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**ADVANCED DEVELOPMENT OF A PRESSURIZED ASH
AGGLOMERATING FLUIDIZED-BED COAL GASIFICATION SYSTEM**

Final Report for the Period May 1, 1983—July 31, 1984

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By
KRW Energy Systems, Inc.
Madison, Pennsylvania

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ADVANCED DEVELOPMENT OF A
PRESSURIZED ASH-AGGLOMERATING FLUIDIZED-BED
COAL GASIFICATION SYSTEM

PHASE II
FINAL REPORT

Period May 1, 1983 to July 31, 1984

DOE Project Manager: R. J. Belt

KRW Project Manager: D. K. Schmidt

Contributors

P. Cherish
G. B. Haldipur
S. Katta
S. S. Kim
J. L. Lucas

KRW ENERGY SYSTEMS INC.
BOX 334, MADISON, PENNSYLVANIA 15663

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GLOSSARY

Agglomeration - growth of high-ash particles by small, partially melted ash particles attaching to each other until the resulting particle becomes too large to remain fluidized.

Analytical models - models using theoretical rather than empirical correlations to predict process behavior.

Bed carbon holdup - mass of solid carbon portion of fluidized bed.

Carbon utilization - fraction of total carbon fed to the gasifier that is gasified or combusted.

Carcinogens - cancer causing agents.

Char - material resulting from devolatilization of coal.

Char/ash separation - process of classifying ash agglomerates from bed char by exploiting their difference of minimum fluidization velocity.

Coal - bituminous, subbituminous, or lignite carbonaceous fossilized material usually containing varying amounts of fixed carbon, volatile material, moisture, and ash.

Coke - material resulting from coal that has been through a coking process. Usually completely devolatilized.

Coke breeze - fine material carried off from coking process that has not been completely devolatilized but is characteristically low in reactivity.

Cold flow model - a fluidized bed that operates at ambient conditions but otherwise attempts to simulate hydrodynamic conditions of a fluidized coal gasifier.

Cold wall - liquid-cooled steel jacket, exposed to the product gas of the gasifier, that cools entrained molten material impacting on its surface and thus inhibits deposit buildup.

Coupons - small samples of test material exposed to typical environment of coal gasifier off-gas in order to test corrosion/erosion characteristics.

Dead-leg - portion of 90-degree turn of solids feed line that is built up from refractory.

Deposit control - means of avoiding buildup of molten material on the walls of vessels and spool pieces of a coal gasification process.

Devolatilization - process by which the volatile and moisture portions of coal are driven off, leaving particles mostly composed of solid carbon and ash.

Dipleg - section of cyclone where captured fines accumulate before they are transported back to the gasifier via lockhopper, nonmechanical valve, or solids injection device.

Dryer mill - device that crushes and dries coal feedstock to appropriate size and moisture content.

Elutriation - process by which fine material from a fluidized bed becomes entrained in the resulting off-gas.

Eutectics - low melting constituents of the coal mineral material.

Feed hoppers - lockhoppers that feed fresh coal to the gasifier.

Feed line - pipe in which coal is pneumatically transported to the gasifier.

Feedstock - fresh feed material, i.e., bituminous, subbituminous, lignite, petroleum coke, coke breeze.

Fines - material that becomes entrained in the off-gas of the gasifier and is typically smaller than 200 microns.

Fluid bed - section of fluidized bed in which the particles are being maintained between their minimum fluidization and terminal velocities.

Fluid bed density - mass per unit volume of a fluidized bed; includes particles and voids.

Freeboard section of fluidized bed gasifier above the fluid bed in which entrained fines can become disengaged from the off-gas.

Gasification - process where solid carbon is reacted with steam or carbon dioxide to form gaseous carbon monoxide and hydrogen.

Gasifier - device in which coal is partially combusted with oxygen and reacted with steam to form a gas mixture of CO, CO₂, H₂, CH₄, etc.

Grid plate - loosely defined as the section of a gasifier in which a conical transition from the ash annulus to a combustion zone is accompanied with a circular row of refractory-embedded nozzles that supply fluidizing gas.

Hardface refractory - refractory which, when cast, results in a hard, durable surface, but has low insulating ability.

Insulating refractory - refractory which, when cast, is relatively soft, but has enhanced insulating qualities. Used with hardface refractory in vessels requiring low heat loss and a durable internal surface.

Jet phenomena - occurrences evolving around the discharge of the oxidant tube into the fluidized bed.

L-valve - nonmechanical device by which fines accumulating in a standpipe are injected in a controlled fashion into the gasifier.

Lignite - a type of feedstock that is lower in grade than bituminous coal. Characteristically it has high moisture and volatile matter and reactivity compared to bituminous coal.

Lockhoppers - vessels in which coal is alternately charged and fed to the gasifier at system pressure.

Molten particle through-trap - a device that forces all elutriated material through a tortuous path of liquid-cooled surfaces in order to freeze any molten material before it passes further in the process.

Mutagen - a chemical agent that causes chromosome damage.

Nonmechanical valve - a device without any mechanically moving parts that controls the flow of solids from a high pressure to a lower pressure.

Oxidant tube - generic term for the tri-coaxial central feed tube in which oxygen, steam, feedstock, and recycle gas are fed to the gasifier.

Plug flow - pattern of flow through a reactor in which no element of fluid overtakes or mixes with any other element ahead or behind. Lateral mixing may occur. The residence time in the reactor must be the same for all elements of fluid.

Priority pollutants - Environmental Protection Agency list of particularly hazardous chemicals that must meet stringent standards before release to the environment.

Process models - set of analytical results and experimental correlations which model solid, liquid, and gaseous phenomena occurring in the system.

Proximate analysis - analysis of coal or char consisting of volatile matter, fixed carbon, moisture, and ash in weight fractions.

Pyrolysis - method by which coke and charcoal are produced by heating. Volatile material is driven off, leaving carbon and ash.

Quench scrubber - unit operation equipment in which hot and dirty off-gas from the gasifier is quickly cooled and particulate matter is separated from the gas by water spraying.

Radial feed - point at which solids are fed perpendicularly to the vertical surface of the gasifier.

Reactivity - rate at which a feedstock char reacts in a coal gasifier relative to coke breeze char.

Reactor - coal gasifier.

Recycle gas - portion of cleaned product gas that is compressed for use as process streams.

Scaleup - process of applying information gained on a small scale, such as from the process development unit (PDU), cold flow scaleup facility (CFSF), and bench-scale studies, to larger-scale gasifiers and peripheral equipment.

Set point - reasonably steady conditions during a PDU test that are similar to conditions called for in a test plan.

Shock heating - process by which relatively cool feedstock particles are very suddenly brought up to high temperatures (~1900°F), usually resulting in shattering of the particle.

Single-stage gasifier - gasification process in which devolatilization, gasification, combustion, and ash agglomeration occur in a single vessel.

Slagging - conditions where heat is not sufficiently dissipated to avoid bulk ash melting or sintering.

Slip stream - a portion of a total product stream that is taken and used for a different purpose.

Solids injection device - a device that can take accumulated solids from a lower pressure and inject those solids into a higher pressure.

Sparger - a ring from which a gas is equally distributed around the circumference.

Species - a particular type of chemical compound.

Specific gasification - rate of solid carbon gasification per unit mass of solid carbon holdup in the fluidized bed gasifier.

Spool - section of steel piping that is flanged on both ends.

Starwheel feeder - star-shaped wheel with pockets in which material is placed. Solids feed rate is controlled by controlling the revolutions per minute (rpm) of the starwheel.

Steady-state - portion of a set point in which various gasifier conditions remain steady according to predescribed criteria.

Subbituminous coal - a class of coal feedstock material that characteristically has less heating value per unit mass and more moisture than bituminous coal.

Thermal oxidizer - device in which all product gas and vent gases are thoroughly combusted.

Through-trap - cold wall device in which molten particles are momentarily trapped, frozen in order to avoid wall deposition downstream, and then evacuated by the gas stream.

Turndown - process by which the throughput of a gasification process is smoothly reduced in order to match the demand for its product gas.

Ultimate analysis - analysis of feedstock material that includes elemental carbon, oxygen, hydrogen, nitrogen, and sulfur.

Water-gas shift reaction - equilibrium reaction in which amounts of carbon monoxide and steam are in equilibrium with carbon dioxide and hydrogen. The associated equilibrium constant is a function of temperature.

Water injection or water quench - a means of avoiding wall deposition downstream of the gasifier by spraying liquid water into the gasifier freeboard, thus cooling the entire bulk off-gas and entrained solids.

ABSTRACT

KRW Energy Systems Inc. is engaged in the development of a pressurized, fluidized-bed, gasification process at its Waltz Mill Site in Madison, Pennsylvania.

The overall objective of the program is to demonstrate the viability of the KRW process for the environmentally acceptable production of low- and medium-Btu fuel gas from a variety of fossilized, carbonaceous feedstocks for electrical power generation, substitute natural gas, chemical feedstocks, and industrial fuels.

This report covers Phase II of the contract period (May 1, 1983 to July 31, 1984) and is a continuation of the work performed in 1983 and reported in the Phase I final report, FE-19122-30. Included is work performed in fiscal 1983-1984 on PDU testing, process analysis, cold flow scaleup facility, process and component engineering and design, and laboratory support studies.

SECTION 1.0

INTRODUCTION

1.1 DESIGN/DEVELOPMENT GOALS

KRW Energy Systems Inc., under contract with the U. S. Department of Energy, its precursor agencies, and the Gas Research Institute (GRI), is engaged in the development of a pressurized, fluidized-bed, coal-gasification process for converting many varieties, sizes, and ranks of coal to a clean and environmentally-acceptable fuel gas. From 1972 to March 1980, this development was conducted by Westinghouse Electric Corporation under Contract EF-77-C-01-1514; from March 1980 to January 1982, the program was conducted by Westinghouse under Contract DE-AC21-80-ET-14752; and from January 1982 to April 1984, the program was conducted by Westinghouse under Contract DE-AC21-82MC19122. In April 1984, Contract DE-AC21-82MC19122 novated to KRW Energy Systems Inc., a new entity formed by Kellogg Rust Inc. (The M. W. Kellogg Company) and Westinghouse Electric Corporation. KRW Energy Systems Inc. will continue the development at the Waltz Mill Site, formerly operated by Westinghouse Synthetic Fuels Division. Progress to April 1983 was presented in Report No. FE-19122-30.

The primary goals of the program, since its inception, have been (1) the development of a low-Btu process for fueling a combustion turbine combined cycle power plant and (2) development of a medium-Btu process for the production of an industrial fuel or synthesis gas that can be used as a feedstock for substitute natural gas or liquid synfuels.

For the period covered by this report, May 1983 to July 1984, the overall objective was to determine the viability of the KRW pressurized, fluidized-bed, gasification system for the future production of low- and medium-Btu fuel gas for application in production of substitute natural gas (SNG), electric power generation, chemical feedstocks, or industrial fuels, as well as to obtain process development unit (PDU) performance and cold flow model scaleup data for the process and components.

Specific objectives were to:

- Complete PDU testing for the development of process capability to produce low- and medium-Btu gas from coal.
- Establish, by test at PDU scale, optimized process design and product characterization parameters for a variety of coal feedstocks to verify the data base for low- and medium-Btu gas production.
- Measure and compile process and environmental and health data base.
- Complete determination of load-following characteristics of the KRW gasifier.

- Complete evaluations of gasifier characteristics under part-load, transient conditions and simulated failure modes.
- Develop, by correlations and analysis of PDU and operating data, laboratory data, and the literature, a data base and unit process models for gasifier design.
- Complete balance-of-plant component performance evaluation for certain critical subsystems.

During the report period, two topical reports were issued:

- FE-19122-45 - Process Analysis Topical Report.
- FE-19122-46 - Cold Flow Scaleup Facility Experimental Results and Comparison of Performance at Different Bed Configurations.

1.2 DESIGN/DEVELOPMENT EVOLUTION

The single-stage process (Figure 1-1) is the result of a design evolution from a two-stage (Figure 1-2) low-Btu process consisting of a devolatilizer and a gasifier-agglomerator. Development began in 1972 under the sponsorship of the Office of Coal Research. During these early years of the program, emphasis was directed primarily to the two-stage, air-blown system for direct integration with Westinghouse combined cycle plants based on the W501D combustion turbine and was intended ultimately to result in the construction and operation of a nominal 130-MW coal gasification combined cycle demonstration facility.

In 1975, the Energy Research and Development Administration redirected the program, deferring the demonstration plant and emphasizing process development. From 1976 to 1978, the proposed applications for the gasification process were expanded to encompass medium-Btu fuel or synthesis gas, and oxygen-blown gasifier experiments were initiated.

In 1979, the Gas Research Institute became a part of a joint program with the Department of Energy, and greater emphasis was placed on the development of the medium-Btu, oxygen-blown process. Based on experimental breakthroughs in the process design, it was demonstrated that caking coals, highly-reactive coals, and coals with low- or high-ash content could be processed successfully in a single-stage gasification process. The single-stage configuration then became the prime design for the process and replaced the two-stage, fluidized-bed system.

1.3 KRW SINGLE-STAGE GASIFICATION PROCESS

The KRW single-stage gasification process is designed to operate in an air- or oxygen-blown mode to produce low- or medium-Btu gas, respectively. Run-of-mine coal is dried to a satisfactory surface moisture content of less than 5 percent and is simultaneously crushed by

Figure 1-1. Westinghouse Single-Stage Coal Gasification Process

Figure 1-2. Westinghouse Two-Stage Coal Gasification Process

an impact mill to a typical feed size of minus 1/4-inch. Feed coal is then transported from storage bins by belt conveyors and bucket elevators to a transfer lockhopper that cycles between atmospheric pressure and gasifier system pressure. The coal is subsequently transferred to a pressurized feed lockhopper and is discharged through a rotary feed valve into a feed line, where it is pneumatically transported by recycled product gas into the gasifier through a central feed jet. Steam and oxygen are injected as a mixture at this point through an external annulus of the injection system. As the coal is combusted, it reacts with the steam and oxygen, and rapid devolatilization of the coal occurs in the oxidizing region of the jet. The rapid devolatilization in the oxidizing envelope, where the high turbulence of the jet induces vigorous mixing and dispersal of the devolatilized coal, allows caking as well as noncaking coals to be processed in the KRW gasifier. A combustion zone, which is caused by the reaction of oxygen with the recycle gas and recirculating char fines, exists in an around the jet. The high temperature of the combustion zone ensures that the products of devolatilization (tars, oils, etc.) are cracked and gasified to methane, carbon monoxide, and hydrogen. For the most part, the cracking reactions limit the by-products from the gasifier to sulfur and ammonia and nontoxic agglomerated ash.

