C-E gasifier is to be used to retrofit the existing Unit No. 2 at the Gulf States Utilities' Nelson Stem Plant in West Lake, Louisiana. It is to be totally integrated with an existing 150-MW boiler. The gas from coal would replace oil and natural gas, which are the present fuels used at the plant.

3.0 BI-GAS HIGH-BTU ENTRAINED-BED GASIFIER

3.1 Project History

Bi-Gas is a process for producing synthesis gas (CO and H_2) and methane (CH_4) by gasifying coal at high pressure and temperature in a two-stage, entrained-bed reactor. The process was developed by Bituminous Coal Research, Inc. (BCR), under contract to the Office of Coal Research. Development, which began in December 1963, progressed through three phases:[3]

- Bench-Scale Testing.
- Process and Equipment Development Unit[4] (PEDU).
- Pilot Plant.

The major expense and keystone of this project is the construction and operation of the 5-ton/hr Bi-Gas pilot facility at Homer City, PA. This pilot plant is a complete, self-contained facility for processing and gasifying coal, purifying and enriching the product to pipeline-quality gas, separating sulfur from the waste gas, and treating waste products to acceptable discharge levels.

Approximately one-fourth of the financing has been provided by the American Gas Association (AGA) and the Gas Research Institute (GRI) with the remainder of the funds being provided by the Federal Government.

3.2 Project Goals

The three major objectives of the Bi-Gas Pilot-Plant Engineering Development Program are:

- Evaluate (at pilot-plant scale) the viability and operability of the Bi-Gas process.
- Establish a reliable data base from which to analyze the technical and economical potential for commercial-scale development of the Bi-Gas process to produce synthetic natural gas.
- Evaluate components and process equipment and develop process data on gas-cleanup and conversion systems.

To accomplish these objectives, it will be necessary to operate all phases of the pilot plant including coal preparation, coal feeding, gasification, gas treating, and methanation. These operations have as their goal the acquisition of meaningful, accurate, and reliable data on a range of process variables to permit optimum plant design and to determine an operable range of conditions for a variety of coal feedstocks.

3.3 Process Description

As depicted in Figure 3-1, run-of-mine coal is wet-ground in a rod mill, screened to remove -100 mesh particles and slurried with water. This coal-water slurry (35 percent solids) is pumped to high pressure (current operation is at 750 psig) and passed through a preheater into a slurry spray dryer where it is dried with recycled product gas.

The resultant dry coal (1 percent moisture by weight) is separated from recycled product gas and moisture by a cyclone in the coal-feed vessel. This coal, along with steam, is fed into the upper (Stage II) section of the gasifier. Stage II is an entrained-bed section in which the coal is devolatilized as it is transported upward and out of the gasifier by hot-synthesis gas from Stage I. This combined stream is water quenched to 800°F before entering the char vessel where the char is separated from the gases by internal cyclones.

Char is recycled to the gasifier by steam eduction through char burners, which mix and ignite the char, steam, oxygen, and natural gas. Lack of a reliable control for the char flow requires that natural gas be fed into the lower (Stage I) section of the gasifier in sufficient quantity to react with all the oxygen to assure safe operation. This prevents oxygen "breakthrough" into Stage II. Stage I temperatures are between 2700°F and 3000 °F, while temperatures in Stage II are between 1600°F and 1800°F.

Quenched, raw product gas leaves the overhead of the char vessel and flows to the gas washer, where entrained char fines are removed and the gas is further cooled to 400°F. Constituents of this washed product gas are listed in Table 3-1. The fines and water slurry from the gas washer are sent to the ammonia

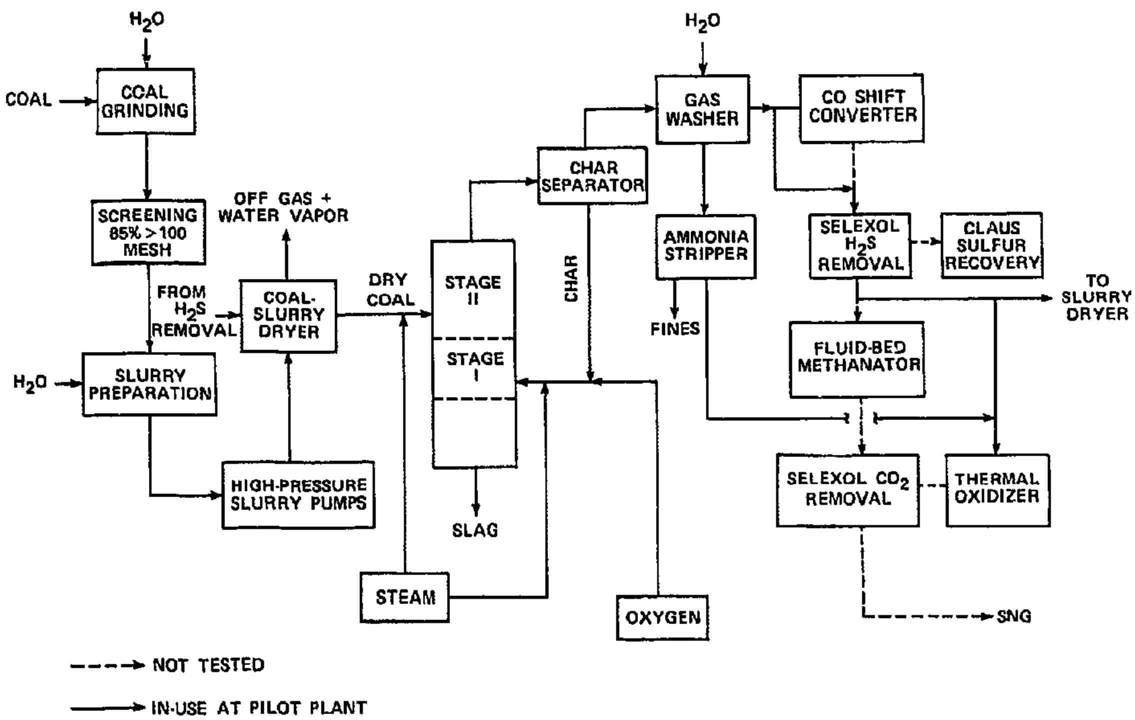


Figure 3-1. Bi-Gas Block Flow Diagram

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stripper, where steam and sodium hydroxide "strip" ammonia from the water. The fines and the waste water are sent to a holding pond, which is periodically dredged. The off-gas from the stripper is sent to the thermal oxidizer where it is flared with other waste gases.

Table 3-1. Bi-Gas Washed Product Gas Composition

Hydrogen (H_2)	40%
Carbon Monoxide (CO)	30%
Carbon Dioxide (CO_2)	15%
Methane (CH_4)	10%
Nitrogen and other constitutents (N_2, H_2S, etc.)	5%
Total	100%

The major advantages of the Bi-Gas process for gasification of coal are:

- Uses all types of coal, both caking and noncaking, without pretreatment.
- No net char production.
- High methane yield from gasifier.
- No tars or oils are produced.
- Operates at high pressure suitable for supplying an existing pipeline.

Major disadvantages are:

- High-temperature slagging environment makes temperature measurement difficult, resulting in reduced control of the 2-stage reactor with char recycle.
- No commercially available high-pressure dry-coal-feed system; therefore, requires coal-water slurry, pressurizing, and drying. (This disadvantage is not unique to the Bi-Gas process.)
- Naphthalene is produced.

3.4 Current Status

Since October 1979, efforts at the pilot plant have been directed toward improving the operations of the coal-feeding and gasification sections of the plant. These efforts were required to insure sustained, uninterrupted performance of these sections and to improve the quality as well as quantity of data generated.

Data obtained from operations conducted through June 1980 have not been adequate for evaluation of the process. The chief obstacles that must be overcome are: (1) inability to operate the complete pilot plant on a predictable schedule and (2) the requirement to feed natural gas to the gasifier as a safety precaution to insure complete consumption of oxygen in Stage I. Unless this supplemental natural-gas feed is eliminated or reduced significantly, evaluation of the Bi-Gas process is not possible.

3.5 Projected Work

Operations in FY 81 will be directed toward developing a process data base. Included as goals of this work are:

- Elimination of supplemental natural-gas feed to the gasifier.
- Operation of auxiliary gas-stream cleanup equipment:
  - CO_2 absorber of the Selexol Unit.
  - Shift converter.
  - Fluidized-bed methanator.
  - Claus sulfur plant (this requires a high-sulfur-content coal feed to the gasifier).
- Operation with bituminous coal and lignite as feedstock since all operation to to date has been on Rosebud subbituminous coal.
- Process-optimization studies.

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Data from these operations will be used to determine the feasibility of constructing a commercial-scale facility based on the Bi-Gas process. The final result of these efforts will be the technical and economic evaluation of the Bi-Gas process as a commercial venture for producing pipeline-quality synthesized gas.

In anticipation of completing the Bi-Gas project in FY 82, other uses for the Bi-Gas facility are being investigated.

4.0 WESTINGHOUSE ASH-AGGLOMERATING FLUID-BED GASIFIER

4.1 Project History

In the early 1970s, the Westinghouse Electric Corporation's Research and Development Center began development on a fluidized-bed gasifier that withdrew ash through controlled growth of ash agglomerates for dry removal. The primary goal was low-Btu gas production for electrical power generation. The initial two-stage configuration gave way to a simpler, less-complex single-stage operation. Subsequent use of oxygen in the system has resulted in broader applications such as SNG production and other medium-Btu gas uses. An integrated program was first jointly funded by the Office of Coal Research and Westinghouse with other industrial partners. The phases of the program have been:

- Integrated program for demonstration-plant development. The 15-ton/day Process Development Unit (PDU) was built under this phase, which includes fundamental R&D studies.
- Redirection of the project to emphasize process-development aspects rather than a demonstration plant.
- Process design verification and balance of plant development/selection.

Approximately 18 percent of the funds expended on the project were provided by Westinghouse, about 8 percent by the Gas Research Institute (GRI), and the remainder by the Federal Government.

4.2 Project Goals

The objectives of the Westinghouse project are:

- Develop and demonstrate the Westinghouse pressurized, ash-agglomerating, fluidized-bed, low-Btu gasification process for combined-cycle power generation.
- Develop and demonstrate the process for medium-Btu gasification for industrial-fuel or synthetic-gas production.

The Westinghouse development program has moved from the gasifier process feasibility stage to the process design-verification stage as shown in Figure 4-1. Scale-up activities for demonstration-size facilities will be finalized by mid-1983.

4.3 Process Description

The heart of the gasification process[5] is the fluidized-bed gasifier. The reactor in the process development unit (shown in Figure 4-2) is a nominal 24-inch I.D. reactor consisting of a mild steel shell with 8 to 12 inches of Harbison-Walker Castolast G refractory lining. The gasifier operates at a pressure of 150 to 315 psia at temperatures of 1600°F to 2000°F.

Run-of-mine washed coal, which has been crushed and top screened to a 3/16-inch x 0-inch particle size, is fed pneumatically from pressurized lockhoppers using recycled product gas to the coaxial oxidant tube inside the gasifier. Coal, oxygen or air, steam, and recycled product gas are fed through the coaxial oxidant tube where the oxygen or air combusts the coal in the jet and provides heat to devolatize the coal particles and to react the carbon with the gasifying agent; steam also enters through the grid plate. The product gases flowing upward through the fluidized bed entrain some of the char fines from the bed. These are collected in an external cyclone and recycled to the fines' lockhoppers for pneumatic transport with the feed coal back to the gasifier.

The raw gases from the cyclone contain hydrogen sulfide and other contaminates, which are scrubbed in a water-quench scrubber. No hydrocarbon tars are present since they are cracked to methane, hydrogen, and carbon monoxide at the high reaction temperature. The raw gas is sent to cooling towers and then burned in a thermal oxidizer. The char/water slurry is separated in an Edens separator prior to disposal.