As the bed of char circulates through the jet, formed at the end of the central feed tube, the carbon in the char is consumed by combustion and gasification, leaving particles that are rich in ash. The unique fluid dynamic design of the gasifier allows the ash-rich particles to agglomerate with each other and form large, dense particles that defluidize from the bed and collect in the ash annulus. These ash-rich particles contain mineral compounds and eutectics that melt at temperatures of 1000 to 2000°F. The liquid phases within the char particles extrude through the pores to the surface of the char, where they stick to other liquid droplets on adjacent particles. In this way, ash agglomerates form that are larger and denser than the particles of char in the bed. The agglomerates defluidize, migrate to the annulus around the feed tube, and are continuously removed by a rotary feeder to lockhoppers. Recycled product gas or steam in the annulus is used to separate the ash and cool it as it is withdrawn.

The ash agglomerates typically discharge from the gasifier at 300 to 400°F at a bulk ash content of 85 percent or higher. Some ash agglomerates exceed 95 percent ash. Carbon loss in the ash agglomerates is small; a 10 percent ash coal feed producing an 85 percent ash agglomerate results in a carbon utilization of about 98 percent. Other carbon losses are small, since the entrained fines from the cyclone are recycled to the gasifier and are gasified in the combustion zone. Overall carbon utilization is approximately 95 percent.

Raw product gas from the gasifier passes through the particulate removal system, which consists of a primary and secondary cyclone, to recover entrained fines. With the primary cyclone, about 95 percent of the fines

generated in the coal preparation and gasification process are recycled. The secondary cyclone was added to improve the overall fines collection and recycle efficiency to 98 percent. Fines collected in the cyclones are recycled into the gasifier. The product gas next passes through heat recovery heat exchangers and is then quenched in a water venturi scrubber. This particulate-free gas is desulfurized in an acid gas removal system, and the clean product gas is ready for use as a fuel or feedstock for subsequent processing. Sulfur is recovered as elemental sulfur, and waste water is treated and recycled. The coal gasification system is shown in the block diagram of Figure 1-3 and the gasifier with the primary and secondary cyclones are shown schematically in Figure 1-4.

1.4 PROCESS DEVELOPMENT

Since the early 1970's, the development of a pressurized, fluidized-bed, gasification process has taken place at the Waltz Mill Site near Pittsburgh, Pennsylvania. Process development tests are being conducted with the PDU, which is capable of processing coals and lignites at capacities ranging from 15 tons per day with air to 30 tons per day with oxygen. The PDU is a pilot-scale prototype of a large-scale commercial gasification system, and its technical feasibility has been successfully demonstrated in more than 9000 hours of hot operation.

In addition to the testing performed in the PDU, extensive development efforts have been conducted at the Westinghouse Research and Development Center in Churchill, Pennsylvania, and at the Cold Flow Scaleup Facility (CFSF) at Waltz Mill, Pennsylvania. Westinghouse Research and Development Center laboratory models are used for studying gasification kinetics, ash agglomeration, and fluidized-bed behavior, as well as cleaning and combustion of process gases. The 10-foot diameter CFSF has been operational since September 1980, and this facility permits full front-face viewing of the fluidized bed through a Plexiglas window, allowing a detailed study of jet behavior, solids circulation, and other phenomena within the fluidized bed. In addition, the CFSF provides a cost-effective tool for defining detailed component hardware designs and for corroborating models developed in the PDU and in the laboratory.

The PDU gasifier vessel is fabricated from carbon steel, measures 50 feet in height, and has a maximum outside diameter of 4 feet. Its shell is internally lined with two layers of refractory--an inner abrasion-resistant layer and an outer insulating refractory. Gas ducts from the gasifier to the quench scrubber, including the cyclones, are similarly constructed of refractory-lined carbon steel. The pressure vessel design basis is 300 psig and 650°F allowable skin temperature. Typically, the gasifier skin operates at 200°F. The PDU routinely operates with a gas outlet temperature ranging from 1650 to 1850°F and with pressures at 130 to 230 psig. Coal can be fed to the gasifier at a rate of 1000 to 1600 pounds per hour for bituminous coals and 1600 to 2500 pounds per hour for subbituminous coals.

Figure 1-3. Coal Gasification System Flow Diagram

Figure 1-4. Westinghouse PDU Single-Stage Coal Gasifier

The single-stage KRW gasifier at Waltz Mill has successfully operated with a variety of carbonaceous feedstocks, using either oxygen or air as the oxidant. Properties of these feedstocks have varied over a wide range with regard to caking properties, as measured by the free swelling index, ash content, ash deformation temperature, moisture, volatile matter reactivity, and heating value. Coals processed in the PDU to date are listed in Table 1-1. Those that have been processed include washed and unwashed run-of-mine coal. None of the coal feedstocks tested in the PDU were pretreated, other than reduction of size and surface moisture to accommodate pneumatic feeding. Feedstock size is generally minus 1/4-inch.

PDU feedstocks tested were readily gasified and the ash successfully agglomerated. There has been virtually no evidence of tars or oils in the exit of the gasifier, cyclone separators, or quench scrubber. The quench scrubber water is routed to a knockout drum and then to a settling pit where the particulate solids are separated and removed.

TABLE 1-1
PDU COAL FEEDSTOCKS

<u>Coal Feedstock</u>	<u>Test No.</u>	<u>Month/ Year</u>	<u>Hot Hours of Coal</u>	<u>Mode</u>
Pittsburgh No. 8 Adamsburg Mine (R-O-M Washed)	TP-016	4-5/78	113	Air
Pittsburgh No. 8 Champion Mine(R-O-M Washed)	TP-013-3	12/77	16	Air
	TP-017	5/78	161	Air
	TP-018-2	7/78	45-1/2	O ₂
	TP-018-3	8/78	69-1/2	O ₂
	TP-018-4	9/78	47-1/2	O ₂
	TP-018-5	9-10/78	85	O ₂
	TP-020-2	5/79	164-1/2	Air
	TP-022-1	6/79	53	O ₂
	TP-022-2	6-7/79	57	O ₂
	TP-023-3	12/79	50-1/2	O ₂
	TP-023-4	3/80	134-3/4	O ₂
	TP-027-2	5/80	64-1/2	O ₂
	TP-027-3	6-7/80	147-1/2	O ₂
	TP-028-1	6/81	33-1/2	O ₂
Pittsburgh No. 8 Federal Mine	TP-034-2	6-7/83	435	O ₂
	TP-035-2	12/83	226-1/2	O ₂
Ohio No. 9 Bannock Mine	TP-023-1	7-8/79	30	O ₂
	TP-023-2	8/79	26	O ₂
	TP-025-2	11/79	14-1/2	Air
	TP-027-1*	4/80	69	O ₂
	TP-027-2	5/80	62-1/2	O ₂
W. Kentucky No. 9 Hamilton Mine (R-O-M Washed)	TP-019-2	11/78	45	O ₂
	TP-019-3	12/78	56	O ₂
	TP-027-4	8/80	66-1/2	O ₂
	TP-032-2	5/82	95-1/2	O ₂
	TP-033-3	12/82	94 1/3	Air & O ₂
Indiana No. 7 Minnehaha Mine (R-O-M Washed)	TP-013-3	12/77	27	Air
	TP-019-1	10/78	37-1/4	O ₂
	TP-019-2	11/78	95-1/2	O ₂
	TP-030-2	5/81	61-1/2	O ₂
	TP-028-2	7/81	144	O ₂ & Mixed
Indiana No. 7 Sycamore Mine (R-O-M Washed)	TP-025-1	9/79	146	Air
	TP-025-2	11/79	61-1/4	Air
	TP-027-1*	4/80	69	O ₂
Rosebud Coal Montana (R-O-M Unwashed) Subbituminous "B"	TP-019-1	10/78	63-1/2	O ₂
Texas Lignite (R-O-M Unwashed)	TP-023-4	3/80	11-1/2	O ₂
Texas Lignite Monticello Mine (R-O-M Unwashed)	TP-027-3	6-7/80	47	O ₂
	TP-027-5	10/80	85	O ₂

* Indiana No. 7 Ohio No. 9 blended during drying operation.

TABLE 1-1 (Continued)

<u>Coal Feedstock</u>	<u>Test No.</u>	<u>Month/ Year</u>	<u>Hot Hours of Coal</u>	<u>Mode</u>
Wyoming (Wyodak Mine) (R-O-M Unwashed)	TP-013-3	12/77	22	Air
	TP-015	4/78	36	Air
	TP-027-4	8/80	50-1/2	O ₂
	TP-027-5	10/80	24	O ₂
	TP-029-1/ -030-1	4/81	60	O ₂
	TP-028-1	6/81	39	& Mixed O ₂
	TP-033-2	10-11/82	75-1/2	O ₂
	TP-034-1	3-4/83	148-1/4	O ₂
	TP-035-1	9-10/83	291-1/4	O ₂
Illinois No. 6 Delta Mine (R-O-M Unwashed)	TP-031-1	12/80	12	O ₂
	TP-029-1/ -030-1	4/81	112-1/2	O ₂
Upper Freeport Seam (R-O-M Unwashed)	TP-023-3	12/79	22	O ₂
Upper Freeport E-Seam, Elton Mine (Unwashed)	TP-032-1	3-5/82	97-1/3	O ₂
	TP-032-2	5/82	53-1/2	O ₂
RSA Coal Bocjosspruit Colliery (R-O-M Unwashed)	TP-031-1	12/80	97	O ₂
	TP-030-2	5/81	53	O ₂
	TP-031-2	10/81	46	O ₂
Texas Lignite Big Brown Mine (R-O-M Unwashed)	TP-028-3	9/81	112-1/2	O ₂
West Virginia Big Mountain Mine (R-O-M Washed)	TP-030-3	11/81	172-1/2	O ₂
Arco Coke Watson Refinery	TP-031-3	12/81	88 1/4	O ₂
Chevron Coke El Secundo, Calif.	TP-031-3	12/81	61-1/4	O ₂
N. Dakota Lignite Indianhead Mine (R-O-M Unwashed)	TP-033-1	7-8/82	67-1/2	O ₂
	TP-034-3	8/83	216-2/3	O ₂
Brookville Ace Drilling Co.	TP-033-1	7-8/82	103-1/4	O ₂

SECTION 2.0

SUMMARY ACCOMPLISHMENTS, CONTRACT DE-AC21-82MC19122

2.1 PHASE II PDU TEST OPERATIONS

During this contract period, all PDU tests were conducted under a single-stage, oxygen-blown gasifier operating mode. Five PDU tests, totaling 1434 hours of hot operation, were completed. The tests with their objectives and accomplishments are summarized in Table 2-1 and are discussed in Section 3.0.

2.2 PDU PROCESS ANALYSIS

During this period, the major work, as reported in Section 4.0, consisted of:

- Secondary Fines Recycle Evaluation
- Gasifier Oxygen Consumption Analysis
- Gasifier Jet Temperature Profile Evaluation
- Feedstock Size Correlation
- Cold Wall Performance Evaluation
- Fines Collection and Recycle Analysis
- Cyclone Performance Assessment
- Elutriation Analysis and Predictions
- Gasifier Performance Analysis
- Feedstock Characterization Update
- Process Analysis Topical Report
- Mechanistic Test Program Modifications

2.3 COLD FLOW SCALEUP FACILITY (CFSF)

The 10-foot (3-meter) diameter CFSF, Figure 2-1, became operational in 1980 and was designed to provide scaleup data to verify the fluid dynamic and similarity criteria developed from smaller laboratory-scale units. Semicircular with a transparent Plexiglas full front face, the CFSF permits easy viewing of the fluidized bed. Jet behavior, solids circulation, and critical phenomena within the bed can be clearly observed during tests that are conducted to obtain fluid dynamic data.

During 1983, twelve tests were performed: (1) four using a 16-inch diameter air tube and an 8-inch diameter feed tube to verify jet velocity, jet characteristics, and gas history, and (2) eight using a 10-inch diameter air tube and a 4-inch diameter feed tube to verify jet characteristics and gas history. The CFSF tests are summarized in Table 2-2 and are discussed briefly in Section 5.0, while test results and analyses are provided in Topical Report FE-19122-46, "Cold Flow Scaleup Facility Experimental Results and Comparison of Performance at Different Bed Configurations."

Since 1983, there has been no formal CFSF test program, aside from data reduction, and this 3-meter facility is being maintained in a standby mode through biweekly inspections and a preventive maintenance program.

2.4 PROCESS AND COMPONENT ENGINEERING AND DESIGN

Major work during this report period included modifications for hot fines recycle, deposit control, and environmental assessment. These are discussed in Section 6.0.

2.5 COAL GASIFICATION LABORATORY SUPPORT STUDIES

Laboratory support studies were performed at the Westinghouse Research and Development Center to:

- extend the fundamental data base and mechanistic understanding of fluidization, gasification and combustion interaction phenomena to support PDU operations through system analysis, and
- develop and/or correlate fluid dynamic data from the cold flow laboratory models using the cold flow scaleup facility (CFSF).

The areas investigated during the contract period and reported in detail in Section 7.0 are:

- Gas Solids Flow Phenomena -- jet phenomena, fine particle history, particle history, and char/ash separation.
- Coal/Ash Behavior -- coal gasification and ash behavior.