The gasifier is somewhat unique in the handling of the ash present in the coal. As the carbon is consumed in the particles of char recirculating through the combustion jet, exposed ash particles reach a temperature at which partial melting takes place. Particles coalesce or agglomerate to form approximate

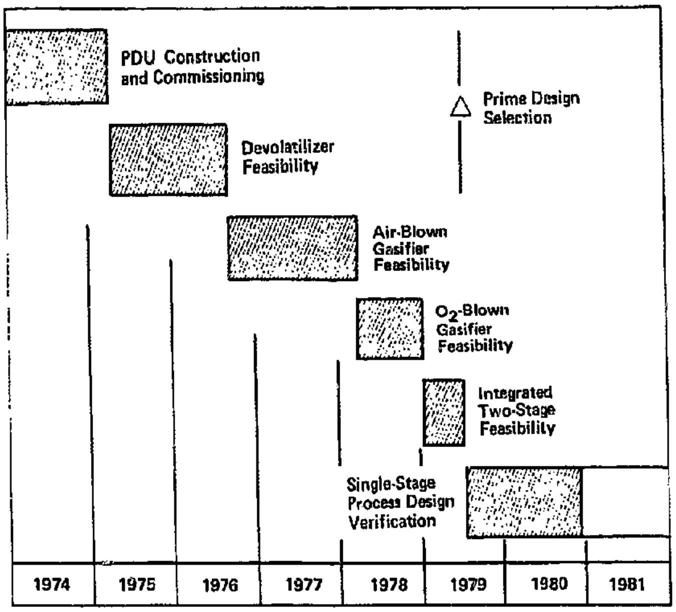


Figure 4-1. Westinghouse Development Schedule

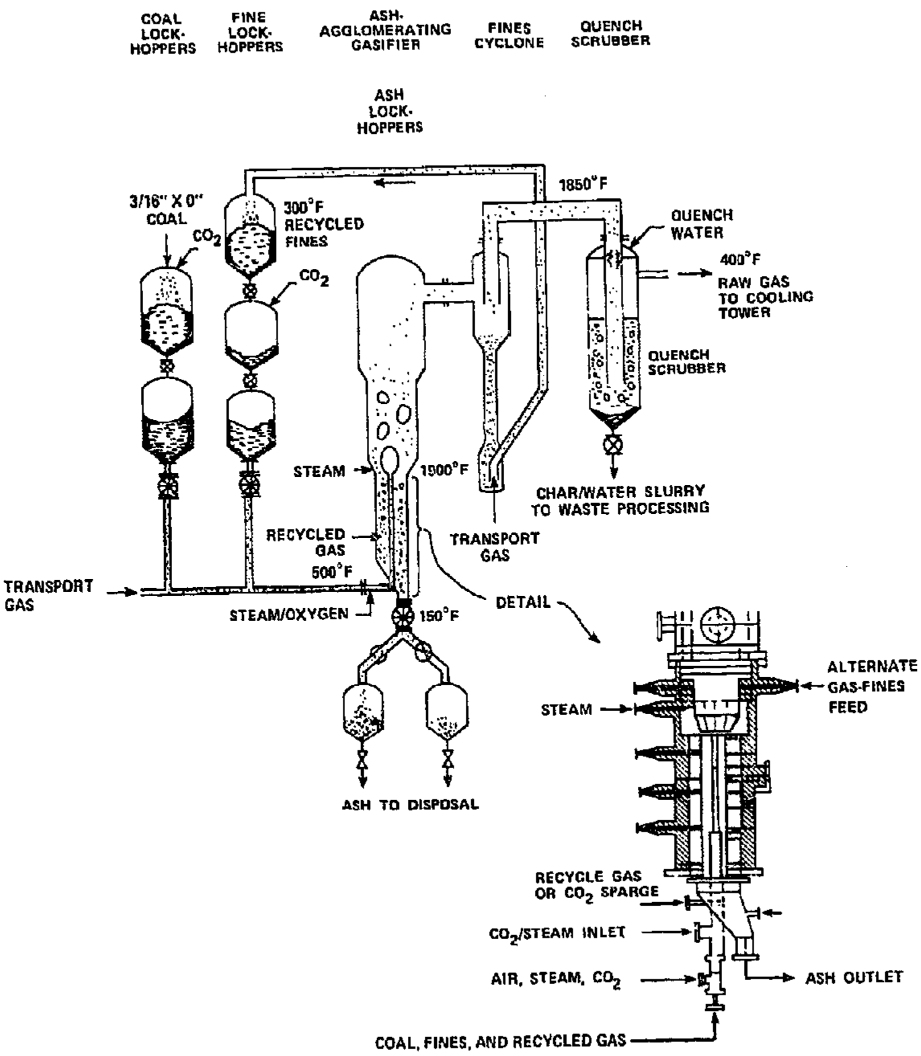


Figure 4-2. Westinghouse PDU Process Schematic

spheroids of relatively pure ash which, after overcoming the minimum fluidization velocity, defluidize and fall to the bottom of the bed. In the char/ash separation zone, the lighter char particles are stripped from the ash agglomerates by the upward flow of recycled product gas, which also cools the agglomerates. The ash is continuously removed by a rotary valve on the bottom of the gasifier.

Typical product-gas compositions for both the air-blown and oxygen-blown PDU operation using Pittsburgh seam coal are shown in Table 4-1.

Table 4-1. Typical Westinghouse PDU Gas Composition

Constituent, Dry Gas	Air Blown, Vol. %	Oxygen Blown, Vol. %
CO	20.1	49.1
H_2	5.1	29.8
CH_4	1.5	3.2
CO_2	11.9	1.72
N_2	61.2	Trace
Minor other gases	Trace	Trace
Heating Value (Btu/scf)	99.	235

4.4 Current Status

4.4.1 Gasifier Tests—The single-stage configuration has been selected as the prime design for the Westinghouse fluidized-bed process for both low- and medium-Btu applications. This process design currently is being optimized in the single-stage process-design-verification campaign with both oxygen- and air-blown tests. Recent efforts have included single-stage, oxygen-blown tests at 130 and 230 psig. The test at 130 psig provided a reactor performance evaluation of the reconfigured coaxial oxidant tube and slipstream heat-recovery apparatus. A gasifier operability shakedown test was made with the modified oxygen system, which has permitted the pressure increase to 230 psig. This test was conducted with Indiana No. 7 and Ohio No. 9 coals. An additional test at 230 psig was a gasifier process evaluation and feedstock-characterization test with Texas lignite and Pittsburgh seam coal.

4.4.2 Commercial Fluidized Systems Facility (CFSF)—Since the technology development program is now being directed toward the enhancement of the data base for the design of commerical-scale hardware, the scale-up of the gasifier is being studied. The results of laboratory modeling and PDU testing will be integrated with the results from a commercial-scale, semicircular, cold-flow model. This Commercial Fluidized Systems Facility[6] (CFSF), when it becomes operational, will permit full front-face viewing of the fluidized bed through a plastic window and, thus, will permit a detailed study of jet behavior, solid circulation, and other phenomena within the bed. This 10-foot-diameter model will provide a cost-effective tool for corroborating models developed on the PDU and in the laboratory and it will define detailed component hardware designs on a nominal 40-ton/hr scale.

4.4.3 PDU Modifications—Modifications currently being undertaken on the PDU include: (1) 230-psig oxygen system, (2) heat-recovery phase 1, (3) coal-preparation facility, and (4) gas-characterization upgrading. The oxygen system has been altered to increase the pressure capability from 130 psig to 230 psig. It was noted, however, that in conjunction with higher pressure and oxygen flow, additional steam will be needed. As a result, upgrading of the steam boiler was started in the near future. The heat-recovery phase 1 was recently installed and three tests were completed. Good results were obtained, although the system only involves a loop of four tube-in-shell heat exchangers that are slipstream to the product gas flow downstream of the roughing cyclone. Over the last several years of operation, testing has been hampered by the inability of the coal-handling system to transport wet coal. To resolve this problem, a Williams impact dryer mill was recently installed. This will serve as a coal-preparation facility for crushing, drying, and sizing bituminous coals, subbituminous coals, and lignites. Efforts to upgrade gas characterization include the design and installation of a sample conditioning train and a total condensables analyzer (TCA), a gas chromatograph (GC), and an infrared (IR) analyzer for the measurement of water and another gas chromatograph for the measurement of sulfur. All of these have been installed on the hot product-gas stream; however, integration of the sample conditioning train for the TCA, IR, and GCs is yet to be accomplished for simultaneous measurement of the water vapor.

4.4.4 Laboratory Support—Current support provided by the Westinghouse Corporate Research and Development Center is in four areas: (1) gas-solids flow modeling, (2) coal/ash behavior, (3) particulate/chemical profiles and control, and (4) environmental-impact assessment. Work in the flow modeling has included completing preliminary tests to simulate double-concentric jet configuration, initiating construction of a circular model, completing a preliminary ash/char separation model, and supporting the CFSF program development. Coal/ash behavior efforts have included completing ash-agglomerator modifications for testing with Indiana coal and completing gasification tests with lignite. Under particulate profiles and control, an integrated deposit-control program plan has been developed and initiated. Also, analysis of the fines recycle system performance has been completed.

4.5 Projected Work

4.5.1 Gasifier Tests—Current plans call for the completion of five additional tests in late 1980. Three of these will be follow-on oxygen-blown tests at 230 psig and will include a process evaluation and feedstock (Pittsburgh No. 8) characterization test, an operability shakedown test with the coal-preparation facility, and a process-evaluation tests. The other two tests will be a variable-pressure gasifier turndown test and a variable bed-height turndown test with the Process Development Unit and Test and Development Center (PDU/TDC) pipeline/combustion systems. The preliminary 1981 test program will consist of one operability test, five combustion and turndown tests with air and oxygen, and two demonstrations or feedstock-characterization tests. The primary emphasis in the next 2-year testing campaign will be directed away from strict process feasibility/development toward process and components optimization to provide scale-up data for a demonstration-size facility.

4.5.2 Commercial Fluidized Systems Facility (CFSF)—The future test program of the CFSF calls for shakedown tests of gasifier cold model operability (which will commence in December 1980), with single air tube and one bed-material testing following in the first quarter of 1981. Gasifier-design performance testing using the single-tube configuration and dual-bed materials will be conducted after the single-material tests. In addition to gasifier performance testing, solids transport line tests and cyclone dipleg operation will be conducted.

4.5.3 PDU Modifications—Modifications to the PDU planned for the future are: (1) fines-collection and recycle system, (2) structural modifications to accommodate the added cleanup equipment, (3) power-distribution changes, and (4) the PDU/TDC pipeline control and auxiliaries. The secondary fines cyclone and recycle system will be employed to increase fines capture and recycle back to the gasifier. This secondary-collection device will resolve technical issues such as: (1) improving carbon utilization to 95 percent, (2) consumption and transport of secondary fines, (3) fines feed control devices, and (4) demonstrate high-temperature fines recycle. The PDU structure will have to be altered to support the secondary collection/recycle system. To handle the additional electric-power demands of the upgraded PDU, increases of the power-distribution loop will be made. Finally, although the pipeline between the PDU and the test and development center will be installed in late 1980, the necessary hold-up and raw product-gas-control devices will have to be added at a later date. Optional modifications are being discussed for possible future inclusion including heat-recovery phase 2 and cold and hot gas desulfurization units.

4.5.4 Laboratory Support—Future support efforts provided by Westinghouse's R&D Center will primarily be to assist with CFSF evaluation and testing, integration of laboratory models, projected commercial-plant performance on particulate/chemical profiles and control, and characterization of lignite ash and Ohio coal ash for environmental impact.

5.0 CITIES SERVICES/ROCKWELL SHORT-RESIDENCE-TIME HIGH-BTU HYDROGASIFIER

5.1 Project History

In 1974, Rockwell began evaluation of its liquid rocket technology for applications in coal conversion to liquid and gaseous products. In 1975, the Office of Coal Research initiated an effort for the partial liquefaction of coal by direct hydrogenation, and a 1/4-ton/hr hydropyrolysis reactor was constructed. The testing on this unit indicated that with higher temperatures and lower residence times carbon conversions yielded higher selectivity to methane.[7] This led to a U.S. DOE-sponsored effort for backup to the Pittsburgh Energy Research Center's Hydrane two-stage reactor.[8] Later, the hydropyrolysis reactor was enlarged to a 3/4-ton/hr unit for hydrogasification. The initial program intended that the preliminary work on this 3/4-ton/hr unit be followed by construction of a 4-ton/hr Integrated Reactor Development Unit (IRDU). This was redirected following an August 1979 review to construct a 3/4-ton/hr integrated PDU with primary emphasis toward longer runs to demonstrate system operability, component durability, and product quality.

Approximately 14 percent of the project financing has been provided by the Gas Research Institute with the remainder of the funds being provided by the Federal Government.

5.2 Project Goals

The major objectives of the Cities Service/Rockwell hydrogasifier project are:

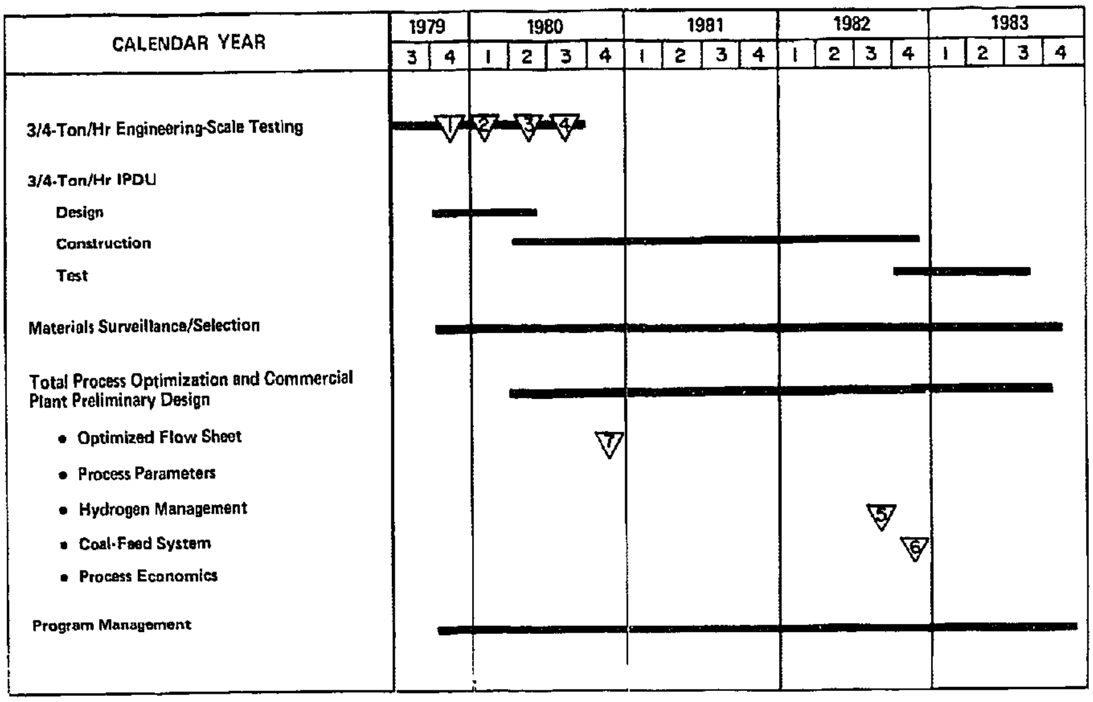
- Prove the Cities Services/Rockwell International (CS/RI) Single-Stage, Short-Residence-Time Hydrogasification Process and advance its development to the feasibility level.
- Operate an engineering-scale test unit to provide data-base information to support decision/selection points for the design and construction of an Integrated Process Development Unit (IPDU).
- Design, construct, and operate the 3/4-ton/hr IPDU and demonstrate it in long-duration continuous operation.
- Develop process data and operating experience to support the design, economic evaluation, and optimization of a viable commercial process.
- Prepare a preliminary design of a practical SNG commercial plant through subcontract to the C-E Lummus Company.

The scope of work consists of a 3-year program involving an integrated combination of design, construction, and operation to demonstrate the feasibility of the CS/RI hydrogasifier for commercial application. The schedule in Figure 5-1 shows the four main tasks of the contract.

5.3 Process Description

The process (Figure 5-2) for gasification uses rocket-engine technology. The basic concept underlying the CS/RI hydrogasification process is direct hydrogenation of the carbon in the coal feed to gaseous products in a single-stage reactor. The hydrogenation reaction is carried out during entrained flow of pulverized-coal particles in a hydrogen-rich gas stream at elevated temperature and pressure. Once initiated, the exothermic reaction is self-sustaining in an adiabatic reactor. However, the reactants must be heated to temperatures of greater than 1400°F to initiate the reaction. Caking coals cannot be heated above 400°F without causing severe problems with agglomeration and devolatilization. Therefore, the pulverized coal is injected by a high-pressure feeder in dense phase flow into the reactor at low temperatures and then heated convectively by rapid mixing with injected hot hydrogen. Requisite heat is supplied by preheating the gaseous hydrogen to a substantially higher injection temperature than the mixed reactant temperature required to initiate sustained hydrogenation.

The design of the reactor is based on the application of rocket-engine techniques to achieve rapid mixing and reaction for a controlled time interval. Substantially more hydrogen is fed to the reactor than is consumed in hydrogenation. Excess hydrogen is needed to favor methane synthesis and to supply the coal-heating function. An in-line heat exchanger (recuperator) is used to preheat the



KEY DECISION/SELECTION POINTS

1. Minimum H_2/Coal Ratio
2. Minimum Severity Conditions for All Gas Production
3. Minimum Severity Conditions for Benzene Coproduction
4. Techniques for Achieving > 95% Material Accountability
5. Hydrogen Production/Cleanup/Separation System
6. Coal-Feeding Technique
7. Optimum Process Parameters

Figure 5-1. CS/RI 3/4-tph Integrated Process-Development Unit Schedule

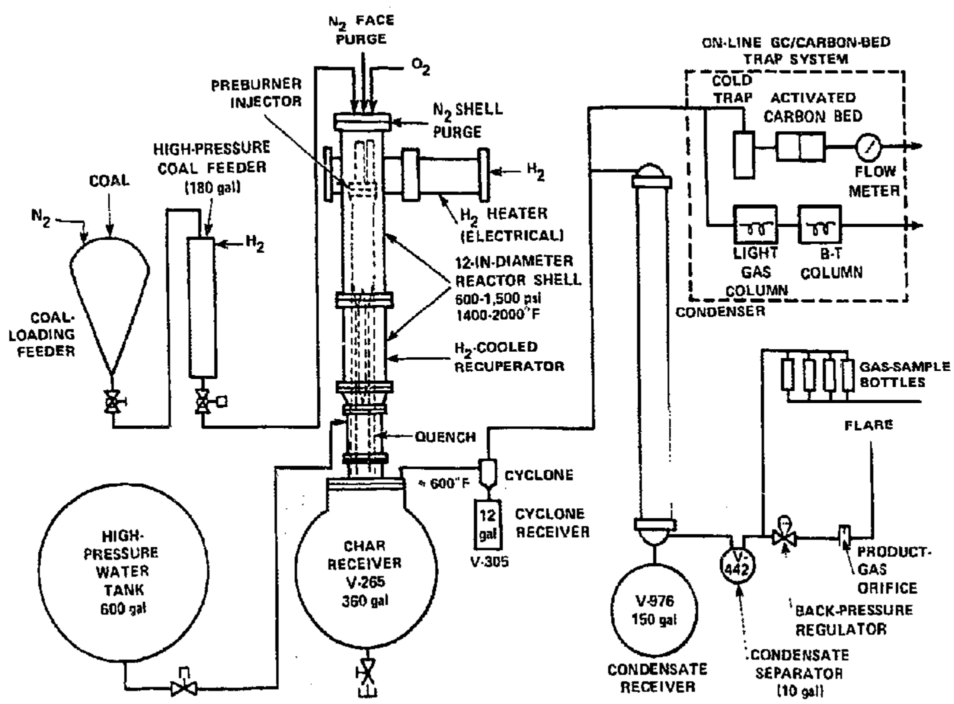


Figure 5-2. Simplified Flow Diagram of CS/RI 3/4-tph Reactor System

hydrogen to approximately 1500°F, and the final increment of heat is provided by partial oxidation with a small amount of oxygen in a preburner at the injector face.

Following the recuperator, the reactants are further cooled by water quench to approximately 900°F. The char (solids residue) is separated from the vapor, which is then reduced in pressure and cooled to condense the liquid products. The vapor stream leaving the condenser is passed through an activated carbon adsorber to recover the uncondensed benzene, toluene, and xylene. An on-line gas chromatograph and gas-sample bottles are provided for gas characterization. The flow rate and composition of the gas stream are measured before the gas stream is vented through a scrubber to a flare.

Typical baseline reactor conditions and product-gas composition for operation in the gasification mode are shown in Table 5-1.

Table 5-1. Typical CS/RI Gasification Mode Baseline Reactor Conditions and Product-Gas Composition

Pressure (psia)		1,000
H_2/Coal (lb/lb)		0.442
O_2/Coal (lb/lb)		0.148
Residence Time (sec)		1,840
Temperature (°F)		1,800
Carbon Conversion Overall (%)		55.9
– Gas		44.3
CH_4	39.4	
CO	4.3	
CO_2	0.3	
C_2H_6	0.3	
– Liquids		11.6
Benzene	11.0	
Toluene	0.1	
Xylene	0.0	
Naphthalene	0.5	

5.4 Current Status

5.4.1 Engineering-Scale Test Unit (ETU)– The coaxial four-on-one injector, although operated at design-flow conditions, has consistently produced large agglomerates that have plugged the hydrogen-cooled recuperator or, when the recuperator had been taken off line, has shown agglomerates in the separated char. The coaxial injector testing was ended after test conditions of lower adiabatic H_2/O_2 flame temperatures and corresponding reactor exit temperatures also led to agglomeration.

Completion of ETU testing, therefore, was to be accomplished with the preburner injector, which had earlier proven to be reliable. The three-tube, hydrogen-cooled recuperator was also reinstalled in the reactor train for final testing. But a pretest check showed that all six bellows of the recuperator had significant leaks in their convolutions, a result of pressure-stress rupture. It was estimated that unwarranted time would be required to repair the recuperator at relatively high cost; therefore, it was decided not to conduct any further tests at the ETU. The ETU data base will be reduced and a summary of findings will be prepared.

In reviewing the data base generated by the ETU operation, the C-E Lummus Company was asked to certify the adequacy of that data base for proceeding into the preliminary commercial SNG-plant conceptual design. Lummus concluded that the data base defining the major product-gas constituents is sufficiently developed to proceed with the conceptual design. Where complete experimental data is currently lacking regarding minor gas phase species (H_2S, COS, CS_2, and CH_4S), Lummus proposed to take conservative approaches to gas phase equilibrium. According to Lummus, the impact of these proposed estimation methods on plant investment and operating costs will not be significant.

5.4.2 Integrated Process Development Unit (IPDU) Design and Procurement–The final design of the IPDU was completed in June 1980. Procurement of long-lead items has been completed with some items (particularly in the coal-handling/preparation system) currently on site. Construction work on the concrete foundations for structural steel and steel shop-fabrication drawings have been started. The coal-feed vessel contractor started field installation work at the Santa Susana staging area. All other subsystems are in the procurement cycle.

5.4.3 Process Optimization and Commercial-Plant Preliminary Design—The C-E Lummus Company was selected in March 1980 as the architect/engineer on this task. It has currently finished its ETU data-base evaluation, generated preliminary results of the char-utilization study, made vendor contacts on study of hydrogen separation processes, and completed parametric studies on the effects of reactor pressures and H_2/coal ratio on overall process economics.

5.4.4 Materials Surveillance Program—The collection of reference data and archived samples is underway. Seventeen specimens made of 13 materials have been exposed for a total of 27 hours to the product-gas and char environment during tests in the ETU facility. The gravimetric and metallographic results of those exposed specimens have disclosed that: (1) TZM, KT-SiC, Inconel 617, Haynes 188, Inconel 671, and Inconel 657 exhibit good resistance to the environment (however, KT-SiC and possibly TZM appear to have sustained mechanical degradation and warrant further testing); (2) Udimet 500 and Hastelloy X sustained intermediate corrosion and show only marginal performance; and (3) Incoloy 800, Type 310 SS, Cru-temp 25, 317 LM, and RA 330 exhibit high corrosion. Significant progress has been accomplished in the design component procurement and assembly of an acoustic emission (AE) system. Design of the AE system has been completed. Procurement of parts for the AE system has been completed, and assembly has been initiated. Identification and procurement of alternate materials for testing will continue through the year, with 14 alternative materials received.

5.5 Projected Work

5.5.1 Integrated Process Development Unit (IPDU) Procurement and Construction—All advanced-procurement orders will be completed by March 1981 and the structural-steel and propane-supply system subcontracts are expected to be completed by December 1980. All long-lead procurement items will be on-site by March 1982, and completion of the IPDU facility construction is scheduled for September 1982. The reactor train design (done in-house by Rockwell) is expected to be completed by October 1981. Fabrication will be complete in March 1982 and the unit will be activated in September 1982. Short-duration testing for process data-base collection is expected to run through July 1983. The 30-day test is scheduled to be run the month of October 1983.

5.5.2 Process Optimization and Commercial-Plant Preliminary Design—A preliminary design review is scheduled for February 1981 and an intermediate review is scheduled for July 1981. The final design review and draft report scheduled for March 1982 will be delayed until IPDU test data becomes available. Completion of the final design is anticipated by late 1983.

5.5.3 Materials Surveillance Programs—This program will continue through October 1983. Subtasks yet to be completed are: (1) preparation of alternate materials for selected IPDU locations (March 1981); (2) installation of acoustic emission (AE) system on selected IPDU components (July 1982); (3) pre-test baseline measurements on the IPDU (August 1982); and (4) analysis and assessment of data from the IPDU operation (November 1983).

6.0 COAL GASIFICATION TECHNOLOGY CROSSCUT

A technology crosscut addresses mechanical and instrumentation problems common to two or more pilot plants rather than process problems that are specific to a particular gasifier configuration. The sources of these mechanical and instrumentation problems are essentially due to the hostile environment of the processes, i.e.:

- High Temperature.
- Corrosive Gases.
- Erosive Material (coal, coal ash, and char).
- High Pressure.

Table 6-1 provides a comparison of the Coal Gasification Pilot Plants by generic areas: coal preparation, gasifier, gas cleanup, and instrumentation. Problems, if any, associated with each pilot plant are summarized under headings within these areas. None of these problems are new or unique; however, when presented in tabular form, one gets a quick "picture" of the current technology situation.

Generally, it can be said that where problems exist in these pilot plants and PDUs, solutions are lacking due to insufficient advancement in the state of the art for gasifier instrumentation and critical process components. However, it must be noted that the sizes of these pilot plants (1 to 5 tons per hour of coal feed) are equivalent to large commercial-scale plants found in the chemical industry. By nature, these commercial chemical plants require of their instrumentation *only* that it be adequate for safe, controllable operation. Inventory management measures raw-materials input against products output. Such equipment and instruments that enable these plants to achieve this input/output balance are acceptable. Unfortunately, what is acceptable for a commercial venture is not adequate for obtaining development and design data. An accurate analysis of what occurs inside the pilot plant envelope is essential.