TABLE 2-1
SUMMARY OF GASIFIER TESTS

TEST NO.	RUN DATE	FEEDSTOCK	HOT* OPERATION (HOURS)	MAXIMUM FREEBOARD TEMP.(°F)	PRESSURE (PSIG)	TEST OBJECTIVE/ACCOMPLISHMENT
TP-034-2	June 83	Pittsburgh No. 8	435	1875	230	<ul style="list-style-type: none"> - Environmental sampling - 15-day test - 95% carbon conversion - Through-trap conversion - Fines elutriation characterization
TP-034-3	August 83	N. Dakota lignite	217	1534	214	<ul style="list-style-type: none"> - Environmental sampling - Characterize fines recycle and radial temperature profiles - Explore low temperature operation - Oxygen blown
TP-035-1	Sep/Oct 83	Wyoming Sub-C Wyodak Mine	291	1540	230	<ul style="list-style-type: none"> - Characterize various fines recycle modes, ash agglomerate and radial temperature profiles - Explore low temperature operation - Oxygen blown
TP-035-2	December 83	Pittsburgh No. 8	270	1840	200-230	<ul style="list-style-type: none"> - Characterize effect of feed size on elutriation and agglomerate - Characterize radial temperature profiles and bed gas composition - Oxygen blown
TP-035-3	June 1984	Pittsburgh No. 8 W. Virginia	221	1850-1915	100-230	<ul style="list-style-type: none"> - Characterize gasifier performance with high temperature fines recycle - Characterize gasifier performance with varying system pressure and feedstock - Obtain baseline gasifier data with two coals at 1850°F freeboard temperature and no direct water quench - Characterize mechanistic gasifier performance within limits of available instrumentation

* Total hot operation for all set points

Figure 2-1. CFSF Transparent Model

6893-60

TABLE 2-2

SUMMARY OF CFSF TESTS

TEST NO	RUN DATE	TYPE OF TEST	BED CONFIGURATION	TEST OBJECTIVES	TEST ACCOMPLISHMENTS
Deep Bed Mods	May 1983/ June 1983		Truncated Annulus 10" Air Tube 6" Conc. Nozzle w/Shroud, 4" Feedline		
<u>PHASE I TESTS</u> TP-M013	July 1983	Solids Circulation, Probe	Same as above	Obtain bubble frequency data, determine jet region and outer boundary, determine bubble region and outer boundary and clarify solid circulation flux around the jet	Using probes, completed 6 set points gathering frequency measurements on the Nicolet 2090 digital oscilloscope at 8 instr. locations at 3 air-tube velocities (100, 150, 200 fps)
TP-M011	July 1983/ Aug 1983	CO ₂ Tracer Gas History	Same as above	Measure gas exchange between different regions of the bed while CO ₂ is injected through the air tube and grid	Gathered tracers using Gow-Mac gas analyzers for 10 setpoints at 2 air-tube velocities (100, 200 fps) with CO ₂ injection through both the air tube and grid
TP-M010-1	Aug 1983	Gas Bubble Dynamics, Movies	Same as above	Obtain qualitative data on jet penetration depth and bubble properties (diameter, velocity, frequency, coalescence)	Completed 18 set points and individually analyzed 72 rolls of movie film to extract data on jet penetration and bubble properties
TP-M014	Sept 1983	Gross Solids Movement in a Bed, Coarse Solids Mixing	Same as above	Study movement of coarse particles (>+6) in fluid bed to determine distribution throughout the bed and/or concentration near the solids injection ports	Completed 4 set points collecting 250 bed samples at 5 locations running at 4 air-tube velocities (75, 100, 150, 200 fps)
TP-M010-2 -3 -4	Sept 1983/ Oct 1983	Gas Bubble Dynamics, Probe	Same as above	Study the effect of bed height on jet penetration depth and jet half angle and study frequency of voidage oscillations close to the jet inlets	Completed 63 individual data set points and collected frequent measurements on online traces at selected probe locations and probe penetrations
TP-M015	Oct 1983	Fines Particle History	Same as above	Study elutriation rate and residence time of fine acrylic particles (75-150 μ m) charged to a fluidized bed or acrylic material	Completed 4 sets points and collected about 117 fines samples at 5 sample locations running at 4 air-tube velocities (50, 100, 150, 200 fps)
Phase II Mods	Oct 1983/ Nov 1983		Truncated Annulus 16" Air Tube 10" Conc. Nozzle w/no Shroud, 8" Feedline		
<u>PHASE II TESTS</u> TP-M016-1	Nov 1983	Gas Bubble Dynamics, Movies	Same as above	Obtain qualitative data on jet penetration depth and bubble properties (diameter, velocity, frequency, coalescence)	Completed 11 set points and collected data on 77 rolls of film as well as nominal operating data running at 2 air-tube velocities (50, 100 fps)
TP-M016-2	Nov 1983/ Dec 1983	Gas Bubble Dynamics, Probe	Same as above	Measure frequency of oscillations and bubble rise velocity in a fluid bed	Completed 10 set points and collected data online via a dual channel spectrum analyzer to produce time and frequency traces for analysis. Also gathered nominal operating data running at 2 air-tube velocities (50, 100 fps)
TP-M017	Dec 1983	Solids Circulation, Probe	Same as Above	Traverse model bed cross section to determine jet region and outer boundary, bubble region and outer boundary and quantify changing solids recirculation rates	Completed 6 set points and collected about 900 Visicorder traces online as well as nominal operating data at 2 air-tube velocities (50, 100 fps). Also observed probe deterioration at high velocities in a deep bed
TP-M018	Dec 1983	Coarse Solids	Same as Above	Study movement of coarse particles (> +6) within a fluid bed to determine distribution throughout the bed and/or concentration near the solids injection ports	Completed 2 set points and collected 500 samples continuously as planned from sample ports. Also collected nominal operating data at 2 velocities (50, 100 fps)

SECTION 3.0

PDU TEST OPERATIONS

During the contract period, all PDU tests were conducted under a single-stage, oxygen-blown gasifier operating mode. Five PDU tests were conducted using coal from three mines and lignite from North Dakota.

A PDU test usually extends over a three-week period of operation. Following routine pressurization and pretest procedures, the gasifier is initially charged with coke breeze and ignited with preheated, compressed air. A switchover to a steam-oxygen mixture is made, and the selected coal feedstock is fed to the gasifier. A nominal 8- to 10-hour bed turnover period purges the gasifier bed of all residual coke breeze and establishes a representative bed of char. Once the gasifier bed is established at pre-selected conditions, set points ranging in duration (from 24 to 72 hours) are conducted. Following completion of all planned set points, the gasifier is shut down and depressurized. Table 3-1 gives a typical operational chronology.

3.1 TYPES OF TESTS

Each PDU test is designed to attain operational and process performance data for a broad range of technology issues which become part of a test plan. A test plan document is prepared for each test which defines the primary objectives, the areas of investigation that take precedence over others. PDU tests conducted during 1983/1984 can be classified in terms of their primary objectives as follows:

A.	Hot Fines Recycle Data	TP-034-2	Bituminous Coal
		TP-034-3	Lignite
		TP-035-1	Sub-C Coal
		TP-035-2	Bituminous Coal
		TP-035-3	Bituminous Coal
B.	Long-Term Steady-State Operation for Environmental Sampling	TP-034-2	Bituminous Coal
		TP-034-3	Lignite
C.	Gasifier Performance Characterization, Mechanistic Test Program	TP-035-1	Sub-C Coal
		TP-035-2	Bituminous Coal
		TP-035-3	Bituminous Coal
D.	Deposit Control	TP-034-2	Through-trap
		TP-035-2	Cold Wall
		TP-035-3	Cold Wall

TABLE 3-1
TYPICAL OPERATIONAL CHRONOLOGY AT THE PDU

- PDU inventory is checked and laboratory analyses are performed to ensure that the feed cut size and chemical analyses meet test specifications.
- Pretest checklist procedures are implemented to ensure that all PDU instruments needed for the test are operational and calibrated.
- Plant is pressurized to 230 psig in 50 psig increments to allow for detection of leaks in major vessel flanges and/or process sampling trains.
- Hot air dryout of the system is conducted by increasing the temperature 50 degrees per hour until 500°F is achieved at the freeboard section of the gasifier. This temperature is held for 12 hours (Hot Air Dryout HOLD), while the ash lockhoppers and solids transport lines from the cyclone are vented to atmosphere to prevent moisture condensation.
- After hot air dryout is completed, coke breeze is transferred from the storage bins to the feed lockhopper and recycle gas or air flows are started in the transport gas lines.
- Coke breeze is introduced into the gasifier, and a fluidized bed is built to an approximate 20-foot height.
- Once the bed is built, the process air temperature is slowly raised from 500°F to a maximum of 1000°F. Combustion of the coke breeze (ignition) usually occurs when the gasifier bed temperature ranges between 650°F to 700°F.
- Immediately after ignition is achieved, the air flow rate is gradually reduced, and a small flow of oxidant (oxygen or air) and steam is introduced through the air tube to ramp the gasifier bed temperature to set point conditions.
- The temperature ramp is controlled by slowly backing out the air flow, and slowly increasing the oxygen flow, while proportionately increasing the steam flow for oxygen-blown operation. In air-blown operation, the air flow is controlled to incrementally ramp the temperature and the introduction of steam is an option.
- Coal feed to the gasifier is initiated and the temperature ramp is continued to establish set point conditions.
- A set point is declared after the gasifier bed has been "turned over" from coke breeze to the selected coal feed material and after 8 hours have elapsed with coal feed.
- After the objectives of the test have been achieved, the gasifier temperature is slowly reduced by decreasing the air flow rate and increasing nitrogen flow. An 18- to 20-foot bed level is maintained until combustion is quenched.
- Once the gasifier temperature falls below 1200°F, depressurization of the system is initiated at a rate of 50 psi per hour. When the gasifier bed is completely withdrawn, through the ash lockhoppers, and the temperature has fallen below 300°F, all flows to the gasifier are shut off and the vessels are allowed to cool by natural convection.

Detailed results on each of the PDU tests conducted during the contract period, including heat and material balance data (with the exception of test TP-035-3 which is covered in the Appendix of this report) were included in the quarterly progress reports prepared and published under the contract as follows: FE-19122-28, -37, -38, -41, and -49. These reports are available from the National Technical Information Service, Springfield, Virginia.

3.2 SUMMARY OF PDU TEST RESULTS

3.2.1 TP-034-2

Long-duration, oxygen-blown gasifier test TP-034-2 was conducted from June 3 to July 1, 1983, using Pittsburgh No. 8 coal as the feedstock. The primary objectives of this fines recycle test were to: characterize gasifier performance with high temperature fines recycle, achieve maximum carbon conversion, and conduct an extended (15-20 day) period of PDU operation.

Test TP-034-2 was conducted in two operational phases. The first startup, conducted from June 3 to 9, was aborted due to deposition in the primary cyclone. The system was disassembled and cleaned and was reassembled. Ignition for the second startup was achieved on June 13, and the test was continued to July 1. A total of 434.8 hours of hot operation were completed, including 412.8 hours on Pittsburgh No. 8 coal feed, representing the longest uninterrupted PDU test at high carbon-conversion conditions.

Notable accomplishments of the test were:

- Achieved operating data with high carbon conversion (92 percent) at 1900°F.
- Achieved long-term operating data with continuous high carbon conversion (>90 percent average, 95 percent maximum) at 1800°F.
- Primary and secondary fines were recycled throughout the test with minimal upsets or operational problems. The nonmechanical valve was operated in the fluidized mode on the primary recycle system, and the solids injection device was operated downstream of the secondary recycle system. The overall fines collection efficiency was measured at 94 percent. The ability of the gasifier to consume fines was substantially demonstrated by the virtual absence of fines sludge accumulation in the quench scrubber system at the end of the long-duration test.
- Obtained deposition information at 1380°F and 1580°F.

- Obtained data for evaluation of the particle "through-trap."
- Obtained extensive isokinetic data for fines carryover predictions and cyclone efficiencies.
- Obtained operating data on the new centrifugal recycle gas compressor.
- Completed significant environmental, health and safety (EH&S) sampling requirements.

Fifty-five gallon drums were procured and used for collection of bulk samples of ash, sludge, and waste water. The empty drums were delivered, handled, stored, labeled, filled, sealed, and prepared for shipping. The following quantities of process withdrawal material were collected and shipped to the Institute of Gas Technology in Chicago for storage and future testing by GRI: 154 drums of ash and 17 drums of sludge. Forty-four drums of waste water were collected as part of a comprehensive wastewater treatability study jointly funded by the Department of Energy (DOE), Gas Research Institute (GRI), the Environmental Protection Agency (EPA), and the Electric Power Research Institute (EPRI). The drums of waste water were shipped to the Radian Corporation in Austin, Texas, to the DOE in Morgantown, and to the DOE in Bruceton, Pennsylvania, for testing and analysis.

A major part of the EH&S program was the occupational health and safety evaluation conducted by the Radian Corporation, Salt Lake City office, during TP-034-2 through air monitoring of specified PDU areas as well as employee personal exposure. Personal exposure monitoring was conducted during six operating shifts, and the process technicians wore personal air sample pumps and passive dosimeters to determine their exposure to organics, polycyclic aromatic hydrocarbons (PAHs), benzene, toluene, xylenes, phenolics, carbon monoxide, and hydrogen sulfide. Area monitoring was conducted on all levels of the PDU structure for carbon monoxide, hydrogen sulfide, and respirable dust.

Oak Ridge National Laboratory (ORNL) personnel were also on site during test TP-034-2. ORNL tested developmental equipment and analytical techniques to detect worker exposure levels to organic materials, particularly the polynuclear aromatic (PNA) compounds. Results obtained, using these new techniques, will be compared to results obtained from traditional sampling and analytical techniques. The instruments and techniques used by ORNL included:

- Derivative ultra-violet absorption spectrometer (DUVAS), a semiportable monitor designed to detect and measure mono- and diaromatic-hydrocarbon vapors such as benzene, toluene, naphthalene, and cresol. It was also used to analyze water samples for phenol content.

- Spill spotter, used to detect and measure surface contamination from PNAs.
- PNA passive dosimeters to determine PNA vapors.
- Synchronous luminescence analysis was conducted on samples to detect their aromatic content.

3.2.2 TP-034-3

TP-034-3 was a single-stage, oxygen-blown, fines recycle test conducted from August 9 to 26, using North Dakota lignite as the feedstock. The primary objectives of this test were to: (1) characterize gasifier performance with hot fines recycle and achieve maximum carbon conversion at a minimum oxygen/coal ratio while maintaining reliable system operability at 1600°F, (2) continue extensive environmental sampling and industrial hygiene monitoring for the EH&S evaluation being performed by the Radian Corporation, and (3) explore low-temperature operation of the PDU gasifier and evaluate reaction kinetics, ash agglomeration, and product gas constituents at 1400°F. Two hundred seventeen hours of hot operation were completed, including 184 hours with North Dakota lignite feed.

Notable accomplishments of the test were:

- Obtained operating data with high carbon conversion rates at two freeboard temperatures: 93 percent at 1520°F and 89 percent at 1410°F.
- Recycled primary and secondary fines throughout the test with minimum upsets or operational problems. Operational performance of both the nonmechanical valve and solids injection device was excellent.
- Obtained operational performance data using a modified material for the solids injection device nozzle/diffuser.
- Obtained reliable isokinetic data for fines carryover predictions and cyclone efficiencies.
- Demonstrated successful operation of the new centrifugal compressor and the nonslagging traversing temperature probe (NSTTP).
- Successfully completed an extensive environmental sampling program, working with the Radian Corporation.

3.2.3 TP-035-1

A PDU mechanistic experimental program was initiated in September 1983 to obtain a fundamental understanding of specific physical and chemical phenomena occurring in the pressurized ash-agglomerating fluidized-bed (PAFB) gasifier. In the course of this test scope, the operating mode of the gasifier was deliberately varied outside the range of optimum design conditions to determine the cause-effect relationships of critical process performance parameters. The initial mechanistic test series, designated by the serial prefix "TP-035" consisted of three tests.