6.1 Coal/Char Feeding

6.1.1 Bi-Gas Coal-Feeding System—Other than lockhoppers, no feed systems are available that will deliver dry coal to a high-pressure gasifier at the design feed rate of the Bi-Gas Pilot Plant (5 tons per hour). Given the pressure (750 to 1,500 psig) and temperature (550°F) at which this coal must be fed, the rotary valves of the lockhopper system have limited durability. Because of this uncertain reliability, coal is fed to the Bi-Gas gasifier by first slurrying the coal with water.

The disadvantage of coal-water slurry feed to the gasifier is the cost to dry the coal or the inclusion of unwanted steam in the gasifier. This disadvantage is coupled with the past difficulties in operating drying systems to evaporate the slurry water. Experience at the Bi-Gas Pilot Plant in drying the high-pressure coal slurry has been very satisfactory. In general, the spray-drying system has performed adequately with a minimum of operational problems.

In the coal-preparation area at the pilot plant, coal is slurried with water to about 35 percent solids. The slurry is then pressurized to slightly greater than gasifier pressure at 765 psia with a triplex plunger pump, and then heated to approximately 450°F in the steam preheater. This slurry is contacted with hot recycle gas, which vaporizes the water. The coal, water vapor, and gas-combined stream reach a net temperature of 550°F. The vaporized water and gas are separated from the dried coal in a cyclone. The gas stream is then water washed (where the bulk of the vaporized water is condensed), compressed, and heated for return to the drying step. Figure 6-1 is a schematic diagram [9] of the spray-drying section.

The spray dryer operates as a cocurrent, downflow vaporizer with a heat duty of about 13 million Btu per hour. Despite handling 10,000 pounds per hour of coal whose size consist, as given in Table 6-2, ranges from 8 mesh to 325 mesh, there have been almost no incidents of plugging in the spray dryer. Line plugs have occurred in the coal-slurry lines upstream and downstream of the slurry pump after system shutdowns because of larger size distribution of the coal. These plug formations have necessitated immediate flushing of these lines and dilution of slurry in vessels to prevent the solids from settling out once the system is shut down.

Table 6-1. Technology Crosscut of Coal Gasification Pilot Plants

UNIT OPERATION	COMBUSTION ENGINEERING	BI-GAS	WESTINGHOUSE	ROCKWELL	KEY REQUIREMENTS
A. Coal Preparation and Feed					
1. Coal Grinding	C-E ball mill produces 70 percent through 200 mesh – requires pre-sized, 1½-inch or less, coal.	Rod Mill produces 15-30 percent -100-mesh fines, which cannot be used.			Method to feed dry coal to a gasifier under pressure.
2. Coal Slurry	Not applicable.				
3. Coal Pressurizing	None.	Must slurry coal to 35 percent solids and pressurize with pumps – requires dryer to remove slurry water.	CO_2 pressure to 300 psi in lockhopper system – requires dry coal – CO_2 purge to gasifier.		
4. Coal Feeding	Pneumatic feed with preheated air (dilute phase flow) – erratic feed due to inability to maintain pressure balances (venturi eductor installed).	Line size reduced from 4 inches to to 1½ inches to give better flow characteristics.	Oversize (≥ ¼") causes obstructions; lockhopper cycle time limits test duration.		
B. Gasifier					
1. Refractory	Water-cooled taphole, "Ruby" brick material. Refractory material "washes out" at 3200°F maximum.	Monofrax "E" (75 percent Cr_2O_3) has longest life.			
2. Slag Tapping	Repeated plugging of taphole until refractory material is "washed out."	Slag consistency (beads vs. strings) depends upon coal-feed size (i.e., finer coal produces "strings").			
3. Tars, Oils, etc.		Naphthalene produced at lower Stage II operating temperatures.	Trace Naphthalene produced at 230 psi in oxygen-blown mode. Not observed in air-blown mode.	BTX (benzene, toluene, and xylene) and naphthalene produced as fines.	Detection/measurement devices for higher hydrocarbons. If not eliminated, then effective knock-down systems required.

Table 6-1. Technology Crosscut of Coal Gasification Pilot Plants (Continued)

UNIT OPERATION	COMBUSTION ENGINEERING	BI-GAS	WESTINGHOUSE	ROCKWELL	KEY REQUIREMENTS
B. Gasifier (Continued)					
4. Ash Removal	Withdrawal to water-filled slag tank and sluiced to dewatering bin. This intermittent mode operation introduces mass-balance uncertainty.	Withdrawal to lockhoppers that are sequentially depressurized to remove accumulated slag. This introduces mass-balance uncertainty.	Continuous withdrawal to lockhopper at 40 lb/hr minimum. For low-ash coals, operation is intermittent. This introduces mass-balance uncertainty.		On-line ash-content measurement devices.
5. Char Recycle	Problems similar to coal-feeding problem as above.	Line size reduced from 4 inches to 1 inch to give better flow characteristics. Inability to measure mass flow of char introduces mass balance uncertainty.	Inefficient fines collection results in weight loss of char equivalent to 10 percent feed coal.		
6. Coal/Char Interjection "Bottom Design"	Continue to modify the coal/char fuel-nozzle design to provide a better fuel/air mixing in the combustor.	Char-burner designs went through several evolutions to eliminate material failures and improve safety.	For O_2-blown mode, added steam shroud to eliminate sintering.	Coaxial 4-on-1 injector causes agglomeration of coal.	Improved, reliable char and coal-injection tubes to eliminate sintering and agglomeration.
7. Low Gas-Heating Value	"Ruby" brick lining to reduce heat loss is not a solution. "Ruby" brick washed out with no observable increase in heating value. Problem appears to be in gasifier operation/control.				
C. Gas Cleanup					
1. Fines Removal	Cyclone does not remove: – 325 mesh material; causes erosion of downstream fan blades. Solution: Multicyclone installed in series with cyclone.	Removing -100 mesh fines required in order to prevent overloading spray cooler. Slag tapping seems smoother after fines are removed.	Ash deposits on cyclone inlet with certain bituminous coals. Solution: Water quench raw gas to lower temperature.		Fines/particulate removal and recycle system to -200 mesh coal and char particles from hot-gas streams.
2. Ammonia	No NH_3 due to high combustor temperaature and low pressure.	Raw gas must be washed, then this wash water is steam and caustic stripped to reduce NH_3 concentration.			

Table 6-1. Technology Crosscut of Coal Gasification Pilot Plants (Continued)

UNIT OPERATION	COMBUSTION ENGINEERING	BI-GAS	WESTINGHOUSE	ROCKWELL	KEY REQUIREMENTS
C. Gas Cleanup (Continued)					
3. Sulfur	COS hydrolized catalytically to H_2S and CO_2. Stretford package unit converts H_2S to sulfur cake.	H_2S removed from gas in Selexol unit.	Cannot gasify high-sulfur coals due to lack of sulfur-removal equipment.		
4. BTX, Tars, $C_{10}H_8$	None.	Naphthalene plugs heat exchangers. Solution: Operate with two exchangers in parallel.	Naphthalene plugs coolers downstream of recycle-gas compressors. Solution: Operate coolers at higher temperatures.		
D. Instrumentation					
1. Bulk Weighing	Acrison-weight auguer. Difficult to keep a constant pressure at discharge pipe. Any back-pressure buildup in the discharge pipe will create a fault reading in acrison-weight auger.				
2. Solids-Level Indicators	Not applicable.	Nuclear-level gauges are difficult to keep calibrated due to high pressure conditions.			
3. Two-Phase Flowmeters a. Solid-Liquid	Not applicable.	Sonic flowmeters not accurate for low-solids concentration (≤ 5 percent). Solution: Magnetic flowmeters will be installed where applicable.			
b. Solid-Gas	The venturi eductor in primary air line is to provide a zero static pressure in discharge pipe beneath the gravimetric feeder. Any pressure variations will create erratic feeding problems.	High-pressure, high-temperature environment excludes most off-the-shelf items. Capacitance detection flowmeter being tested.			
4. Temperature Measurement	Infrared-radiation thermometers used in measuring the temperature in both the combustor and diffusor have provided satisfactory results.	Thermocouple durability in slagging environment is suspect. Optical pyrometers are being tested.	Cannot measure temperature in coal-feed injector.		Improve temperature-measuring devices in hot product streams and gasifier vessels; primarily for durability.
E. Components					
1. Pressure Letdown Valves	None.	None.	Erosion.		

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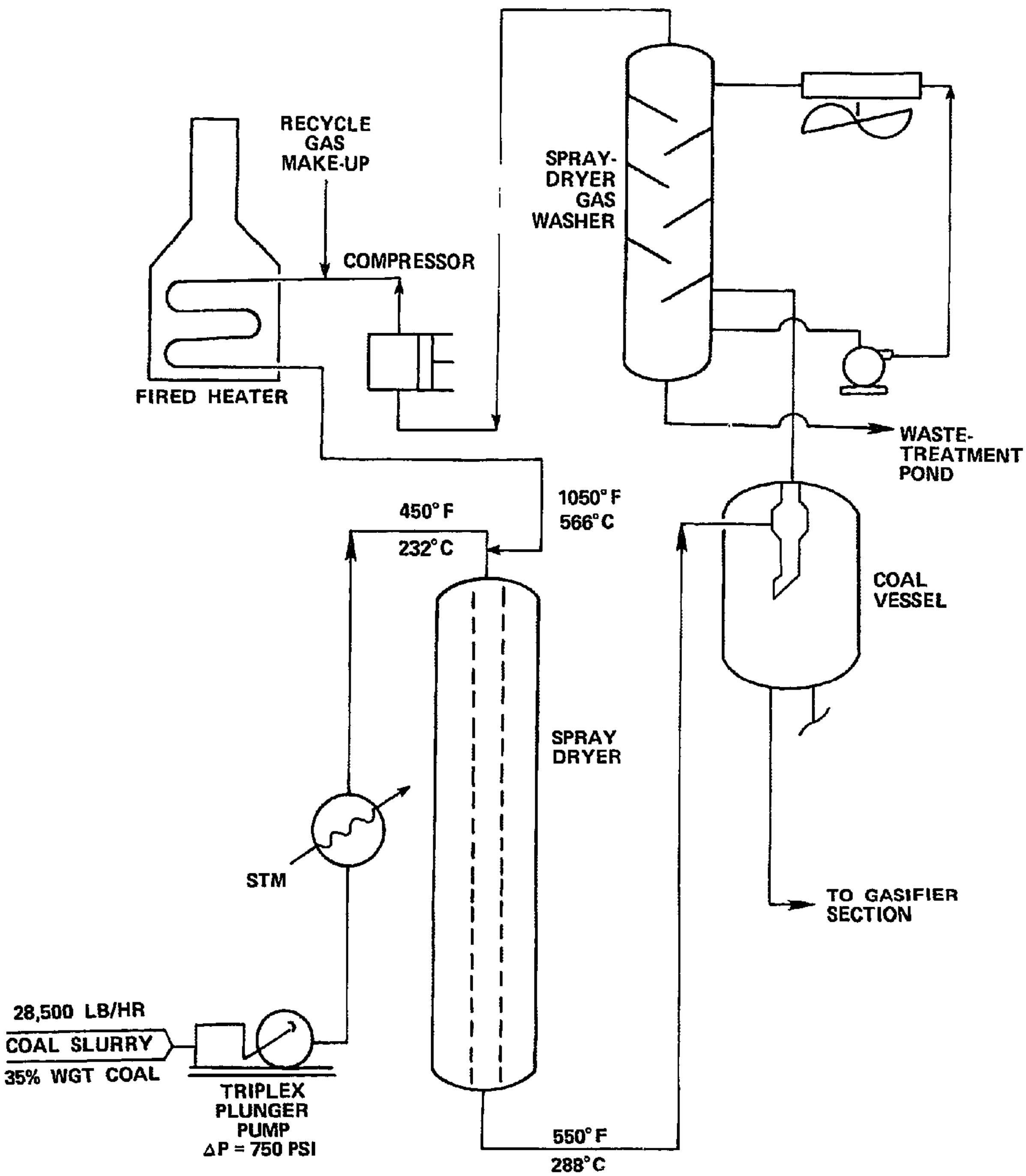

Figure 6-1. Bi-Gas Coal-Slurry Spray-Drying Section

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Table 6-2. Coal Feed to Slurry Dryer

Size, U.S. Sieve	Wt % on Screen
8	1.6
12	2.5
20	12.6
50	35.5
100	21.5
200	11.6
325	5.8
PAN	8.9
Specific Gravity	1.133
Solids, Wt. Percent	34.6
Ash, Wt. Percent	13.4
Volatile Matter, Wt. Percent	38.1
Fixed Carbon, Wt. Percent	48.5

The high-pressure coal is fed into Stage II of the gasifier through two coal-feed nozzles on opposite walls of the gasifier vessel. These nozzles penetrate the wall of the vessel at a +30° angle from the horizontal. Coal flows through the center tube of the nozzle due to the differential pressure between the coal-feed vessel and the gasifier. Steam, which is controlled to maintain Stage II temperature, is transported through the outer annulus of the nozzles.

This method of high-pressure dry-coal feed has performed satisfactorily. As noted, this system is coupled with a slurry-spray drying system and high-pressure slurry pumps. However, it remains to be shown whether the thermal penalty necessitated by drying the coal will be offset by a mechanical and equipment penalty for a lockhopper system or some future developmental dry-feed system.

As originally designed, the Bi-Gas Pilot Plant coal and char feed legs were 4-inch-diameter lines. However, coal and char feed is essentially by gravity although at pressure. In addition, both coal and char are eventually fed into the gasifier through 1-inch-diameter lines. A few simple calculations show that the 4-inch lines have excess capacity:

$$W_D = \rho A_D \sqrt{gD}$$ [10]

where:

D is the internal diameter of the feed leg in feet

g is acceleration due to gravity = 32.2 ft/sec^2

ρ is the feed density = 92 lb/ft^3 for Rosebud coal

A_D is the cross-sectional area of the feed leg in square feet

W_D is the feed rate through the line in lb/sec

For a 4-inch line:

$$A_4 = \frac{\pi}{4}\left(\frac{4}{12}\right)^2 = 0.087 \text{ ft}^2$$

$$W_D = (92)(0.087)\sqrt{(32.2)\left(\frac{4}{12}\right)}$$

$$W_D = 26.2 \text{ lb/sec or } 94{,}320 \text{ lb/hr}$$

A similar calculation for a 1½-inch line yields:

$$A_{1\frac{1}{2}} = 0.012 \text{ ft}^2$$

$$W_D = 2.2 \text{ lb/sec or } 7{,}920 \text{ lb/hr}$$

In the past with 4-inch lines, flow was difficult to control since the valves were always only open slightly (~ 5 to 10 percent). Therefore, the two coal-feed legs were changed to 1½-inch-diameter lines, and the three char-feed legs were changed to 1-inch-diameter lines. These changes have virtually eliminated the plugging problems.

6.1.2 Combustion Engineering Coal/Char-Feeding System—The venturi eductors provided in the primary air lines of the pulverized coal and char system are included to provide a slightly negative or zero static pressure in the drop legs beneath the auger-gravimetric feeders. The pulverized coal or char delivered by the feeder falls by gravity into the throat of the venturi eductor where it is picked up by the high-velocity primary air stream flowing through the throat of the venturi eductor and is then distributed to combustor- or reductor-fuel nozzles by a multibranch primary air-pipe network.

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The many incidents of erratic coal/char-feeding problems can be related to a positive back pressure in a feeder drop leg caused by premature and frequent over-filling of the bag filter on a drop-leg air lock. Once a bag filter becomes overloaded with coal dust, back pressure of perhaps 10 inches of water can cause plugging, erratic flow, and inaccurate weighing in the feeder.

The initial solution to the drop-leg back-pressure problem was to design and install new venturi eductors in the primary air line. The performance of the newly designed eductor was air tested maintaining a regulated back pressure on the venturi-eductor discharge to simulate fuel-distribution-system resistance with both coal and air flowing at design conditions. Several designs, each with different size cones, were tested but none of them provided satisfactory results.

The erratic feeding problem was not solved during the first five test runs. In October 1978 a C-E Raymond exhauster with primary air piping in the pulverized coal-firing system was installed to prevent pressurizing the drop legs from the gravimetric feeders and to eliminate the erratic feeding problems. Initial performance tests of the primary air exhausters were excellent and maximum desired coal-firing rates were attained in the combustor. Encouraged by the performance of the coal exhausters, a similar type of exhauster was added to the primary air line of the char-feed piping.

The installation of an exhauster in both the coal-feed and char-feed systems apparently eliminated the erratic feeding problems, although it has not been possible, to date, to operate the gasifier at its designed Maximum Continuous Rating (MCR) conditions. The exhauster has experienced no operational problems, and indications are that the MCR coal-feed and char-recycle rate can be obtained.

6.1.3 Westinghouse Coal Feeding System—Westinghouse uses a pressurized (300-psig ambient-temperature) lockhopper and pneumatic transport of dry coal/lignite feedstock with recycled product gas as the transfer medium. The feed material is batched from storage bins via belt conveyors and bucket elevators to a transfer lockhopper, which cycles through atmospheric and system pressures. Batches of feed are then transferred to the pressurized feed lockhopper from which a rotary feed valve (starwheel feeder) discharges the material into a 1-inch-diameter pneumatic-transport feed line. Wet feedstock (surface moisure 40 percent) has caused restriction problems for discharge through lockhoppers and rotary valves and has also caused plugs in the 1-inch feed lines. The solution to this has been the recent installation of a Williams Impact Dryer Mill system, which sizes the feed to -6 mesh and reduces the surface moisture below 1.0 percent.

The design basis for the PDU material-handling equipment is 1,200 lb/hr of feed for each lockhopper train. The lockhopper-cycle time limits the maximum coal feed capacity to 1,600 lb/hr for long-duration testing. This has been improved recently by a modification to combine the pneumatic transport streams from two parallel hopper trains to obtain a total feed capacity of approximately 2,000 lb/hr.

A system that removes tramp material and properly sizes and dries the feedstock on site is critical to preventing nuisance interruptions in PDU testing. The Williams Impact Dryer Mill—which has a patented hot inert-gas system that dries, sizes, and conveys the feedstock—has proven to be effective in solving both problems in one system.

6.2 Fines Management

6.2.1 Combustion Engineering Particulate/Char-Removal System—The unburned char entrained with the hot product gas that exits from the top of the gasifier contains around 45 to 50 percent carbon. This char is recovered from the gas stream through a char-removal system, which recycles the char back to the combustor for further combustion. The current char/particulate-removal system is composed of the following components: a spray dryer, a multiclone in series with a single-stage cyclone, a wet venturi scrubber and separator, and a sludge thickener.

During the PDU shakedown period, the discharge pressure of the booster fan, which is located between the wet venturi scrubber separator and the acid-gas absorber, was found to steadily increase, accompanied by a progressive increase in fan vibration. Analysis of changes in product-gas pressure indicated that the high booster-fan outlet pressure probably was caused by plugging of the raw-gas cooler that is located between the booster fan and the acid-gas absorber. The raw-gas cooler was inspected and found to exhibit nearly complete plugging of the upstream, gas-side face with a soft fly-ash deposit, while the

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downstream, gas-side face of the cooler was clean. This indicated that a problem existed in the char/particulate-removal system.

The venturi scrubber's demister was redesigned to prevent excess water and ash carryover to the booster fan. During the post-run inspection of Test Run 5, the char cyclone was found to be very clean, but a large amount of sludge was found in the scrubber system, and the gas reheater following the scrubber was heavily coated and virtually plugged with sludge. The sludge accumulation at the booster-fan inlet duct was 2 feet deep (equivalent to 300 gallons of sludge) and 18 inches deep in the discharge scroll which houses the fan rotor. Most of the water and sludge found between the scrubber/separator outlet and the booster fan is presumed to have carried over from the scrubber-separator assembly just prior to shutdown. This accumulation was postulated to have resulted from partial or complete blockage of the gravity drain line from the scrubber/separator to the thickener. Foaming and/or high water levels in the separator chamber caused priming through the separator demister and erratic pressure excursions throughout the product-gas system just prior to shutdown. Rerouting of the drain line from the venturi scrubber to the thickener was completed during December 1978. This eliminated horizontal runs and multiple elbow configurations that serve as accumulation points for the sludge. A particulate-loading measurement at the cyclone inlet and outlet during Test Run 6 showed the cyclone to be operating with a removal efficiency of 78 percent.

This poor efficiency was believed to result primarily from the small size of the particulates generated during Run 6. Particulate loading, size distribution, and other data related to cyclone performance in Runs 5 and 6 are shown in Table 6-3. Because of the poor single-stage cyclone efficiency, a 32-tube multiclone was installed in series with the existing single-stage cyclone.

Measurement and calculations were made during both Runs 7 and 8 to determine the performance of the PDU particulate-removal system. Results of these evaluations have shown that the overall particulate-removal efficiency varied over the range of 99.2 to 99.6 percent, corresponding to a particulate loading of 0.1 to 0.3 grains/scf in the product gas. This overall efficiency resulted from the 87.5- to 89.4-percent removal efficiency of the cyclone/multiclone combination, in series with the 93.6- to 96-percent wet-scrubber efficiency. These results do not correspond to the 0.05 grain/scf that has been established for the PDU as a goal for test purposes.

To date, wet-scrubber removal efficiency at the PDU has been relatively poor. For the usual particle-size distribution, wet-scrubbing equipment efficiency of 99 percent or higher is expected when operated at the ΔP used at the PDU. If the wet scrubber were to perform at its rated efficiency, overall PDU particulate-removal efficiency would be ~99.9 percent and the 0.05-grain/scf test-facility goal would be achieved or surpassed.

Additional particulate-loading tests will be made in Run 9 to establish dust loading when the gasifier is operating at design-temperature conditions. It is postulated that char recirculation at the higher temperature will decrease to the extent that a noticeable improvement will result. Based on results of these tests, additional attention may be directed at improving the performance of the wet scrubber.

*6.2.2 **Westinghouse Char Recycle***–Westinghouse's char-recycle system is designed to remove the fine char particles entrained in the hot-product-gas stream exiting the gasifier and return these particles to the gasifier char bed for further gasification. The Westinghouse PDU presently accomplishes this in an external primary cyclone, which is a single-barrel refractory-lined unit. The hot-char fines that are collected are then cooled and conveyed to a set of feed hoppers using recycled product gas. From these hoppers, the fines are control fed to the gasifier by starwheel feeders through the pneumatic-transport system. With a normal collection efficiency of 70 percent, the primary cyclone operates at 1500°F to 1800°F and 230 psig. The feed lockhoppers operate at about 200°F and 230-psig system pressure. With this 70-percent efficiency, the roughing cyclone allows more than 10 percent of the coal feed to be lost in the quench scrubber system. To improve collection efficiency for char recycle, it is planned to add a secondary fines-collection system to substantially reduce carryover of fines to the water system. This approach should improve the 85- to 90-percent carbon utilization to the 90- to 95-percent range.

A second problem arises from deposits of ash constituents building up in the cyclone inlet. Under certain circumstances with Pittsburgh seam coals, involuntary test

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Table 6-3. Combustion Engineering Single-Cyclone Performance

	Typical Measurements	
	Run 6 (3/12/79)	**Run 5 (10/3/78)**
Particulate Loading, Cyclone Inlet, grains/scf	29.5	74
Particulate Loading, Cyclone Outlet, grains/scf	6.4	1.13
Collection Efficiency, percent	78	98
	Cumulative Weight Percent	
Particle Size, Microns	**Run 6**	**Run 5**
> 2.5	100	100
> 3.2	99	—
> 4.0	96	99
> 6.4	83	96.5
> 10.1	54	90.1
> 16.0	24	78.4
> 20.2	14.5	71.4
> 25.4	8	64.1
> 32.0	2	58.2
Operating Conditions	**Run 6**	**Run 5**
Product Gas Flow, lb/hr, Cyclone Inlet	45,420	39,500
Total Coal, lb/hr	6,000	6,750
Char Rate, Cyclone Inlet, lb/hr	2,538	2,750
Temperature, Cyclone Inlet, °F	240	277
Pressure, Cyclone Inlet, inches water	-8	~ -8
Solids Composition, Char from Cyclone, Weight Percent		
Carbon	33	59
Ash	65	37
Volatiles	2.2	2.7
Moisture	0.5	0.8
	(3/5/79, 1,500 hrs)	(10/3/78, 1,200 hrs)

termination has resulted. Westinghouse's solution to this problem has been to quench the raw product gas coming off the top of the gasifier with water prior to entering the cyclone. After investigation by the Westinghouse R&D Center, it was found that iron sulfide and an alumina-silica-potassium aggregate found in the Pittsburgh seam coal were the major constituents adhering to the cyclone wall. The eutectic temperature was found to be about 1540°F and to prevent cyclone ash deposit, the gas was kept below 1300°F. A second approach has been the use of a cyclone cold-wall heat exchanger placed at the tangential cyclone inlet point to cool the ash constituents before they adhere. These two approaches have proved to be effective in preventing cyclone buildup in the last several tests.

In conjunction with the char recycle system, Westinghouse modified the char reinjection to the gasifier from radial feed into the fluid bed to mixed feed with the input coal fed through the coaxial oxidant tube. This modificaton helped to increase the feed capability and eliminated the possibility of bed stagnation at the grid where the char was radially fed. A reduction in both the steam requirement and recycled gas-to-coal ratio results from this change.

6.3 Ash/Slag Removal

6.3.1 Bi-Gas Slag-Removal (Tapping) System—Stage I of the Bi-Gas gasifier reacts char, oxygen and steam to form syngas (CO + H_2). These reactions occur at temperatures of 2700°F to 3000°F. The ash contained in the char becomes molten at these temperatures and, because of the swirling vortex motion of the char and gases in Stage I, deposits on the cooling-water tubes, which form a vertical wall for Stage I. A layer of solid slag (ash) that forms on the cooling-water tubes increases in thickness until the slag on the surface reaches the temperature at which it becomes free-flowing. This solid slag coating on the cooling-water tubes behaves like a refractory.[11]

The free-flowing layer of molten slag flows by gravity down the "wall" formed by the solidified slag. The liquid slag reaches a tapstone arrangement, which comprises the bottom of Stage I in the Bi-Gas gasifier (Figure 6-2). Flowing over the refractory tapstone, the molten slag then drains through the 2-inch-diameter taphole. A slag-heating burner in Stage I and a slag-tap burner diametrically opposite the slag-heating burner in the slag-quench section insure that the fluid slag remains molten into the quench section.