TP-035-1, a single-stage, oxygen-blown test, was conducted from September 23 through October 26, using Wyoming Sub-C coal as the feedstock. Two hundred ninety-five hours of hot operation were completed, including 267 hours feeding coal. During the first four steady-state periods, with both cyclones operating, the overall fines collection efficiency ranged from 92 to 94 percent and yielded an overall carbon utilization between 90 and 93 percent. Ash content in the gasifier withdrawal material ranged from 84 to 93 percent.

Notable accomplishments were:

- Obtained baseline gasifier performance data on Wyoming Sub-C coal with high-temperature fines recycle, as exemplified by Steady States 1A, 1B, 1A1 and 1A2.
- Attained a fines collection efficiency of 94 percent and carbon utilization of 93 percent.
- A significant achievement was demonstration of agglomeration and separation on the Wyoming Sub-C highly-reactive feedstock.
- The ash content in the gasifier withdrawal material ranged from 84 to 93 percent. Prior tests on this coal yielded an ash content lower than 65 percent.
- Obtained sensitivity data on carryover at different cyclone collection efficiencies during Steady States 2A, 3A, and 4A, when the two cyclones were deliberately switched off in sequence. Data from these set points will be used to evaluate the per-pass consumption of fines in the gasifier.

In addition, radial temperature profiles were measured in the gasifier combustion zone and char bed during Set Points 1, 1A and 2. The test was performed in three operational phases because of recurring deposit formations in the quench scrubber inlet. During the 7-year operating history of the PDU gasifier, this is only the second incidence of a deposit problem in the quench scrubber. The first occurred during the August 1983 test using North Dakota lignite. Analysis of the plug material indicated the presence of crystalline calcium carbonate (CaCO_3).

bonded in layers to the carbon-steel downcomer pipe, where a water spray quenches the gas and fines by adiabatic humidification cooling. The following results were obtained from an investigation of this operational anomaly.

- The deposit characteristics were typical of western U.S. coals which contain greater than 5 percent calcium oxide in their mineral matter. No such deposit was encountered during the 15-day PDU test using Pittsburgh No. 8 coal (0.1 percent calcium).
- The quench water circuit is a partially-closed loop with a purged stream of waste water from the gravity separation pit. In recent PDU tests, the cyclones operated at peak efficiencies (greater than 90 percent), thereby reducing the fines loading entering the quench system. It is not normal operating practice to periodically purge the waste water within the quench system; therefore, the concentration level of calcium salts could gradually increase and aggravate the precipitation potential of calcium carbonate in the system. Further evaluation of the waste water was conducted by a water treatment company which recommended the addition of specialty chemicals for inhibiting the formation of crystalline deposits.

3.2.4 TP-035-2

The second PDU mechanistic test, TP-035-2, was conducted during December 1983, using a Pittsburgh No. 8 coal. During the test, 270 hours of hot operation were completed, including 226.5 hours feeding coal. Baseline gasifier performance data were obtained with high-temperature fines recycle using two feedstock sizes, namely 1/4-inch by zero and 10 mesh (0.079-inch) by zero. Data were also obtained on the effect of feedstock particle size on gross fines carryover, the effect of gasifier temperature, the per-pass consumption of methane, the effect of primary water injection on gasifier bed cooling and shift equilibrium, and the effectiveness of cold wall piping in preventing deposits.

Notable accomplishments from this test were:

- Obtained baseline gasifier performance data on Pittsburgh No. 8 coal with high-temperature fines recycle using two feedstock sizes, as noted above.
- Obtained carbon utilization in excess of 90 percent and a withdrawal ash concentration ranging from 93 to 96 percent during Set Points 1 and 3.
- Obtained data on the effect of feedstock particle size on gross fines carryover, using the isokinetic fines measurement probes. The cyclones operated at a high fines collection efficiency.

- Obtained data on the effect of gasifier temperature on performance during Set Points 1 and 2 at freeboard temperatures of 1828°F and 1739°F. Notable differences were observed in the gas heating value (237 versus 184 Btu/scf) and the ash content of agglomerates (87 versus 79 percent).
- Conducted radial traverses with the nonslagging traversing temperature probe (NSTTP). During PDU high-temperature operation, a peak temperature of 2200°F was measured approximately 2 to 3 inches past the centerline of the gasifier. During low-temperature (~1700°F) operation, a peak temperature of 2050°F was recorded at the same location.
- Obtained radial gas-concentration profile measurements. Preliminary data indicate that a distinct profile in moisture content was observed, i.e., 22 percent along the centerline and 8 percent at the wall.
- Obtained data on the per-pass consumption of methane in the gasifier during Set Points 1 and 3, with and without external methane injection in the coal transport line. Additional process analysis is underway to evaluate the effect of higher methane partial pressures on the carbon-hydrogen-methane pseudo-equilibrium.
- Demonstrated the effectiveness of cold-wall piping in preventing deposits. No deposits were found on the internal metal-cooling surface; however, the cooling capacity of the jacket was found to be insufficient to quench the gas and fines to a temperature less than 1400°F. The cold-wall jacket will be extended in future tests to accomplish this objective.
- The effect of primary water injection on gasifier bed cooling and shift-equilibrium was partially studied during Set Point 4. Numerous ash annulus upsets occurred during this set point; therefore, the data obtained are inconclusive.

Repeated upsets in the char/ash separator occurred during the latter part of the test. From post-test inspection of the gasifier and an evaluation of key events during the test, the following was generally concluded:

- A thermocouple located in the gasifier combustor region was found to be inserted 6 inches, rather than the usual 4 inches, to obtain a more accurate internal temperature measurement. This greater penetration apparently impeded solids circulation and promoted formation of a sintered-ash mass in the gasifier grid area.

- The high-pressure carbon dioxide (CO₂) vaporizer system, which delivers motive gas to the solids injection device (SID), failed and caused cold gas to enter and shock the gasifier. The thermal shock to the refractory walls could have fractured the sintered-ash material adhering to the walls in the vicinity of the thermocouple.
- The large pieces of sintered material broke loose and migrated to the bottom of the char/ash separator, blocking the gasifier ash withdrawal channel. Periodically, the separator was pressure pulsed with CO₂ to clear the block; however, only temporary relief was gained since the sintered material was thrust back into the gasifier and then gradually again sank to the ash withdrawal channel, where it blocked the exit.

3.2.5 TP-035-3

TP-035-3, the third mechanistic test, was conducted from June 8 to 21, 1984, using Pittsburgh No. 8 coal and West Virginia washed-bituminous coal as the feedstock. PDU performance data were obtained at high fines recycle rates and maximum carbon utilization levels for both feedstocks. The test was conducted in two operational phases. Fines elutriation and gasifier performance data were obtained at pressure levels of 100, 160, and 230 psig. Mechanistic data were obtained with the nonslagging traversing temperature probe (NSTTP), the gas sampling probe, and the oxygen-sensing probe. Two hundred and twenty-one hours of hot operation were logged, including 146.5 hours feeding Pittsburgh No. 8 coal and 50.3 hours feeding West Virginia coal.

Notable accomplishments were:

- Obtained PDU performance data at high fines recycle rates and maximum carbon utilization levels on two coals. Estimated carbon conversions ranged from 87 to 91 percent for all set points and the withdrawal ash concentration ranged from 84 to 94 percent.
- Obtained satisfactory performance data on the full cold-wall device (four sections) in preventing ash deposition in the piping downstream of the gasifier. These process data were free of any compounded effects due to water injection spray which was used in conjunction with the partial cold wall in previous PDU tests.
- Obtained fines elutriation and gasifier performance data at three pressure levels: 100, 160 and 230 psig.
- Obtained mechanistic data with three types of probes: traversing temperature (NSTTP), gas sampling (NSTGC) and oxygen-sensing (O₂).

As reported in Quarterly Progress Report FE-19122-49, damage occurred to the oxygen probe during the first operational phase of TP-035-3 (Set Points 1 and 2), and the damaged probe-tip cover was removed to inspect the sensor and thermocouple. The sensor was intact and showed no leaks when pressure tested at the maximum system pressure; however, the thermocouple tip was partially melted.

A functional test of the oxygen probe was performed, using helium with a maximum of 2 ppm oxygen for the sample gas and air for the reference gas. A separate reference thermocouple was used to determine the actual temperature. It was observed that the temperature indicated by the reference thermocouple could be changed depending on its distance from the probe end plate; therefore, the tips of the two thermocouples were physically fastened together to ensure they were measuring in the same area. The probe was then placed into a furnace and was heated to ~1200°F. Sample gas was introduced into the reference side of the probe, and the two thermocouple temperatures and sensor voltages were recorded approximately every four minutes while helium flowed through the probe. The two thermocouple temperatures were always within 30 degrees of each other. The test was conducted for 2.5 hours, and the oxygen concentration (calculated from the sensor voltage and both thermocouple readings) showed a gradual drop to <2 ppm with a maximum sensor voltage of 0.22 volt. This test verified that the damage to the oxygen probe, during TP-035-3, affected only the protective cover.

3.3 MATERIALS TEST PROGRAM

3.3.1 Material Corrosion Evaluation Program

In cooperation with the Metal Properties Council (MPC), KRW participated in a coal gasification pilot plant material corrosion evaluation program that was directed to critical assessment of potential corrosion problems in a variety of coal gasification environments. Fabricated assemblies of metal coupons were exposed to diverse environments at pre-selected locations that were deemed to have significant corrosion potential. After a period of exposure, the coupons were removed and analyzed for corrosion. These analyses, together with results from other laboratory tests conducted under the direction of MPC, were used to provide increased confidence in materials selection and corrosion-rate prediction for coal gasification plants.

Test coupons were installed in January 1983 at test locations 2A, 4, 5, C-122 vapor side, and C-122 aqueous side as shown on Figure 3-1 and noted in Table 3-2. The coupons were exposed to PDU hot operation during tests TP-I-83-1, TP-034-2, TP-034-3, TP-035-1, and TP-035-2 with 1463 cumulative hours of exposure time. The test coupons were removed in February 1984 and were sent to the Illinois Institute of Technology Research Institute (IITRI) of Chicago for analysis. Post-test samples from locations 4 and 5 are shown in Figure 3-2. New sets of coupons were installed at test locations 2A, 4, 5, 6 and 7 as part of a continuing program.

Figure 3-1. Materials Test Locations for Coupon Samples

TABLE 3-2

MPC PHASE II PILOT PLANT CORROSION TESTING, PDU STATUS

Location*		1	2	2A	4	5	6	7			Hot Operation Exposure Time (hours)	
Sample Group	Status	C-115	C-119	C-110	C-111 Vapor	C-112 Aqueous	C-113 Vapor	C-113 Aqueous	C-122 Vapor	C-122 Aqueous	Cal. Year	Total Accum.
I	Installed 2/81	x	x	-	x	x	x	x	x	x	---	---
I	Removed 1/20/82	x	x	-	x	x					1100	1100
II	Installed 1/21/82	x	x		x	x						
II	Removed 1/10/83	x	x		x	x	x	x	x	x	804	1904
III	Installed 1/25/83	-	-	x	x	x	-	-	x	x		
III	Removed 2/84	-	-	x	x	x	-	-	x	x	1463	
IV	Installed 2/84	-		x	x	x	x	x				

*Refer to Figure 3-1.

C-111 Post Test
Location 4
Vapor
2-14-84

C-112 Post Test
Location 5
Aqueous
2-14-84

13 1020-2197.4

Figure 3-2. Exposed Coupon Samples from Locations 4 and 5

3.3.2 Ceramic Cloth Exposure to Product Gas

Ceramic cloth, from 3M Company, was wrapped to a six-layer thickness around a 1/2-inch carbon steel pipe and was held in place with spirally-wound stainless steel wire, 0.025-inch diameter. This test assembly, Figure 3-3, was installed into the C-120 cyclone dome in January 1984 and was exposed to the gasification environment during PDU test TP-035-3. During the 221 hours of PDU hot operation, the temperature varied from 524 to 1196°F, the operating pressure varied from 100 to 230 psig, and the gas composition ranges were as follows:

	<u>Percent</u>
CO ₂	24.60 to 34.26
H ₂ S	0.82 to 1.07
H ₂	18.34 to 24.70
N ₂	0.36 to 1.50
CH ₄	1.61 to 3.85
CO	41.46 to 46.97
H ₂ O	9.89 to 15.11

Upon removing the ceramic cloth test assembly, after test TP-035-3, the cloth snagged on the refractory pilot hole at several places along the first 19 inches of length. It was also noted that the cloth was discolored and brittle for approximately 1.5 inches where it passed through the refractory pilot hole. During removal of the cloth from the half-inch pipe, it was observed that the fabric had melted and adhered to the pipe in the first-wrap thickness around the pipe. Upon evaluation, the ceramic cloth was found to be not heat treated. The 3M Company recommended heat-treated material for future PDU tests, and they indicated a willingness to supply material and participate in additional material evaluation tests.

Wrapped

End Plane →

Unwrapped

Flange Plane →

13 1020-2197.5

Figure 3-3. Post Test Condition of Ceramic Cloth

SECTION 4.0

PROCESS ANALYSIS

4.1 SECONDARY FINES RECYCLE SYSTEM EVALUATION

A review of the secondary fines-recycle system was performed, starting from the addition of a second cyclone to the PDU fines collection and recycle system and prior to conducting test TP-028-1 in June 1981. As originally conceived, the fines collected by the secondary cyclone fell into a surge pot through an interconnecting downcomer pipe (dipleg). The fines recycle rate to the gasifier was controlled by a starwheel feeder from which the fines dropped into the throat of an eductor, which was a subsonic gas nozzle that redirected the fines flow into a radial injection nozzle. Because of the temperature limitations of the teflon seals in the starwheel feeder, both the dipleg and the surge pot were glycol cooled. This configuration was used through TP-032-2 with various nozzle inner diameters.

Prior to TP-033-1, in August 1982, a hot solids injection device (SID) was installed in place of the surge pot, starwheel feeder, and eductor. Additionally, the original dipleg was replaced with a refractory-lined dipleg that extended from the secondary cyclone directly to the SID. The SID was designed to recycle the fines radially to the gasifier at 600 to 800°F (versus 200°F in the previous configuration) to increase the thermal efficiency by reducing the heat load on the gasifier. Furthermore, the SID was equipped with a sonic converging-diverging nozzle to cause a pressure seal between the gasifier and the cyclone dipleg. Details are reported in Quarterly Progress Report FE-19122-37 and Topical Process Analysis Report FE-19122-45.