Slag tapping is continuous during operation of Stage I. Once the molten stream of slag flows through the taphole, it falls into water in the slag-quench section. The water cools, solidifies, and fractures the slag into spherical beads. Quench water containing the slag particles drains into one of the two lockhoppers connected to the bottom of the gasifier. These lockhoppers are operated automatically in sequence to remove the slag-quench-water slurry, depressurize the slurry, and transfer the slurry to the wastewater holding pond.

During gasifier Tests G-3 through G-3G and Tests G-5 through G-5C (September 1977 through September 1978), ground limestone was fed with the coal into the gasifier Stage II, collected with the char in the char-cyclone vessel, and fed with the char to Stage I of the gasifier. In Stage I, the limestone was to combine with the slag generated from the char and improve the flow characteristics of this slag by decreasing its viscosity.

During Tests G-3 through G-3G, limestone supplied by Winfield Lime and Stone Co., Inc., of Winfield, PA, was ground in the plant's ball mill before being slurried with the coal feed to the gasifier. During Tests G-5 through G-5C, limestone from Germany Valley Limestone Company of Rivertown, West Virginia, was fed to the gasifier. This limestone was used in place of the Winfield limestone because of its higher, more uniform calcium-carbonate content. Table 6-4 gives typical analyses of these two limestones.[12]

Benefits derived from addition of limestone as a fluxing agent were minimal. Its use was discontinued after the G-5 test series. When the limestone flux was added to the coal, deposits in Stage II of the gasifier were discovered during postrun inspection. These deposits revealed a high percentage of calcium oxide (lime). A typical analysis of one of these deposits [13] is given in Table 6-5.

In earlier tests, slag had a tendency to solidify in long, thin strings extending from the tap hole into the slag-quench section. These strings, called "angelhair," would fragment into smaller needles which formed "nests" that plugged the lines to the slag lockhoppers. Two mechanical solutions were applied to solve this problem:

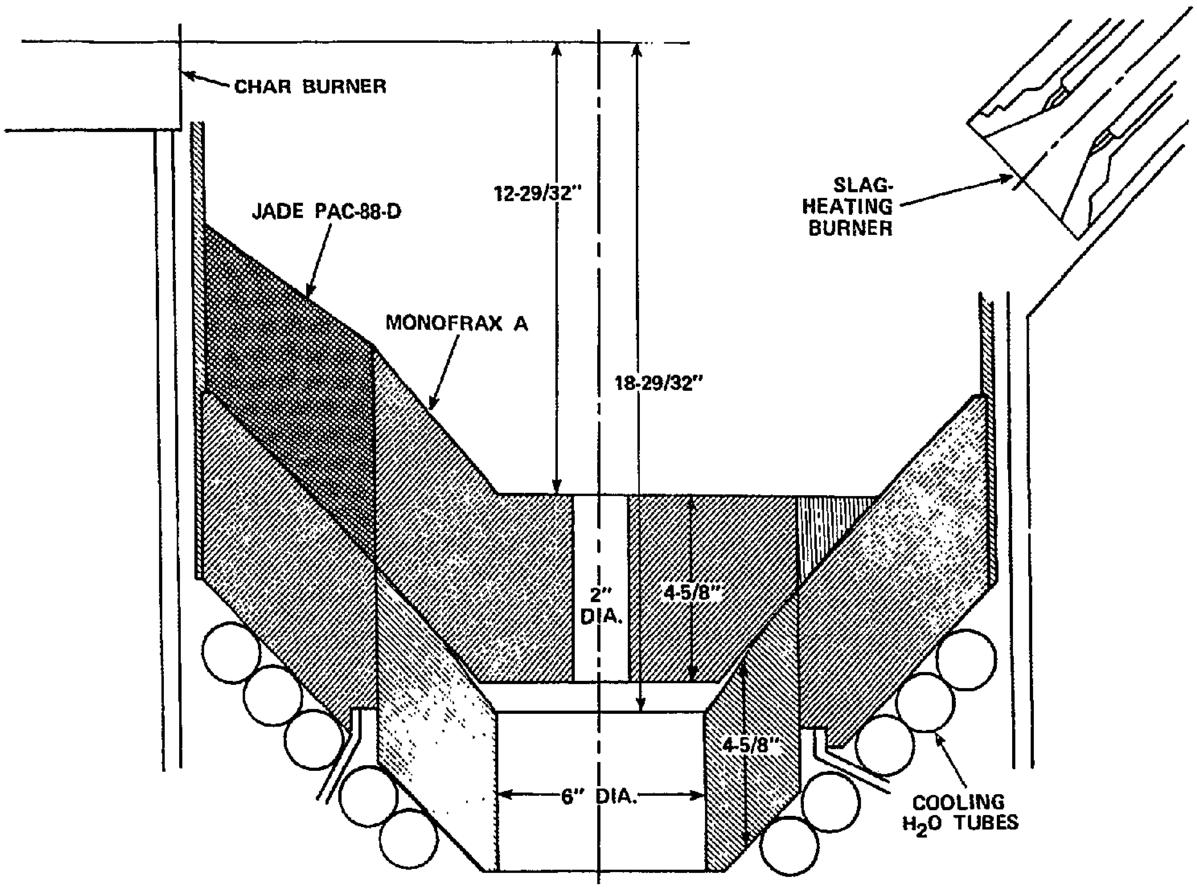

Figure 6-2. Bi-Gas Tap-Stone Arrangement

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Table 6-4. Typical Analyses of Ground Limestone

WINFIELD LIMESTONE (TESTS G-3 THROUGH G-3G)

SIZE ANALYSIS

U.S. Sieve	Wt. % on Screen
50	2.0
100	13.6
200	39.4
325	6.4
PAN	38.6
Total	100.0

CHEMICAL ANALYSIS, Wt. %

Moisture	0.9
Loss on Ignition	36.0
Carbon	11.1
Chemical Composition	
SiO_2	21.6
Al_2O_3	6.9
Fe_2O_3	4.6
CaO	61.8
MgO	1.5
TiO_2	0.5
MnO_2	0.2
Na_2O	0.1
K_2O	1.2
SO_3	0.6
Total	99.0

GERMANY VALLEY LIMESTONE (TESTS G-5 THROUGH G-5C)

SIZE ANALYSIS

U.S. Sieve	Wt. % on Screen
20	0.1
50	3.2
100	17.9
200	22.0
325	10.6
PAN	46.2
Total	100.0

CHEMICAL ANALYSIS, Wt. %

Moisture	0.1
Loss on Ignition	43.1
Carbon	11.8
Chemical Composition	
SiO_2	1.5
Al_2O_3	0.6
Fe_2O_3	0.6
CaO	93.9
MgO	1.0
TiO_2	0.2
MnO_2	ND[1]
Na_2O	ND[1]
K_2O	0.2
SO_3	
Total	98.0

[1]ND = Not Detected

Table 6-5. Mineral Analysis of Stage II Deposit After Test G-5B

Component	Wt. Percent
SiO_2	26.8
Al_2O_3	11.1
Fe_2O_3	4.8
CaO	54.8
MgO	2.2
TiO_2	0.55
MnO_2	0.12
Na_2O	0.26
K_2O	0.21
SO_3	0.25
Loss on Ignition 4.5 wt. percent	

- A mechanical agitator (consisting of four blades at the bottom of the slag-quench section) was installed. This agitator alternately rotates 90° clockwise and counterclockwise to break up any slag strands that form in the water and aids in the transfer of slag to the lockhoppers.
- A stalactite breaker was installed. This stalactite breaker is simply a water-cooled mechanical arm that rotates underneath the slag tap hole to break off any slag stalactites that may form below the tap hole.

6.3.2 Combustion Engineering Slag-Removal (Tapping) System—The tap hole at the bottom of the combustor has a diameter of 24 inches. This diameter was selected to serve as a manway for gasifier internal inspection during scheduled or unscheduled PDU shutdown.

Initially, the gasifier was operated intermittently for about 90 hours, with operations finally being terminated due to bridging of solidified slagged ash over the combustor's slag tap hole. During that period, several attempts were made to keep the tap hole open. Oil firing, limestone addition, and lancing were tried, but melt-through of the blockage was not achieved. The tap-hole plugging was thought to be due to intermittent operation that caused bridging of the tap hole. This problem was not noticed until it progressed to a total closure.

Since then, tap-hole plugging has always been associated with the operation of the gasifier. Several measures—such as water lancing, cessation of coal firing, rodding, and building a refractory dam around the tap hole—have been tried to mitigate the problem, all with limited success. Installation of a new water-cooled slag tap hole in the floor of the combustor to eliminate refractory erosion at the tap hole and to provide reliable tap-hole performance appeared to work well. However, it was also observed that no refractory was left on the combustor water wall. Apparently, the slag tap-hole plugging problem and the washing out of the refractory are closely related. The impact of mixing spalled refractory on slag fluidity has not been completely analyzed.

6.3.3 Westinghouse Ash-Removal System—The method of controlling the Westinghouse fluidized bed, its ash agglomeration and withdrawal, and the recycle of char fines has been developed exclusively using a rotary valve (in Westinghouse terminology, the starwheel feeder). The starwheel feeder gives precise flow measurement and smooth operation for transfer of coal from the lockhopper into the pneumatic transport feed to the gasifier. The fluidized bed is controlled by balancing the starwheel coal feeder with another starwheel feeder withdrawing ash at the bottom of the gasifier. The rate of withdrawal of ash agglomerates from the fluid bed is critical to successful operation of the gasifier. Once the recovered char fines from the "J" leg of the primary cyclone are gathered in the fines lockhopper syste, their feeding into the multifeed line is done through the use of a starwheel feeder. No real problems have been encountered with the use of starwheel feeders at these control points. However, the service is at a relatively low pressure (less than 300 psi) and low temperatures (~200°F). Westinghouse is currently evaluating a rotary valve developed by others for operation at ~600°F.[14] There may be difficulties with the 600-psig-pressure operating range proposed in the Westinghouse SNG plant preliminary conceptual designs.

Many of the critical interfaces in operation of the ash-agglomerating fluid-bed gasifier are controlled mechanically through use of the starwheel feeder. This has proved to lend simplicity to the operation with good reliability. Areas in which investigation and testing are yet to be done are to integrate the operation of the starwheel feeders under central control and to test their operation under more severe service.

6.4 Pilot-Plant Instrumentation

6.4.1 Bi-Gas Flame Detection at High Pressure[15] --One of the problems encountered in operating the Bi-Gas Pilot Plant was the unreliable flame detection of the pilot burners in the high-pressure gasifier. Since the operation of the slag-tap burner (STB) and the slag-heating burner (SHB) are prerequisites for the gasifier start-up as well as prolonged operation, verification of a flame is important to the pilot-plant operation. The original Bailey Meter Company's "Flamon" ultraviolet detector did not provide that reliability as evidenced by numerous shutdowns of the gasifier. Contributing factors to the gasifier-shutdown problem included signal deterioration as a result of moisture condensation on the quartz lens, dirt and/or char collecting on the lens, misalignment and temperature distortion of the 10-foot-long sight tube between the detector and burner tip, movement of the flame front with pressure, and adverse flow conditions of the natural-gas feed through the sight tube. A more effective means of flame detection was necessary to promote extended operation of the pilot plant and to provide a unit that might be used in a commercial design.

Three commercially available units were tested at Bi-Gas:

- Honeywell Model C7076, an ultraviolet detector.
- Honeywell "Purple Peeper," an ultraviolet detector.
- Electronics Corporation of America "Fireye," an infrared flame detector.

Of particular interest was how each detector was affected by sight-tube misalignments, since this was suspected to be the primary reason for the Bailey detection problem.

It was concluded that slight deflections of the sight tube, through which the detector receives its spectral transmissions, cannot be tolerated when using an ultraviolet flame-detection device. It was also determined that slight deflections of the sight tube do not cause serious problems in flame detection when using an infrared detector. Therefore, Electronic Corporation of America's "Fireye" has been adapted for this situation where the flame and the flame-detection device are separated by several feet of sight tube.

6.4.2 Bi-Gas Stage I Temperature Measurement[16] –The control of the Bi-Gas gasifier is largely predicated by the temperature within Stage I. Difficulty has been experienced, however, in developing the equipment needed to reliably measure this temperature. During operation, the environment within Stage I is both erosive and corrosive due to the high-temperature (2700-3000°F) combustion of coal char with the formation of molten ash/slag and the liberation of hydrogen by the steam-char reaction. Two types of temperature-measuring devices have been tested and evaluated: thermocouples and an infrared radiometer.

The two-color infrared, optical radiometer is a noncontact method for measuring Stage I temperature. The equipment measures the energy emitted at wavelengths of 1.6 and 2.15 microns, compares the two signals, and calcuates a temperature based on laws of black-body radiation. For accuracy, the radiometers must have exactly overlapping fields of view. As the sight tube becomes partially restricted by either slag or char, the calculated temperature may shift by several hundred degrees. Another problem is the inability to select the distance into the reactor that the equipment is measuring. While the response time of this equipment is faster than a thermocouple, the instrument appears to detect the individual char-particle temperatures, which cause unacceptable swings in the calculated temperature.

Thus far, the thermocouple that has shown the best durability in the Stage I environment is tungsten 5-percent rhenium versus tungsten 26-percent rhenium. The "hot" section has loosely compacted aluminum-oxide (Al_2O_3) insulation, while the 43-inch cool section has tightly compacted Al_2O_3 insulation. The junction is grounded. The two thermocouple wires are twisted together and wrapped with tungsten-rhenium wire and the tip is welded in an inert atmosphere. Figure

6-3 is a schematic diagram of the Stage I thermocouple.

The thermocouple tips require protection from the hostile Stage I environment. Nine different types of thermowells were tested over the tips of the otherwise conventional thermocouples to evaluate their ability to withstand the environment of Stage I. The performance of these thermowells was recorded after each gasifier test and it was determined that a molybdenum thermowell that has been flame-spray coated with chromium oxide gives the best protection. The thermowells now used in Stage I consist of two sections that are welded together. The thermowell tip—which is made of molybdenum flame sprayed with 0.015-inch chromium oxide (Cr_2O_3)—is 9 inches long, 5/8-inch O.D. and bored to 5/16-inch I.D. The balance of the thermowell is 304 stainless-steel tubing 5/8-inch x 0.065-inch wall thickness and 48-1/4 inches long.

6.4.3 Bi-Gas Char-Flow Measurement—As described previously in this report, measurement of char flow to the gasifier is critical to the Bi-Gas process. Until January 1980, the philosophy was to pursue the development of new instruments for this measurement. This approach, however, over a 3-year period resulted in few successes. Thus, given the urgency of the problems and the need for a timely solution, the approach was changed to testing and evaluation of commercially available instruments.

A number of solids-flow-instrument vendors have been contacted. One vendor, Auburn International, modified a capacitance-detection flowmeter for installation at the pilot plant, and this instrument is currently under evaluation.

6.4.4 Westinghouse Gasifier Instrumentation[17]—Westinghouse's ash-material balances have not been in a desirable range. The major portion of the ash is removed from the fluidized bed as dry-ash agglomerates containing 85- to 90-percent ash. These agglomerates are fed via starwheel feeders to lockhoppers, allowed to cool to near ambient temperature, and then after pressure letdown are dumped into tote bins that are then weighed on a scale. This weigh system and relatively heavy fines carryover to the water-quench system has led to ash-material balances in the approxmate 70- to 80-percent range.

A continuous on-line measurement of ash content in the ash and fines streams is needed. Improved weigh systems and an efficient collection of secondary fines are required to improve the ash balance.

6.5 Special Topics

6.5.1 Bi-Gas Solids-Sampling System—To obtain reliable data, it is necessary to sample solid streams in coal-gasification processes at the high temperature and pressure conditions of these processes. One such system has been employed at the Bi-Gas Pilot Plant to sample both coal and char from the high-pressure feed vessels.

This sampling system, which is depicted in Figure 6-4, consists of four main pieces of equipment: (1) a sample probe-block valve assembly that consists of a charge valve (ROV-4617) and manual probe-block valves ("A" and "B"); (2) an H.P. collection vessel that is designed to withstand the operating pressure and temperature of the char-feed vessel, 800 psia and 700°F, respectively (the vent nozzel has a small porous-metal filter to prevent solids from plugging the vent line); (3) an L.P. sample bob that is designed to contain the hot coal/char sample below 150 psig (it is a light-weight metal container used to transport the sample to the lab); and (4) a control panel, located one floor above the sample system, that contains controls for the remote-operated valves and the block and throttle valves for N_2 and purge-gas purges and vent valves [small high-pressure flow-sight glasses are installed for flow indication on the vent, nitrogen (N_2), and purge gas lines; collection-vessel pressure and temperature indicators also are located on this panel board].

The essential operating feature of this system is that the differential pressure between the vessel from which the sample is to be collected and the H.P. collection vessel is maintained at a safe but sufficient range to insure flow of material. Likewise, the venting and purging systems insure that the lines remain free and clear and the pressure in the H.P. collection vessel can be reduced to enable the hot sample to be transferred into the L.P. sample bomb. Perhaps the best aspect of the system is that it is remotely operated during the actual high-pressure sampling operation.

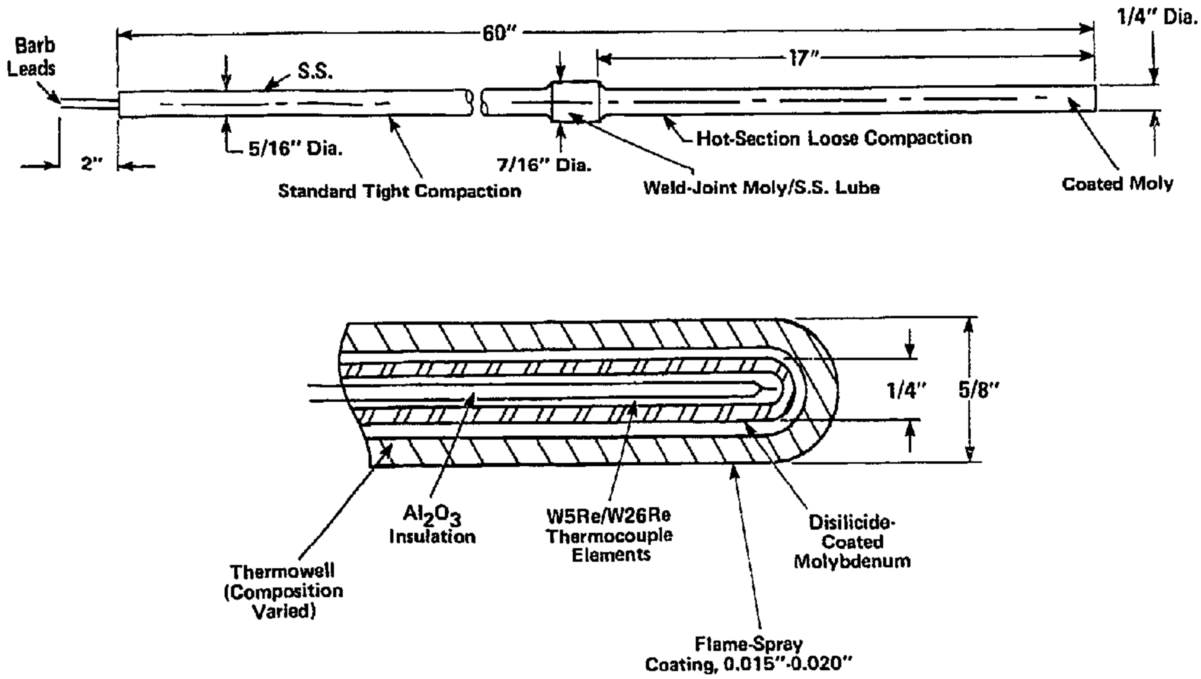

Figure 6-3. Bi-Gas Stage I Thermocouple and Thermowell

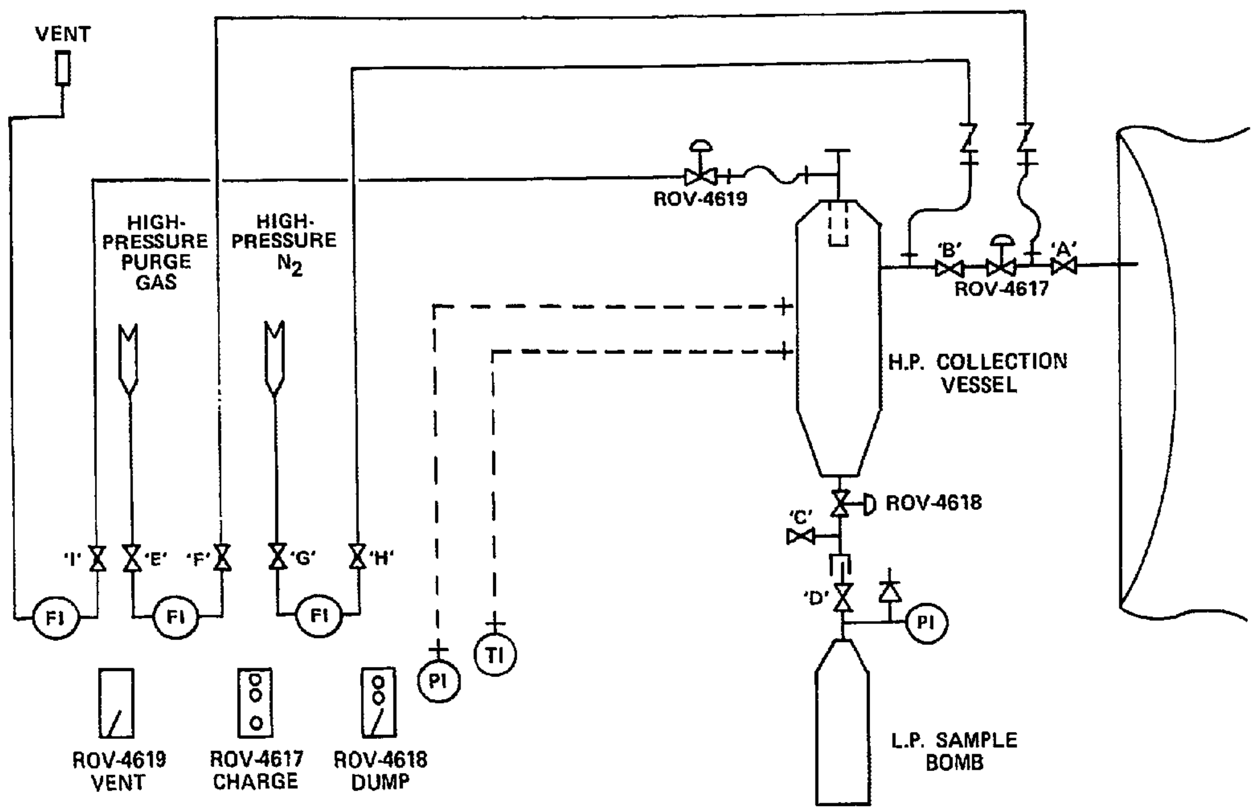

Figure 6-4. Char-Feed Vessel-Sample System

6.5.2 Bi-Gas High-Pressure Gasifier-Burner Ignition System[18] –A principal feature of the plant is the two-stage, entrained-bed high-pressure (1,500-psig maximum), oxygen-blown, and ash-slagging gasifier unit constructed by the Babcock and Wilcox Company (B&W). The gasifier is designed such that its lower region (Stage I) is the combustion zone where oxygen and steam contact and react with recycled char. As with other combustion systems, provisions must be made to initiate combustion at startup, to reinitiate combustion in case of a process upset where combustion is lost, and to continuously monitor the presence of combustion. An ignition system had to be developed capable of reliable and repeated operation at pressures up to 1,500 psi in a methane-rich or otherwise reducing atmosphere.

The initial development work was done by Babcock and Wilcox and included development of both the ignitor system and the flame-confirmation system. B&W's initial proposal specifically dealt with investigating a hypergolic (chemical auto-combustion) igniter, but prelimary experiments attempting ignition with both a spark source and a hot wire were also done. The spark and hot-wire concepts proved unacceptable for the Bi-Gas system, so the hypergolic-ignition system was pursued.

Hypergolic ignition is the spontaneous combustion of a compound upon contact with an oxygen-containing media. This oxygen source includes air, oxygen, carbon dioxide, and water. The liquid compound studied was triethylaluminum [$Al(C_2H_5)_3$] otherwise identified as TEA and supplied by Ethyl Corporation, Baton Rouge, Louisiana. The hypergolic-ignition system for the Bi-Gas pilot-plant gasifier has been operated successfully and has proven reliable at high pressure (750 psig) through repeated testing over a 4-year period.

6.5.3 Combustion Engineering Refractory Problems–Refractory experts from Combustion Engineering's Refractories Division evaluated many refractories in an effort to identify which ones would perform best in the PDU environment. Of particular concern was the interaction of these refractories with slag and gaseous compounds found in the PDU gasifier. Initial work involved an extensive survey of published literature and results from Government-sponsored test programs. These sources indicated that chromia refractories appeared promising for high-iron-content slag applications.

Static slag-screening tests, which compared the behavior of design slag with degree of penetration and chemical reaction for various types of refractories, were performed to select candidate materials for the dynamic-slag refractory erosion-corrosion test. These screening tests showed that alumina-chromia refractory is the most resistant to chemical attack by the coal-ash slag from Pittsburgh-seam coal.

A total of 21 commercially available refractory materials were subjected to the dynamic-slag erosion-corrosion tests. The results showed that alumina-chromia containing refractories are relatively better than other compositions tested with the possible exception of the magnesia-chromia fusion cast and rebonded fused-grain refractories.

The stability, thermal-shock resistance, and slag-penetration strength of the candidate refractories selected for the PDU were tested under hydrogen (both dry and wet) and simulated product-gas environments in a high-temperature gas atmosphere furnance. The results indicated that alumina ram-type refractories do not show any evidence of degration or spallation when exposed to product gas for 100 hours at 1700°F or 2200°F, and 50 hours at 2600°F. The fusion-cast aluminia-chromia Monofrax K-3 was found to be the most susceptible component in the refractory system to spall failure during heat-up and cool-down of the PDU.