4.2 GASIFIER OXYGEN CONSUMPTION EFFECTS

An analysis was performed of the oxygen/coal ratio for PDU tests on Pittsburgh No. 8 and western coals to determine the influences of steam/coal, total moisture/coal, water injection/coal, recycle gas/coal, fines elutriation/coal, fines loss/coal, and coal feed rate on overall oxygen demand. The steady-state data with the best oxygen/coal ratio, moisture ash free (MAF) from each test since TP-023-4 were used and grouped by coal. Wyoming Sub-C and North Dakota lignite test runs were grouped together. A multiple linear regression analysis with oxygen/coal MAF as the dependent variable was performed. A regression equation was generated for Pittsburgh No. 8 and for the Wyoming/N.Dakota blends during PDU testing, producing multiple R^2 values (fraction of variation) of 0.9405 and 0.9064, respectively. Also, the individual independent variables were ranked in the order of significance. The preliminary results indicated that total moisture (including water injection), recycle gas, and fines loss were the primary influences on the oxygen/coal ratio. Fines elutriation showed the least influential effect.

4.3 GASIFIER JET TEMPERATURE PROFILE EVALUATION

Models of the gasifier jet hydrodynamics and temperature profiles are being developed. PDU data on jet temperature profiles over a variety of gasifier operating conditions are being used both to test and refine the models as well as to extract key gasifier behavior trends. The modeling and PDU data results will provide a data base for scaleup of the gasifier performance.

The gasifier jet hydrodynamic model is being developed based on fundamental balance equations for mass and momentum in the jet and the surrounding emulsion phase. Both axial and radial balances at the jet-emulsion interface are considered. The hydrodynamic model is time-averaged and spatially smoothed to yield an average jet behavior in comparison to the actual, highly fluctuating jet behavior. The smoothing and time-averaging procedure is expected to result in a model which is representative of both flame-like jets and bubbling jets. From solutions to the hydrodynamic model, the gas and particle velocity along the jet axis and across the jet-emulsion interface are obtained. Estimates may also be made of the jet half-angle and the jet penetration from the model solutions, and comparisons with available jet data on jet half-angle and penetration are being performed. The sensitivity of the model results to model parameters and model assumptions will be determined.

Data from previous PDU tests for which jet temperature data were collected have been compiled (TP-033-2, -033-3, -034-3, -035-1, and -035-2), and estimated jet temperature profiles were generated for each of the 16 sets of test conditions. Solids and gas circulation rates were extracted from these data. Comparisons are being made between the predicted and measured temperatures and the predicted and experimentally-estimated gas and solids circulation rates. Preliminary results of the comparisons show good agreement between the measured and predicted jet temperatures, i.e., within a maximum deviation of 150°F. The accuracy and uncertainties in the PDU data are being estimated also to test the significance of the correspondence between the models and the data.

Future PDU tests are being planned on the basis of providing critical data for this modeling effort. In addition to the temperature profile data to be evaluated from future tests, oxygen profile data will be collected and evaluated as another key segment of information about the gasifier jet behavior.

4.4 FEEDSTOCK SIZE CORRELATION

A correlation has been found between the Hardgrove Grindability Index (HGI) and the average particle size of fines content of coal feedstocks, as reported in FE-19122-37. Since the ease of pulverizing a coal increases as the Hardgrove Index increases, a coal with a high HGI produces a smaller average particle and more fine material than a coal with a lower HGI; this is after grinding in a preparation mill. Lower HGI coal generally produces a larger average particle size and less fine material.

For example, the average particle size of Texas lignite from the Monticello Mine (HGI=82) is 720 microns, while the average particle size of West Virginia coal (HGI=52) is 970 microns. Although subbituminous coals do not always have a high grindability index and do not produce large amounts of fines during preparation, they contain high amounts of intrinsic moisture which causes more particle breakup in the gasifier. As such, subbituminous coals produce higher amounts of fines in the gasifier than bituminous coals. Operation of the coal preparation mill and the size of the unprepared coal have an effect on particle size and must be considered in the estimate.

4.5 COLD WALL PERFORMANCE EVALUATION

A buildup of mineral matter deposits in the primary cyclone and gasifier-to-cyclone spool piece occurred in almost every PDU test from the TP-012 series in 1977 through 1981 PDU testing. Exceptions were recorded with western coals when gasifier temperatures were below the deposit threshold temperature or when water injection was used. In some cases, the deposits were so massive that they forced a shutdown of the plant. Although water injection was proven as an effective means to prevent these deposits, this technique would result in reduced thermal efficiency in a commercial application; therefore, alternate methods of deposit control were investigated.

An internally water-cooled metal patch was installed in the primary cyclone and was evaluated during 1980 and 1981 PDU testing. Although deposition occurred in other areas of the cyclone, no deposits adhered to the cold wall patch; therefore, a full cyclone cold wall was installed in the PDU for evaluation as a deposit control device during TP-032-1, which was conducted in April 1982. A diagram of the cold wall, as installed, is shown in Figure 4-1. The full cold wall consisted of four separate sections constructed of 0.25-inch thick Type 310 stainless steel. Sections A and B were cooled through one water loop and Sections C and D were cooled from another water loop. Section A was cylindrical while Sections B through D were rectangular.

Three PDU tests included test objectives to evaluate cold wall performance. The first test, TP-035-1, was a proof-of-concept test; therefore, the surface metal temperature was maintained conservatively low because of the unknown deposit threshold temperature. During the following two tests, as soon as steady-state process conditions were achieved, the surface metal temperature was incrementally increased in an effort to identify the temperature at which deposits begin to stick to a metal surface. Because of this operating procedure, there were short periods when the surface metal temperature exceeded pre-established limits.

Deposition did not occur on any of the cold wall sections during any of the three PDU tests. Neither did deposits occur downstream from the cold wall. The product-gas/fines temperature drop across the four cold wall sections exceeded 400°F in each test, and the product-gas/fines temperature was below 1350°F at the exit of the cold wall device. This temperature is below the deposit "sticking" temperature for each of the coals tested.

Average gas-film heat-transfer coefficients for each cold wall section showed that the heat transfer coefficient for cold wall Section A is significantly higher than those for Sections B, C, and D. This is due to the greater gas impact on the surface created by the cyclone swirl in this section.

Post-test inspections revealed no mineral matter buildup on the cold wall surfaces that were in contact with the gas-fines mixture during any of the three tests. Ultrasonic wall measurements of the cold wall piping showed no significant erosion except in the cyclone barrel section (Section A) where the gas-fines mixture followed a rotational path. In this area, erosion reduced the metal wall thickness by 0.025 to 0.040-inch; this translates to approximately 450 to 700 mils/year. A detailed analysis is reported in the Process Analysis Topical Report FE-19122-45.

4.6 FINES COLLECTION AND RECYCLE ANALYSIS

An evaluation of the nonmechanical-valve system performance during the long-duration test with Pittsburgh No. 8 coal, TP-034-2, was completed. It was generally concluded that:

- primary fines recycle system performance was excellent following correction of startup difficulties,
- coal feedline plugs are frequently followed by apparent nonmechanical valve bridging, and
- the particle size of the primary cyclone fines reached a steady-state in 3 to 6 hours.

Since it was determined that the main difficulty with the nonmechanical valve during startup is the time required to heat the char-leg refractory lining sufficiently to prevent moisture condensation, a startup technique for improved startup was evaluated. Results of this evaluation are reported in FE-19122-45.

4.7 CYCLONE PERFORMANCE ASSESSMENT

The performance of the primary and secondary fines recycle systems during tests TP-034-2 and TP-034-3 were analyzed. Results of this study are summarized below and are reported in FE-19122-45.

The internal designs of the two PDU cyclones conform to conventional Lapple and Stairmand geometries as described by Koch and Licht⁽¹⁾. The primary cyclone is a refractory-lined vessel, while the secondary cyclone is fabricated of sheet metal and is supported in a refractory-lined containment vessel. The methods of fines recycle employed by the primary and secondary systems are, respectively, a fluidized-bed dipleg and a gas-solids eductor.

Measurements of total and fractional collection efficiencies were made with the aid of isokinetic sampling probes situated at the inlets and outlets of both cyclones which provided estimates of particle loading and size distribution. The experimental values of efficiency were then compared to theoretical estimates based on a technique given by Koch and Licht.

Agreement between the predicted and actual efficiencies was very good for the primary cyclone, but not as good for the secondary cyclone. Some factors supporting this observation are:

- Because the fluidized dipleg provides minimum interference, the primary cyclone functions like a free-standing cyclone, similar to the classical devices which have been theoretically modeled by Koch and Licht. The gas-solids eductor, however, draws significant quantities of gas from the secondary cyclone dust outlet, thereby distorting its cyclonic separation process.
- The secondary cyclone, being a metal device supported on a refractory ledge, is likely to allow gas and fines to bypass the inlet swirl and leak through the top cover to the cyclone gas outlet. The primary cyclone would not suffer from such gas leakage because of its refractory construction.
- The accuracy of the isokinetic sampling system is a function of the dust loading encountered in the gas stream. Because the dust loading in the outlet of the secondary system is considerably lower than that in the other sampling locations, it is conceivable that the experimental values of cyclone efficiency for the secondary system incur a greater absolute error than those for the primary system.

The results of fractional efficiency (the efficiency for specific particle size ranges) showed some discrepancies. For example, the actual fractional efficiencies showed an increase with a decrease in particle size which is contrary to hydrodynamic theory. This is attributed to the difficulty of obtaining an accurate size analysis of very fine particles which tend to adhere to, or form clumps in, the absolute filter in the isokinetic sampling system.

(1) W. Koch and W. Licht, "New Design Approach to Cyclone Efficiencies," Chemical Engineering, November 7, 1977.

Because the dust loading is measured from a gain in weight of the absolute sampling filter, the errors in measuring overall dust loading are not expected to be affected by particle size.

Based on this performance evaluation, it was recommended that the sheet metal secondary cyclone be replaced with a refractory-lined device similar to the primary system. Because the usefulness of the fractional efficiency calculation is suspect, it was recommended that only total collection efficiencies be monitored and assessed in the future.

4.8 ELUTRIATION ANALYSIS AND PREDICTIONS

Work was continued on elutriation analysis and predictions using data from TP-034-2, TP-034-3, and TP-035-1. The most recent data, using 14 steady states, are based upon PDU operation with the nonmechanical valve recycle system on the primary cyclone while the previous data (58 steady states) were based on the lockhopper recycle mode. Elutriation rates based on isokinetic sampling indicate that the carryover increased from 300 to 500 percent with the nonmechanical valve system. An attempt to verify the rates by using the steady-state rate data is planned. If the higher rates are confirmed, new constants for the elutriation model will be generated. Refer to FE-19122-45 for a more complete discussion.

4.9 PDU PERFORMANCE ANALYSIS

A study on the analysis and prediction of PDU performance with western coals has been completed. PDU steady-state data obtained with Wyoming Sub-C coal and Texas and North Dakota lignite feedstocks were analyzed to study the effect of temperature and steam on the gasification rate. PDU performance was predicted using a bed volume sizing model, and kinetic data were developed on carbon gasification reactors. The following conclusions and recommendations are made based on the results of this study:

- The specific gasification rate increased with an increase in temperature for Wyoming Sub-C coal and Texas lignite. The temperature range covered for North Dakota lignite is very narrow and no significant effect of temperature was noticed.
- There was a significant decrease in the specific gasification rate of Wyoming Sub-C coal with an increase in the steam/carbon ratio for the narrow temperature range of 1515 to 1600°F, $\pm$ 150°F. This observation is in sharp contrast to the behavior of Pittsburgh Seam coal. Data on the two lignites were too limited to extract any information on the effect of steam.

- The gasification rate of Wyoming Sub-C coal was about four times higher than that of Pittsburgh Seam coal in the temperature range considered, assuming that the data on the Pittsburgh coal can be extrapolated.
- The predicted bed volumes were in reasonable agreement with measured bed volumes for the western coal feedstocks considered.
- Since the rate determined on a thermogravimetric analyzer (TGA) represents true kinetic rate, it should be combined with mass transfer rate calculations (from bubble phase to particulate phase) to obtain an overall reactivity for high-reactive coals, such as Wyoming Sub-C coal and the two lignites studied.

PDU steady-state data obtained with Western Kentucky, Indiana No. 7 and Illinois No. 6 coal feedstocks were analyzed to study the effect of temperature and steam on gasification rate. Bed volume (bed carbon holdup) was predicted for these feedstocks using the gasification model, and these values were compared with measured values. A study on the analysis and prediction of PDU performance with midwestern coals was completed and the following conclusions are made:

- There was a decrease in specific gasification rate with an increase in temperature and steam/carbon ratio. These results indicate that there is no gasification rate advantage in operating the gasifier at temperatures higher than 1800°F with these feedstocks.
- The predicted bed volumes were in reasonable agreement with measured bed volumes for the three feedstocks.
- The reactivity of Indiana No. 7 coal, determined on the TGA, was close to the reactivity value used for the predictions. For Western Kentucky and Illinois coals, reactivities used for predictions were less than the reactivities determined on the TGA, indicating possible existence of a mass transfer effect (from bubble phase to particulate phase).

Work was initiated on the extension of the bed volume sizing model to western coals. Several correlations to estimate the mass transfer rate from the bubble phase to the particulate phase have been examined. Estimates of mass transfer rate will be made and compared with estimated chemical reaction rates and gasification rates measured in the PDU to determine the effect of the mass transfer rate on the overall reaction rate.

In support of PDU test TP-034-2, a procedure was developed for enhancement of the ash concentration in the withdrawal stream to maintain the ash percentage above 85 percent. This procedure included an evaluation of ash agglomeration, ash balance, and char/ash separation efficiency.

Variability of the ash withdrawal concentration during Set Point 1 was investigated, i.e., agglomeration was verified through microscopic examination of ash withdrawal samples. The ash balance was then reviewed with respect to variability in the coal feed and ash withdrawal rates and was found to be in balance within a reasonable tolerance. Particle size distribution of high-ash and low-ash content samples were compared. The low-ash content samples contained a much higher fraction of large particles (<12 mesh) than the high-ash samples. An increase in char/ash separator velocities resulted in fluidization of these large particles and more consistent ash withdrawal concentrations during Set Point 2.

4.10 FEEDSTOCK CHARACTERIZATION

The feedstock property tables were updated to add coal characteristics from recent PDU tests. These data are contained in Process Analysis Topical Report FE-19122-45.

SECTION 5.0

COLD FLOW SCALEUP FACILITY

5.1 GENERAL

Cold flow modelling has been employed since 1971 at the Westinghouse Research and Development Center to understand the critical hydrodynamic phenomena occurring in the KRW gasifier. These cold flow model studies, conducted in support of KRW fluidized-bed coal gasification process development, have contributed significantly to the successful design and operation of the PDU.

Since it is both time consuming and prohibitive in cost to construct a full-scale commercial reactor solely for generating desired data, a large-scale cold flow model, approaching the size of a commercial reactor, was considered a cost-effective means in the overall scaleup strategy. Effects of pressure and temperature, normally absent in cold flow model studies, can be obtained by analyzing and comparing the data from the PDU and a pilot-scale cold model; although they can also be deduced from data published in the literature.

To ensure successful scaleup; however, the fluid dynamic models and similarity criteria developed from small cold flow units to describe different critical phenomena have to be verified or modified using data obtained in a large-scale unit. Therefore, a large-scale, semicircular cold flow scaleup facility (CFSF) was constructed at the Waltz Mill Site near the PDU. The CFSF reactor is 10 feet (3-meters) in diameter and 30 feet high. This facility, an integral part of the scaleup strategy, is best described in Figure 5-1 which depicts the progression from exploratory studies through bench-scale and pilot-plant studies to eventual large-scale commercialization. The CFSF, schematically shown in Figure 5-2, has been operated since August 1980, and the test plans were designed to reduce the uncertainties of fluidized-bed behavior in a large-scale gasifier.

Results of cold flow model studies have been combined with (a) kinetic models, (b) rate equations generated from bench-scale hot models, and (c) data obtained from the pilot-scale PDU to construct a realistic mathematical model for predicting reactor performance. Some areas for substantial improvement in understanding gas and solids flow behavior for fluid dynamic scaleup design are:

- Large-scale design limitations. The largest single oxidant tube employable without an adverse effect on fluidized-bed performance can be evaluated. If multiple tubes are necessary, the jet interactions and operational stability can be studied and the optimal tube arrangement can be identified.

Figure 5-1. Structure of Gasifier Scaleup

Figure 5-2. CFSF Perspective

- Distribution of gases and solids in scaled-up plant equipment. Because of the scaled-up size of plant equipment, distribution of gases and solids can become a critical problem. These include the conical grid in the gasifier and the gas distributor for stripping gas in the char/ash separator. Stagnant regions are also more probable in a large unit if the gas distribution grids are not adequately designed. The CFSF offers unique opportunities for studying the operating conditions and design parameters to achieve optimal separation in large-scale equipment.
- Downcomer (dipleg) and pneumatic transport line design. Larger downcomer and pneumatic transport lines can be designed and tested to provide data and experience in transferring and circulating a large quantity of solids from cyclones or other feed systems.
- Startup, shutdown, and turndown operational modes. These are critical subjects to be studied in a large-scale plant. The CFSF, with the capability of continuously feeding and withdrawing bed material, fulfills this unique need.
- Assessment of maximum bubble size and propagation dynamics. Researchers disagree about whether a maximum bubble size exists in a fluidized bed. If the maximum bubble size exists, a big bubble will split into smaller ones in the fluidized bed so that none of the bubbles is greater than the maximum size. This maximum size may, in turn, dictate the number and size of the oxidant tubes feasible in a large-scale plant.

5.2 OBJECTIVES

The primary objectives of the cold flow scaleup test facility were to study the size effect (scaling) on critical phenomena in the KRW fluidized-bed gasifier and to verify the similarity criteria developed from small laboratory-scale cold flow units. Secondary objectives were established to use this test facility for evaluating and troubleshooting PDU problems and for operator training.

Specific objectives for the contract period were to operate the CFSF in the gasifier mode to evaluate operable geometries for the oxidant tube, ash withdrawal annulus, and other critical areas of the gasifier. Based on the operating cold flow data, unit process correlation models for critical sizing of parameters for gasifier configuration, pneumatic transport lines, and cyclone downcomer operations were studied.

5.3 FACILITY DESCRIPTION

The cold flow scaleup facility was designed for visibility, accessibility, and flexibility in changing into different fluidized-bed configurations.

- The test vessel comprises six identical semicircular sections and is 10 feet in diameter, with transparent Plexiglas plates at the front (flat side) and transparent windows at the back (circumferential side) to permit viewing inside the vessel during test operation. On the curved face, viewing is limited to individual circular windows, whose location and number are dependent on the expected fluidized-bed level.
- Bed depths up to 20 feet, superficial gas velocities up to 4.2 feet per second, and particle sizes up to 1/4-inch can be studied.
- Single or multiple (four or seven) oxidant feed tube designs can be tested.
- One or two solids feed streams can be provided through operating two solids feed hoppers and the model can be operated continuously with solids feed and withdrawal.
- Pneumatic transport lines up to 8 inches in diameter are provided.
- Continuous solid fines recycle into the reactor bed is provided through downcomer (dipleg) operation that is incorporated into the design.

A simplified process flow diagram of the CFSF is given in Figure 5-3. When the bed materials arrive on site, they are unloaded and transported into the storage hoppers, and they are pneumatically fed into the feed hoppers. In these feed hoppers, the solids are weighed and fed into the fluidized bed at controlled rates by means of rotary feeders.

Outlet gas from the vessel is treated in a cyclone. Solids collected in the cyclone flow down the dipleg and are recycled to the fluidized bed by either a radial or an axial feed line. Gas from the cyclone is vented into the baghouse.

Solids withdrawn from the bottom of the fluidized bed are recovered from a recovery cyclone and are directed to one of the three storage hoppers, to either one of the two feed hoppers, or to a waste bin. By feeding the discharge from the recovery cyclone to one of the feed hoppers, a continuous operation, with simultaneous solids feed into and withdrawal from the fluidized bed, can be performed at a steady state.

Figure 5-3. Simplified CFSF Flow Diagram

Bed material consists of -10+60 mesh crushed acrylic plastic particles with an average size of 1000 μm and a density of 68 lb/ft³. The shape and density of the crushed acrylic plastic particles used at CFSF are comparable to those of the PDU char particles. For char/ash simulation tests, acrylic is substituted for char and a special sand is used for ash.

Attached to the underside of the bottom viewing section is an ash-char drawoff cone with a feed tube assembly. The drawoff cone fixes the feed tube laterally within the model and allows vertical adjustment of the feed tube relative to the steam grid cone. Located internally, within the lower viewing sections, the simulated steam grid cone forms a conical annulus around the feed tube. The conical surface is perforated and is subdivided into several annular regions, a section of which may be supplied with pressurized air. Bed sample tubes, positioned within the test section, permit direct withdrawal of materials from the interior of the bed. Design of the vessel and auxiliary piping facilitates changes in the feed tube size and configuration, the drawoff cone configuration, and the steam grid cone configuration.

5.4 CFSF TEST OPERATIONS

The Phase I test series specified the modified deep-bed CFSF model configuration which permitted operating the fluidized bed of acrylic up to a height of 18 feet from the opening of the air tube. Prior CFSF testing was confined to a fluidized-bed height of 13 feet. Figure 5-4 is a schematic of the modified model which has a truncated ash annulus section, wherein the internal conical grid and air tube are lowered. The air tube assembly during Phase I testing comprised a 10-inch outer tube containing a 6-inch inner tube to convey solids. Phase I included test plans TP-M010-1, TP-M010-2, TP-M010-3, TP-M010-4, TP-M011, TP-M013, TP-M014, and TP-M015.

Phase II tests were conducted following the Phase I test series and system modifications to provide a deep-bed configuration with a 16-inch air tube. Phase II testing essentially replicated the tests in Phase I and included test plans TP-M016-1, TP-M016-2, TP-M017 and TP-M018.

A summary of each individual test follows.

5.4.1 CFSF Phase I Tests

5.4.1.1 TP-M010-1 Gas Bubble Dynamics

The operation of selected set points for TP-M010-1 was documented by taking motion pictures to obtain quantitative data on the jet penetration depth, bubble diameter, bubble velocity, bubble frequency and bubble coalescence. Motion pictures were taken at each view section of the model (approximately each 5 feet of bed height). Camera speed was set at 64 frames per second.

Figure 5-4. Configuration for Deep Bed without Annulus

The first two set points were run at a bed height of 13 feet above the jet nozzle. At this height, a direct comparison could be made to the data compiled and analyzed from test plan TP-M005-3 which was conducted in August 1982. Differences between the two sets of data were used to assess the effect of operating with a truncated ash annulus section.

Similarly, comparison of the remaining set points (3 through 18) from TP-M010-1 and corresponding set points from TP-M005-3 were used to assess the effect of operating the model with a deeper bed. Set Points 3 through 18 were run using a combination of four different air tube velocities (50, 100, 150 and 200 ft/sec) and four different solid loadings (0, 3000, 6000, and 9000 lb/hr).

The frame-by-frame analysis of motion pictures taken during this test has been completed and is reported in Typical Report FF-19122-46, "Cold Flow Scaleup Facility Experimental Results and Comparisons of Performance at Different Bed Configurations." In addition to the jet length, two estimates of bubble size were developed at two views, namely 1.5 feet to 5.5 feet and 6.0 feet to 13 feet--the elevations here are referenced from the jet opening. The frequencies of bubble formation and coalescence were also recorded.

A comparison of operating data and visual assessment of fluidization characteristics showed that the truncation of the ash annulus did not significantly affect the hydrodynamics of the jet and combustor region of the model. It must be emphasized that the gas flows in the ash annulus during this test were very similar to flow rates used in the previous shallow-bed configuration.

5.4.1.2 TP-M011 Carbon Dioxide Tracer Studies

Eight set points were conducted to measure the gas exchange between different regions of the bed while carbon dioxide (CO₂) was injected through one of two injection locations, the air tube or the grid. Two air tube velocities (100 and 200 ft/sec) and two solid loadings (0 and 6000 lb/hr) were investigated during TP-M011.

Instrumentation for obtaining data consisted of CO₂ probes, gas analyzers and fast-speed chart recorders, similar to that used in prior CO₂ tracer gas tests. Twelve instrumentation locations were used during each set point, with the CO₂ probe traversing across the cross-section of the CFSF reactor bed at each location to record the gas measurements. Eight of these locations are on the front wall as shown in Figure 5-4, and they run in a vertical path, starting directly above the jet nozzle and extending to a maximum height of 17 feet.

5.4.1.3 TP-M013 Solids Circulation Studies

The purpose of this test was to obtain semi-quantitative and qualitative information on solids circulation patterns existing in the fluidized bed and in particular around the jetting region.

Eight instrumentation locations were used for each set point with a probe being traversed across the cross-section of the bed in small incremental steps. Six of these locations were at the front of the model, in a vertical path, starting directly above the jet nozzle and extending to a maximum height of 12 feet. The remaining two locations were at the rear wall in a vertical path directly above the repositioned grid at a height of about 10 to 12 feet above the jet nozzle.

Six set points were completed varying air tube velocities and solids loadings. Two of the set points were conducted with a 13-foot bed height and the remaining were conducted with an 18-foot bed height. In parallel with this test, a calibration test was completed on the probe using a lift line. Readings obtained in the lift line at known gas and solids loadings were compared to actual readings from the fluidized bed during the test.

5.4.1.4 TP-M014 Gross Solids Movement Test

TP-M014 comprised a series of tracer material residence-time and distribution set points that were conducted with a slug tracer of coarse particles injected into the fluidized-bed through the coaxial feed tube. The test objective was to estimate the dispersion rate of the coarse particles in the fluidized bed (analogous to the mixing and decaking of fresh coal in the PDU gasifier) and to evaluate the sensitivity of thorough mixing to selected operating conditions. Approximately 500 pounds of solids, ranging in size from 0.25-inch to 0.13-inch (+6 mesh), were injected into the fluidized bed of -6 mesh particles. Four transient set points were conducted at varied conditions, and samples of bed material were extracted at 30-second intervals from five sampling locations during each set point to determine the mixing at each of these bed levels.

5.4.1.5 TP-M015 Fines Particle History

This test was similar in method to the previously-described coarse-particle tracer study (TP-M014). The difference was in the size of the particles injected coaxially into the fluidized bed; for this test, a slug of -100 mesh particles was injected. The weight of fines collected in the cyclone was monitored over a period of time, until the slug of fine tracer material was elutriated from the bed.

5.4.1.6 TP-M010-2, -3 and -4 Frequency Measurements

This test series on gas bubble dynamics was a continuation of TP-M010-1 and was conducted to investigate the effect of varying bed heights and gas velocities on bubble frequency. The technique used was different than the visual analysis of the high-speed motion pictures. A fast Fourier spectral analyzer was interfaced with a Nicolet digital oscilloscope recorder to process raw signals from sensing probes which were traversed across the cross-section of the fluidized bed. It was thus possible to obtain on-line measurements of frequency distribution and extract the characteristic major frequency of fluid-bed fluctuations. The major frequency of bed oscillations was measured at the same probe locations used in TP-M010-1, and this frequency was compared to the local bubble frequency measured visually from TP-M010-1 data. Three tests were completed using the Fourier analyzer techniques described below.

TP-M010-2 - A probe was held at the 7-foot elevation while the bed was operated at six different levels, ranging from 8 feet to 18 feet. At each bed level, the air tube velocity was varied incrementally from 50 to 200 feet per second. Further, each operating condition consisted of two sub-set-points, namely, one with 600 lb/hr solids loading and one without solids loading.

TP-M010-3 - A probe was held close to the air tube outlet, 2-foot elevation. At a constant air tube velocity and zero coaxial solids loading, major frequency readings were taken while varying the bed level at seven elevations within the range between 8 and 18 feet.

TP-M010-4 - With the bed height held constant at the 18-foot level, probe readings were taken at various locations within the bed. A set of readings was obtained for each of the four air tube velocities (50, 100, 150 and 200 ft/sec).

Preliminary observations derived from this series of tests were:

- Bubble frequency decreases with distance from the jet opening.
- The rate of decrease in frequency with change in bed height is high in the first seven feet from the jet; thereafter, the frequency decreases at a much reduced rate between 7 and 18 feet. This suggests very high bubble coalescence in the lower regions of the bed and the existence of fully-developed bubbles near the top of the bed.
- Frequency of porosity waves close to the jet opening varies with air tube velocities, whereas the frequency in the upper regions of the bed approaches the theoretical slugging frequency for the system.

5.4.2 CFSF Phase II Tests

5.4.2.1 TP-M016-1 Gas Bubble Dynamics

High-speed cameras were used during this gas-bubble dynamics test to obtain qualitative data on jet penetration and bubble properties, i.e., diameter, velocity, frequency, and coalescence. Eleven set points were completed and data were compiled on 77 rolls of motion picture film. Nominal operating data were also collected while operating at air tube velocities of 50 and 100 feet per second.