Test methods and detailed results are reported elsewhere.[19,20]

Based on the above analysis and test results, the refractories to line the PDU gasifier were selected. As shown below and in Figure 6-5, different refractories were installed side-by-side in the slagging areas of the gasifier to provide comparative evaluation under actual operating conditions.

- *Slag Outlet Neck Lining:*
  - Burn-Kemram Brick (C-E Refractories)

- *Combustor Floor, "Pie-Shaped" Segments of:*
  - Ruby Brick (Harbison-Walker)
  - Monofrax K-3 (Carborundum)

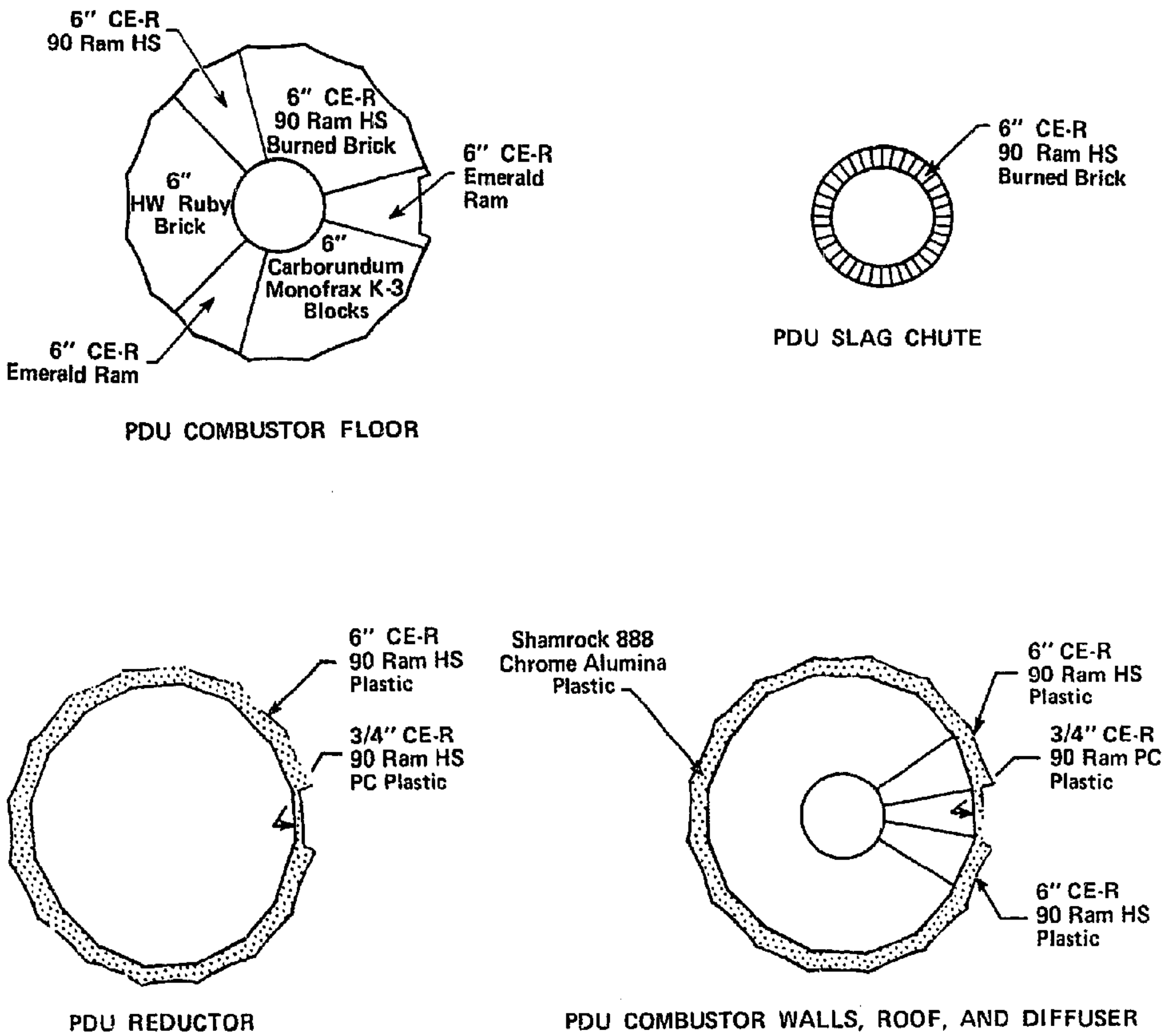

Figure 6-5. C-E PDU Gasifier Refractory-Lining Materials

- Burn-Kemram (C-E Refractories)
- 90 Ram HS (C-E Refractories)

  Note: 90 Ram PC (C-E Refractories), 2 to 3 inches thick, will "underlay" these above materials.

- *Gasifier Walls, Slagging Area:*
  - Test Panel (1 of 16 gasifier-wall panels)–90 Ram PC (C-E Refractories)
  - Waterwalls, 15 of 16 gasifier wall panels–A composite was used as follows:
    - LW 87-40 (C-E Refractories) insulation immediately adjacent to waterwalls (3/4-inch to 1-1/2-inch) thick.
    - Shamrock 888 (Taylor) 5-3/4-inch thick, 13 of 15 waterwall panels overlay the LW 87-40.
    - 90 Ram HS (C-E Refractories), 5-3/4-inch thick, 2 of 15 waterwall panels.

    Note: The Shamrock 888 and 90 Ram HS overlay the LW 87-40 and, as such, form the innermost refractory materials subjected to the gasifier slagging environment.

- *Gasifier Walls, Non-Slagging Area (Reductor):*
  - Test Panel (1 of 16 waterwall panels)–90 Ram PC (C-E Refractories)
  - Waterwalls (15 of 16 waterwall panels)–As in the slagging walls, a composite is used:
    - LW 87-40 (C-E Refractories) insulation immediately adjacent to waterwalls (1-inch to 1-3/4-inch thickness)
    - 90 Ram HS (C-E Refractories) 5-1/2 inches thick overlaying the LW 87-40.

    Note: A studded-tube-wall refractory system was used in the installation of the selected refractories in the gasifier.

Significant spalling of Monofrax K-3, which comprises 1/4 of the combustor floor, was observed during the post-curing inspection. After some 30 hours of operation, an internal inspection of the combustor refractory indicated that chunks of refractory as large as 1-foot wide and greater than 3-feet deep had fallen out of the combustor wall adjacent to three of the eight windbox openings. Insufficient anchoring of the refractory around the windbox openings may have caused the loss of the refractory. After the gasifier was operated intermittently for about 90 hours, the gasifier's refractory lining, which was in good shape, was covered by a glazed coating of fused ash and limestone.

Approximately 80 percent of the refractory in the combustor and the diffuser throat area had fallen out or eroded away after 80 gas-making hours. The tests were continued without relining the lost refractories.

One significant point is that the test panel is in very good shape and covered with a frozen slag refractory layer of 1/2-inch to 1-inch thickness after almost 2,000 hours of operation. The same refractory material, CE-R90 Ram PC plastic, which was used for the test panel, will be the lining for future commercial-size gasifiers.

After Test Run 8, the gasifier combustor (floor, walls, and roof) and the diffuser wall were relined with a solid solution bonded 90-percent Al_2O_3, 10-percent Cr_2O_3 Harbison-Walker Ruby brick. A post-operation inspection (after less than 100 hours of operation) revealed that 80 percent of the Ruby bricks were eroded away. During that short operating period, slag tap-hole plugging hampered the PDU operation.

A decision was made in June 1980 to replace the Ruby brick in the combustor zone with studded CE-R 90 Ram plastic refractories, which is the same material used in the test panel. The penalty of using a high thermal-conductivity refractory such as CE-R 90 Ram plastic, is a larger heat loss to the water walls. Based on past experience, a thin layer of slag, which has a fairly low thermal conductivity, will be deposited on the surface of the Ram plastic refractories that will compensate for the heat loss to some degree.

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7.0 SUMMARY DISCUSSION OF COAL GASIFICATION PILOT PLANTS

7.1 Combustion Engineering Low-Btu Entrained-Bed Gasifier

The Combustion Engineering PDU gasifier at Windsor, Connecticut, logged its first gas-making run in mid-June of 1978. Since that date, 4,000 hours of gas production have been accomplished. However, performance of the PDU gasifier has fallen short of the original goal of 100 Btu/scf without char accumulation. Failure to meet the expected performance has been due to a refractory-wear/heat-loss problem specific to the PDU design geometry rather than to process limitations. Despite the fact that the PDU has operated with high heat loss, the resultant degradation in gasifier performance has not hampered the generation of useful data nor interfered with process evaluations. Heating values for the gas produced by the PDU gasifier have been in the 60- to 80-Btu/scf range. Such gas can still be burned in boilers without addition of supplemental fuel.

Efforts during the latter part of 1980 were directed toward verification of the process in support of the design of a 150-MW coal gasification demonstration plant. Data from these process-verification runs provided assurance that atmospheric entrained-bed gasification of coal is feasible on a large scale.

During 1981, operation and testing of the PDU gasifier will be with oxygen-enriched air to produce a higher heating value gas. This improved gas quality would enable the process to be applied to certain retrofit boilers. Thus far, only Pittsburgh-seam bituminous coal has been tested in the PDU gasifier.

Testing of other coals in the PDU in conjunction with the oxygen-enriched air mode will begin. Coals to be evaluated are Illinois No. 6 bituminous (a very-high-sulfur coal), Wyoming-seam subbituminous coal, and lignite.

7.2 Bi-Gas High-Btu Entrained-Bed Gasifier

Located at Homer City, Pennsylvania, the Bi-Gas Pilot Plant has been operated since December 1976. All operations to date have been with Rosebud subbituminous coal and at a pressure of 750 psig. Design pressure is 1,150 psig with a coal-feed rate of 5 tons per hour, which confines the gasifier to a lower coal-feed rate of about 3 tons per hour at 750 psig. Numerous problems plagued the plant through 1979 and only a total of 362 hours of coal feed were achieved. Most of these problems were solved, and 1980 saw a dramatic improvement in gasifier operations with 659 hours of coal feed for this year alone.

Near-term project objectives are two-fold: (1) demonstration of all phases of the process including coal preparation, coal feeding, gasification, gas treating, and methanation; and (2) development of a sufficient data base from which a commercial-size process can be designed and constructed. Lack of commercial interest in the Bi-Gas process may preclude the pursuit of the second objective. Investigations are currently underway to recommend alternative uses of the Bi-Gas Pilot Plant, which is the *only* fully integrated facility in the U.S. for completely treating gases produced by coal-conversion processes. Space at the Bi-Gas site is available to erect other gasifiers and merge these units with existing equipment.

7.3 Westinghouse Ash-Agglomeration Fluid-Bed Gasifier

The Westinghouse pressurized, ash-agglomerating, fluidized-bed gasification process, under development since 1972, has operated in the 24-ton/day process-development unit for more than 7,000 hours since 1975. Operation at design temperature and pressure has been achieved, using both air and oxygen, on reactive western as well as highly caking eastern coals. The process through steady operation of the PDU, has been shown to be technically sound, readily operable, and adaptable to the production of both low- and medium-Btu fuel gas.

The near-term efforts on the program will deal primarily with resolution of ash-deposition/control problems, utilization of secondary-recycle fines, and combustion/turndown operability testing. With the development program moving from the gasifier process-feasibility stage to a process design-verification and scale-up stage, much of the future efforts are keyed toward "balance-of-plant" designs and systems evaluation. The Commercial Fluidized Systems Facility will be operated to evaluate process fluid dynamics and to define the process designs scaledup to a nominal 40-ton/hr commercial scale. Further PDU modifications may include the addition of phase 2 heat-recovery systems and slip-stream desulfurization systems. Future PDU air and oxygen testing will continue to gather additional process-design and operability data.

7.4 Cities Service/Rockwell International Hydrogasification

The Cities Service/Rockwell International Hydrogasification (CS/RI) process, which has been under development since only 1975, has progressed from the bench-scale 1/4-ton/hr hydropyrolysis reactor to an engineering-scale, batch-operation 3/4-ton/hr (ETU) test unit. Through recent short-duration testing, the ETU has provided information leading to the establishment of a data base that is still being developed. This data base consists primarily of an analytical-reactor model, information concerning process operability, experience on various reactor-injector configurations and heat-recovery (recuperation) techniques, and the results of material balances under optimum test conditions. The analytical-reactor model has been formulated based on data correlations between the literature and both hydroliquefaction and hydrogasification testing on bituminous and subbituminous coals and peat. Use of this data base has enhanced the confidence in the design of the next stage of development, the Integrated Process Development Unit (IPDU).

Upon completion of the IPDU-stage testing, long-duration and continuous operation of the process will have been demonstrated. At that point, the process data and operating experience will have been sufficiently demonstrated to support the design, economic evaluation, and optimization of a viable commercial process. Currently, the CS/RI hydrogasification process represents a part of the "third-generation" gasification program. Thus, in relation to the other gasification systems discussed in this report, the CS/RI process development program is approximately 2 to 3 years behind in achieving reliable, steady PDU operation to provide meaningful, amply demonstrated process feasibility.

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