5.4.2.2 TP-M016-2 Gas Bubble Dynamics

This gas-bubble dynamics test was developed to measure the frequency of oscillations and bubble-rise velocities in the fluidized bed. Ten set points were completed and data were collected on-line through a dual channel spectrum analyzer to produce time and frequency traces for analysis. Nominal operating data were again collected while operating at air tube velocities of 50 and 100 feet per second.

5.4.2.3 TP-M017 Solids Circulation

TP-M017 was designed to traverse the model bed cross-section with sensing probes to (1) investigate jet-region and outer-boundary solids circulation characteristics and determine the bubble region and (2) quantify the changing of solids circulation rates. Six set points were completed, collecting approximately 900 Visicorder traces on-line. Nominal operating data were also gathered at air tube velocities of 50 and 100 feet per second. Probe deterioration was observed at high velocities in this deep-bed configuration.

5.4.2.4 TP-M018 Coarse Solids

This coarse-solids mixing test was developed to study movement of coarse particles (greater than +6 mesh) with a fluid bed to determine whether distribution extends throughout the bed or is concentrated near the solids injection point. Two set points were completed, and 500 samples were collected from five sample ports. Nominal operating data were collected at air tube velocities of 50 and 100 feet per second.

5.5 CFSF STATUS

At the conclusion of Phase II testing, the CFSF was shut down; however, before the shutdown procedures could be completed (water was not completely drained), an overnight drop to freezing temperatures caused damage to the CENTAC compressors, the chiller-dryer units, and the CO₂ heating system. The damaged equipment was rebuilt, and the cold flow scaleup facility is being maintained in a standby mode through biweekly inspections and a preventive maintenance program.

5.6 CFSF TOPICAL REPORT

By the end of the Phase II test program, a valuable data base had been accumulated on cold flow hydrodynamic modeling of the ash-agglomerating fluid-bed gasifier. Table 5-1 displays a matrix of this data base and identifies the areas (NONE) that need to be addressed in future testing.

All data from the Phase I and Phase II test programs are reported, along with comparisons and correlations to previous tests, in Topical Report FE-19122-46, Cold Flow Scaleup Facility Experimental Results and Comparison of Performance at Different Bed Configurations.

TABLE 5-1

MATRIX OF COLD FLOW MODELING HYDRODYNAMIC DATA

Critical Scaleup Phenomena	TEST FACILITY					
	12-Inch Dia. R&D Model	Shallow-Bed CFSF		Deep-Bed CFSF		CFSF Multi-Tube
		16-in. Tube	10-in. Tube	16-in. Tube	10-in. Tube	
Jet-Bubble Dynamics (Films)	1981-82	1982	1982	1983	1983	Future
Gas Fate In and Out of Jet (Pitot tube and CO ₂ Tracer)	1983	1981-82	1981-82	NONE	1983	Future
Solids Circulation Flux Around Jets (Solids Circulation Probe)	1983 Probe Devel.	NONE	1983	1983	1983	Future
Gross Solids Movement in Bed (Tracer Solids)	1983	NONE	NONE	1983	1983	Future
Fines Particle History (Tracer Solids)	1983	NONE	NONE	NONE	1983	Future
Dynamics of Particle Separation	NONE	1981	1983	NONE	NONE	

SECTION 6.0

PROCESS AND COMPONENT ENGINEERING AND DESIGN

Engineering activities during the report period were directed toward PDU modifications required for improved operation and environmental sampling. These are reported here in approximate chronological order.

6.1 CENTRIFUGAL RECYCLE GAS COMPRESSOR

The centrifugal recycle gas compressor was installed in the recycle gas system. Rated flow conditions are 204 pounds-per-minute at an inlet pressure of 223 psia and an outlet pressure of 300 psia. The operational performance of the unit to date, under PDU operating conditions, has been unacceptable. The unit reaches surge limits and experiences frequent stoppages; however, it has good restart capability which minimizes the upset conditions during a test.

To better assess surge flow limits, a gas-flow measurement loop was added to the system to measure the flow through the compressor. This gas-flow loop measures pressure, temperature and orifice differential pressure, and it uses an analog multiplier/divider to calculate the flow in absolute cubic feet per minute (acfm). The acfm-signal actuates a warning alarm in the PDU Control Room when the compressor flow is 5 percent above the surge limit. Operating procedures were revised, a flow check was conducted in phases, and a no-load test and pressure test were completed. Preliminary test results indicate that the off-design operating range of the compressor may be limiting and that different impellers may be required to meet the full operating range.

Operating time logged to date for this compressor totals 100 hours, and system operation during Set Point 1 of TP-034-2 was satisfactory. Post-test inspection of the compressor internals following this test period revealed no sign of wear on the rotating or mating components; however, operating time has not been long enough to realistically assess wear characteristics.

6.2 ENVIRONMENTAL MODIFICATIONS

Modifications for improved environmental sampling included a new sample train to obtain a slip-stream analysis of the product gas before it enters the first quench scrubber (C-111). Flow indicators were replaced by flow recorders to measure the water flow to the quench scrubbers, and a chute was fabricated and installed on the solids wastewater removal system to facilitate collecting samples in 55-gallon drums.

6.3 PRODUCT GAS FLOW METER

A Taylor Instrument segmented wedge-type flow-measuring element was installed and performance tested in the product gas line, downstream from the C-113 gas cooler. It consists of a wedge-shaped restriction within a pipe, and it features close-coupled seal-pressure connections for mounting a diaphragm-type differential-pressure measurement transmitter. This new flow element was positioned in series with, and in the same vicinity as, PDU product gas standard orifice-plate flow element FE-26. The Taylor element was installed to compare its operating performance to that of the standard orifice-type element in a wet solids-laden gas stream, with the intent to improve PDU system measurement accuracy and reduce operator maintenance during test operation. The standard orifice-type flow element has required frequent on-line blowdowns to dislodge plugs from the flange tops. The plugs were formed when water droplets escaping the cooler-scrubber mixed with the fine char particulates in the gas stream.

Performance test results were inconclusive, however, and further evaluation is required to gain a better understanding of the merits of the Taylor device. Information gained from this test follows.

- Response time of the wedge-type element was the same as the standard orifice-plate element and the data plots linearly followed each other.
- Flow measurements from the wedge-type element were 20-25 percent lower than those from the standard orifice-plate element. The standard element more closely matched the process heat and material balance data.
- The wedge-type element was more susceptible to material buildup in the wedge. This was exhibited by an intermittent plugging and self-unplugging characteristic which was diagnosed by the increasing slope of the differential-pressure measurement and the sharp declines when the plug cleared. Operationally, this is a disadvantage unless rod-out cleaning devices can be incorporated as part of the design.

6.4 METHANE INJECTION SYSTEM

Design engineering and procurement of a methane supply and injection system was completed for use in the December 1983 PDU mechanistic test. Varying amounts of methane were injected into the recycled product gas to study the mechanisms of methane formation in the gasifier.

A methane supply truck was placed adjacent to the deactivated propane supply tank, and piping was installed to the existing propane piping system. The propane piping system was upgraded, modified, and utilized to transport gas from the methane supply truck to the PDU. A new flow-control loop was designed and installed on the PDU to inject methane gas

into the gasifier in controlled doses. The methane injection system performed well during PDU test TP-035-2, and then it was dismantled.

6.5 DEPOSIT CONTROL COLD WALL

Two cold wall sections were installed at the exit of the PDU gasifier for control of ash deposition during the December test, feeding Pittsburgh No. 8 coal. A failure mode analysis was completed for each system component and the cooling-water flow system prior to placing them in service. In addition to the two sections of cold wall, an auxiliary water-injection spray was installed in the refractory-lined pipe immediately downstream of the second section. The water spray was installed to cool the exiting gas/fines stream to a temperature less than 1400°F.

6.6 GASIFIER REFRACTORY REPAIR

Following TP-035-3, the char/ash separator refractory was replaced. The previous lining showed excessive thermal spalling and cracking as a result of being in test operating service for two years.

6.7 ASH ROTARY FEEDER

Following TP-035-3, the ash rotary feeder, located beneath the gasifier, was replaced with a high-temperature stainless-steel feeder. The new feeder was originally procured in 1981 for a hot-fines recycle application, and it had to be modified to adapt to existing PDU gasifier piping.

6.8 COAL FEED LINES

The PDU feedline design consisted of flanged sections with ring-joint seals. Misalignment of the coupling flanges resulted in the solids feed being deflected to impinge on the feedline insert liners during test operation and caused plant shutdowns to repair the leaks in the feed lines. During the report period, the PDU coal feed lines were redesigned to incorporate castable elbows and self-aligning flange joints. The new design should improve alignment of the coupling joint between the feedline pipe elbow and the transport pipe which is constructed of 1-inch Schedule 40, Incoloy-825 material. The new feedline coupling is made by Grayloc, and it should provide better self-aligning capability and result in improved performance as well as ease of replacement during on-line testing, if required. Purchase orders were released and these couplings are scheduled to arrive at KRW in March 1985.

Until the redesigned couplings are available, all PDU feedline elbows will contain the standard carbon-steel liners to alleviate erosion and wear, except for the feedline elbow closest to the gasifier which will contain a ceramic liner.

6.9 PLANT COOLING WATER MODIFICATIONS

A thorough review of plant cooling-water requirements was completed, and an urgent need to upgrade the piping and pumps associated with this system was revealed. This is also true for the auxiliary system that provides cooling water to the cold-wall jackets. During the report period, procurement of piping material and two single-stage 50 horsepower centrifugal pumps was initiated. Electrical power requirements and Motor Control Center wiring revisions were also reviewed, and a design package was prepared. The upgraded system was installed as reported in Quarterly Progress Report FE-19122-41.

6.10 DATA ACQUISITION SYSTEM

Improvements were identified and evaluated for the PDU data acquisition system, and alternative solutions were developed. Priorities were established on the basis of: their importance to more reliable operation of the PDU, manpower effort required, capital equipment dollars available, and human engineering factors that would improve overall operation.

6.11 GASIFIER SAMPLING PROBES

6.11.1 Oxygen Probe and Drive System

A motor-driven drive assembly and mechanical supports were designed, fabricated and mounted on the PDU gasifier to support and guide insertion of an oxygen probe. Additionally, operating commodity lines and associated support control instrumentation were installed and connected to the main probe assembly. A stabilized zirconia electrolytic cell (oxygen probe) was procured from the Battelle Laboratories, Columbus, OH, and was installed into the above drive assembly. This probe was designed to measure differences in oxygen partial pressure within the gasifier and operate within temperatures ranging between 752 and 1742°F (400 and 950°C). The probe sensor consisted of a platinum-coated zirconia material and a Type K thermocouple. A more complete description is given in Quarterly Progress Report FE-19122-49.

6.11.2 Nonslagging Traversing Temperature Probe (NSTTP)

Two air-driven nonslagging traversing temperature probe assemblies were designed and installed on the PDU gasifier to measure the internal vessel temperatures during test operation. These devices are Type K thermocouples housed in water jackets to prevent deposition of sticky ash material on the probe body. The temperature sensing probe tip is separated from the water-cooled body by nonconducting ceramic spacers.

6.11.3 Nonslagging Traversing Gas Chromatograph Probe (NSTGC)

The nonslagging traversing gas chromatograph (NSTGC) probe was designed and is also installed on the PDU gasifier into a drive similar to that used for the NSTTP and oxygen probes. The NSTGC probe is housed in a water jacket to prevent ash deposition and is equipped with a porous-media filter to exclude char particles. The gas sample line maintains the gas above its dew point and conveys it to a gas chromatograph for measurement of the gas composition elements (CO, CO₂, H₂, CH₄, N₂, O₂, H₂O and H₂S).

6.11.4 Gasifier Deposit Probe

A gasifier deposit probe was designed and is being fabricated for installation into the gasifier vessel at the freeboard section. This probe will be used to determine (1) the critical surface temperature for deposit initiation and (2) the relationship between the critical temperature and the gasifier bed temperature for a given feedstock type. While the probe is several feet in length, only the front 6 inches will be inserted inside the gasifier and will be directly exposed to the hot gasifier products.

Most of the probe's length is protected by a water-cooled jacket which localizes the deposit formation to a small, controllable zone. Several thermocouples are arranged around the circumference of the probe in the exposed zone to record the surface temperature of the probe as a function of time and to detect the initiation of deposit formation. A nonslagging thermocouple is also positioned at the tip of the probe to measure the local gasifier freeboard temperature. A detailed description of this device appears in Quarterly Progress Report FE-19122-49.

6.12 FINES RECYCLE SYSTEM MODIFICATION

Presently, the bulk of the PDU recycled fines, namely those from the primary cyclone, are returned into the gasifier bed through a fluidized dipleg and a nonmechanical valve. Most of these recycled fines do not become back-mixed into the higher velocity combustion zone because of (1) the high gas velocity maintained in the gasifier bed and (2) the small size of the recycled particles. The recycled fines, therefore, are not exposed to the higher temperatures nor do they come in contact with oxygen at the jet inlet. Carbon must be consumed primarily by char gasification reactions, and there is little opportunity for the recycled fine ash to be consumed by agglomeration.

Modifications to the fines recycle system to allow a mechanistic study of the effect of primary fines reinjection location upon fines consumption were investigated and evaluated this report period. An option including two nonmechanical valves and a more-efficient primary cyclone design was selected, and detailed engineering was begun.

The selected configuration, using two cyclones, diplegs and nonmechanical valves will allow primary fines to be fed to a gasifier region where there is recirculation of solids down to the jet. It is suggested this will improve process performance. Furthermore, the primary cyclone can be idled deliberately to cause the nominal secondary cyclone and recycle system to act as the actual primary cyclone. This design allows studying the effect of injection location on fines consumption from various set points within a single test. These modifications are discussed in detail in FE-19122-49.

Until the proposed modifications are installed, various options for easing startup, operations, and upset recovery with the existing design were defined. As a result, the fines recycle system startup procedure was modified and the procedure was successfully implemented.

6.13 PDU HOT GAS CLEANUP

6.13.1 Conceptual Design

The potential benefit of removing sulfur from the hot gas stream of a coal gasification system has been recognized for optimizing a coal gasification combined cycle (CGCC) plant, in which the gas cleaning components represent 15 to 40 percent of the process capital cost (Stone & Webster 1977). Sulfur removal from medium- or low-Btu hot gas is required to meet environmental standards for sulfur emissions and also to meet the process requirements for economical turbine operation.

The U. S. Department of Energy's Morgantown Energy Technology Center (METC) has tested a variety of sorbents for sulfur removal, including iron oxides, zinc oxides and zinc ferrite (Grindley and Steinfeld 1983). In the METC testing, it was found that the iron oxide was suitable for removing large quantities of sulfur to a level between 200 and 400 ppm, while zinc oxide could reduce the sulfur level to a 10 ppm level. To combine these effects in one reactor vessel, two oxides are mixed in an equimolar ratio and called zinc ferrite. The zinc ferrite sorbent was tested in a 6-inch reactor to determine (1) its ability to remove hydrogen sulfide from coal product gas and (2) the sorbent regeneration with a steam-air mixture. The results of these tests were promising, and it was recommended that the zinc ferrite sorbent be tested in a larger unit for ultimate commercial plant application.

Stone & Webster Engineering Corporation, "Comparative Evaluation of High- and Low-Temperature Gas Cleaning for Coal Gasification Combined Cycle Power Systems," EPRI-AF-416, April 1977.

Grindley, T. and G. Steinfeld, "Zinc Ferrite Hydrogen Sulfide Sorbent," Third Annual Contaminant Control in Hot Gas Derived Gas Streams Contractors Meeting Proceedings, December 1983.

KRW performed a conceptual design of a zinc ferrite hot gas cleanup system to be installed in the Process Development Unit at Waltz Mill, PA. The design requirements were defined as removal of sulfur and solid particulates from the hot gas stream to meet environmental standards and turbine requirements. The objectives of the hot gas cleanup program are listed in Table 6-1. The design basis is nominally one ton-per-hour PDU product gas with oxygen-blown Eastern coal feed. Pittsburgh No. 8 coal, with an extensive PDU data base, was selected for the design coal. The design process requirements are given in Table 6-2.

The conceptual design for the PDU hot gas cleanup process includes a high-temperature cyclone, a zinc ferrite desulfurization unit, and a final stage particulate removal system. A typical process flow diagram is shown in Figure 6-1. Presently, the product gas from the gasifier flows through two cyclones, then into the quench scrubber, C-111. For the proposed cleanup system, a slipstream or full-flow from the second cyclone will be directed through a tertiary cyclone, C-140. Exit gas from the cyclone will then pass through the fixed-bed of zinc ferrite in the desulfurization unit and the final cleanup system, C-160. The projected operating conditions for the overall cleanup system are:

Temperature	1000 to 1200	°F
Pressure	230	psig
Flow Rate for Slipstream	2500 lb/hr	(34520 scfh)
Flow Rate for Full Stream	4000 lb/hr	(55231 scfh)
Space Velocity	200 to 800	hr ⁻¹
Face Velocity in Bag Filter	2 to 6	ft/min
Test Duration	200	hours

In this conceptual design study, seven cases were studied and were evaluated both technically and economically. The variables for the case study were gas flow rate and the type of particulate cleanup device. The PDU gas flow was taken as full or slipstream flow, and the devices considered were a ceramic bag filter and an electrostatic precipitator. The seven cases are:

- 1A Slipstream flow in desulfurization unit with a partial flow in a bag filter.
- 1B Slipstream flow in desulfurization unit with a partial flow in electrostatic precipitator (ESP).
- 2A Slipstream flow in desulfurization unit with a ceramic bag filter.
- 2B Slipstream flow in desulfurization unit with ESP.
- 3A Full stream flow in desulfurization unit/ceramic bag filter.
- 3B Full stream flow in desulfurization unit with ESP.
- 3C Full stream flow with two desulfurization units and a ceramic bag filter.

TABLE 6-1

OBJECTIVES OF PDU HOT GAS CLEANUP PROGRAM

SULFUR REMOVAL

- Evaluate effectiveness of sulfur removal in a large scale zinc ferrite bed using PDU generated gas.
- Determine the regeneration characteristics of the bed.
- Obtain process and operational data for commercial plant design.

PARTICULATE REMOVAL

- Reduce the particulate loading to keep the desulfurization unit operational.
- Reduce the level of particulate emission to meet the turbine operation standards and the New Source Performance Standards.

TABLE 6-2

OVERALL PROCESS REQUIREMENTS

SULFUR REMOVAL EFFICIENCY - 91%

Inlet Concentration	1.1% of H ₂ S and COS
Clean Gas Concentration	0.1% of H ₂ S and COS

PARTICULATE REMOVAL EFFICIENCY - 99.14 to 99.69%

Particulate Loading in Raw Gas	0.0074 to 0.0272 lb/lb gas
Particulate Loading in Clean Gas	63.0 to 84.0 ppm

Figure 6-1. Typical Process Flow Diagram for Hot Gas Cleanup

The main feature of the design is an adsorption process of a zinc ferrite fixed-bed reactor. The chemical reactions occurring in the bed are:

- Upon initial contact with CO and H₂ in the hot fuel gas, the zinc ferrite undergoes the reaction:

This reaction simplifies more complex chemistry that is involved with solid solutions of varying compositions.

- In the presence of H₂O and catalyzed by Fe₃O₄, COS will form H₂S as:

- Gas desulfurization occurs with both Fe₃O₄ and ZnO, namely,

These reactions are slightly exothermic and have very favorable equilibrium constants; therefore, the H₂S concentration in the exit gas stream will be affected by the concentrations of H₂O and H₂.

- The concentration of H₂O in the reaction zone is a direct function of the water-gas shift equilibrium:

- Iron oxides, particularly magnetite, Fe₃O₄, have strong catalytic effects on the shift reaction. Zinc ferrite is regenerated by oxidation of sulfides in the following reactions:

These are highly exothermic reactions. Thus, the bed temperature will be closely monitored so it does not exceed the maximum sorbent temperature of 1500°F in the regeneration cycle.

The technique of process instrumentation was adopted from PDU operating experience. Most of the PDU measurement techniques will be applied to evaluate the equipment and process performance. Table 6-3 summarizes the performance requirement and the proposed method of measurement. The on-line data acquisition system employs a PDP-11 dedicated computer.

TABLE 6-3
PERFORMANCE DATA REQUIREMENTS

Performance	Measurement Technique
Tertiary Particulate Removal System	
Temperature and Pressure	Thermocouple/Pressure Gauges
Gas Flow Rate	Orifice Plate
Gas Composition	Gas Chromatograph
Plugging	Differential Pressures
Particulate Removal Efficiency	Isokinetic Sampling
Particulate Characterization	Size Analysis, Bulk Density and Chemical Analyses
Desulfurization	
Bed Temperature Profile	Thermocouples
Pressure Drop of Bed	Pressure Gauges
Sulfur Removal Efficiency	Gas Chromatographs
Sulfur Breakthrough	Gas Chromatographs, Bed Samples
Bed Attrition	Isokinetic and Bed Samples
Regeneration Gas Flow Rate	Orifice Plate
Final Stage Removal System	
Temperature and Pressure	Thermocouple/Pressure Gauges
Gas Flow Rate	Orifice Plate
Particulate Removal Efficiency	Isokinetic Sampling
Durability of Bag Filter	Visual Inspection

To assist in the selection of which case, or cases, to recommend for the detail design, a cost comparison and technical evaluation were made for the seven cases named above. From these analyses, the following conclusions and/or recommendations were made:

- Case 3C, a full flow capacity and two desulfurization units, was selected as the proposed design configuration. This option provides a means to attain the ultimate goal of gas turbine testing integrated with the coal gasification hot gas cleaning capabilities. This case was also proposed as the commercial design configuration for the coal gasification combined cycle plant. The following modifications to the original Case 3C design were recommended, however, to reduce the high initial capital cost:
 - Defer one desulfurization unit. The concept of desulfurization using zinc ferrite sorbent can be proven with one reactor for exploring the process parameters.
 - Eliminate the cyclone/hopper system (C-140 and C-141). Particulate removal from the hot gas stream can be tested independently with the final stage removal system (C-160 and C-161) using ceramic bag filters. The PDU plan, under the mechanistic test program, is to modify the second cyclone and fines recycle system to improve efficiency.
- Since the design cases which use the electrostatic precipitator (ESP) result in higher costs and higher risks, eliminate the ESP for the primary design consideration.
- Define a test program with four PDU tests: one shakedown test, one or two exploratory tests, and one or two process evaluation tests.

6.13.2 Evaluation of Hot Gas Cleanup Technology

Hot gas cleanup technologies for particulate, sulfur, and alkali removal for a coal gasification combined cycle power (CGCC) plant have been identified and evaluated through research programs (Keairns, et al, 1984).

The bases for the hot gas cleanup technology evaluation are the KRW air-blown, single-stage, fluidized-bed gasifier and the Westinghouse 501 combustion turbine with a 2200°F inlet temperature. A reference plan hot gas cleanup system is presented that incorporates cyclones and a ceramic woven-bag filter for particulate control, a once-through fluidized-bed sulfur removal unit using naturally occurring dolomite, and a fixed bed of emathlite pellets for alkali removal.

Keairns, D.L., D.M. Bachovchin, D.F. Ciliberti, and N.H. Ulerich, "Hot Gas Cleaning Technology for Combined Cycle Power Plants," KRW Memorandum, June 1984.

The evaluation process for the various component technologies for development of a hot gas cleanup system for CGCC plants is summarized in Tables 6-4 through 6-6. The major components for this system include:

- A dual-stage cyclone system followed by a tertiary particulate removal device known as a ceramic woven-bag filter (constructed of zirconia silicate with an overseam of Nextel thread) for collection of particles finer than 5 micron.
- A once-through desulfurization system using naturally-occurring dolomites.
- A packed bed of emathlite pellets for removal of alkaline sulfates.

It is expected that any nitrogenous compounds not oxidized during coal combustion will eventually be decomposed and oxidized with the aid of the dolomite. Although dolomite is the recommended sulfur sorbent because of its abundance and low cost, zinc and iron oxides have also been proven effective as durable sulfur leaching reagents. The more expensive zinc oxides are recommended as gas polishers because of their potent cleaning capacity over a broad temperature and pressure range: 752 to 2372°F (400 to 1300°C) and 0 to 15 atmospheres, respectively. Iron III oxide (Fe_2O_3) is regenerable with steam and yields up to 30 mole percent of hydrogen sulfide for sulfur recovery regeneration. Both the iron and zinc oxides are promising, viable alternatives should the porous, attrition-resistant dolomite generate excessive fine dust in the desulfurization process.

TABLE 6-4
SUMMARY OF PARTICULATE REMOVAL SYSTEMS

TYPE OF DEVICE	POTENTIAL FOR MEETING SPECIFICATIONS		PROBABILITY OF SUCCESS FOR HOT GAS CLEANUP	DEVELOPMENT STATUS	DEVELOPER OR SUPPLIER	CAPABILITIES	ADVANTAGES	DISADVANTAGES
	TURBINE	NSPS						
I. INERTIAL DEVICES								
A. Cyclones								
1. Rotary Flow	Low	Low	Low	Commercial	Ten Jet & Aerodyne	All of these devices are suited for rough cleaning and recycle duty.	All are very good for removing particles >5 um.	None of these devices can reduce particulate concentration to comply with limits set by NSPS.
2. Electrostatic Enhanced	Moderate	Low	Low	Bench-Scale	General Electric			
3. Conventional High Efficiency	Low	Low	High	Commercial	Buell & Ducron			
4. Cyclocentrifuge	Moderate	Low	Low	Bench-Scale	Mechanical Technology Inc.			
B. Rotary Impaction Filters	Low	Low	Low	Bench-Scale	Westinghouse	All of these devices rely on centrifugal forces, gravity & inertia for particle separation/removal.	Not known.	None of these devices afford high collection efficiencies for the particles <5 um as required in tertiary cyclones.
C. High Velocity Wedge Separators	Moderate	Low	Low	Bench-scale & Sub Pilot	Linhardt Associates			
II. HIGH TEMPERATURE FILTERS								
A. Hot Electrostatic Precipitators*	Moderate	High	Moderate	Pilot Scale	Research Cottrell, Denver Research Inst. and Federal Republic of Germany	High collection efficiencies for particles <5 um.	Low pressure drop. Stable corona can be held at temperatures ranging from 1472 to 1652°F.	High power consumption. Since char particles tend to have low resistivity at elevated temperatures, these particles could be retained on the precipitator collect. electrode.
B. High Temperature Scrubbers								
1. Solid Dry Plate*	Moderate	Low	Low	Bench-Scale	Air Pollution Technology Inc.	Solids collecting media is in its counter-current flowing fluidized state via process gas flow.	Avoids problems encountered with handling molten glass.	Distributor plate plugs which may be due to re-entrainment of particles caused by motion of the solid collection media.
2. Molten Glass	Moderate	Low	Low	Bench-Scale (Abandoned)	General Electric	Not known.	Not known.	Difficult to control flow molten glass. Poor contact in collecting fines. Alkali species inherent in glass saturated product gas.
* DOE Sponsored								

TABLE 6-4 (Continued)

TYPE OF DEVICE	POTENTIAL FOR MEETING SPECIFICATIONS		PROBABILITY OF SUCCESS FOR HOT GAS CLEANUP	DEVELOPMENT STATUS	DEVELOPER OR SUPPLIER	CAPABILITIES	ADVANTAGES	DISADVANTAGES
	TURBINE	NSPS						
II. HIGH TEMPERATURE FILTERS								
C. High Temperature Filtration								
1. Granular Bed Filters	Not known	Not known	Not known	Not known	Not known	Not known	Not known	Not known
1a. Static Filter Bed*	Moderate	Moderate	Low	Pilot Scale	Westinghouse with Ducon	Capable of high collection efficiencies.	Not known	Difficult to control backflush cleaning. Mechanical problems with blowback distributor.
1b. Moving Bed	Moderate	Moderate	Moderate	Semi-coal burning pilot scale at high temperature.	Combustion Power Inc.	Collection efficiencies range from 98 to 99% after 1000 hours of cumulative operation.	Not known	System requires large, pressurized embodiment. Needs complex solids handling system. Too many operating difficulties. Expensive.
2. Rigid Porous Filters**								
2a. Sintered Metal Filters***	High	High	Moderate	Commercial (Tests run at 1500°F and 165 psia)	Westinghouse and Pall	Absolute filtration efficiencies.	Not known	Not recommended for hot gas cleanup application because element became embrittled from exposure to high operating temps. Does not tolerate exposure to reducing gas atmosphere--causes intergranular corrosion.
2b. Porous Ceramic Candle Filter***	Very high	Very high	High	Commercial	Westinghouse-Schumacher	Not known	Can be used in high temperature applications.	Significant decrease in permeability that levels off to a steady state. Can only be manufactured in short modules (1 to 1-1/2 meters) in length which makes commercial scale-up for hot gas cleanup difficult. Expensive (\$300.00/ft ²).
2c. Ceramic Cross Flow Filter*	Very high	Very high	Moderate	Bench-Scale (Still have to operate w/multiple elements.)	Westinghouse, Coors, and GE	Corrugated geometrical design of the filter membrane affords absolute filtration.	Compact design permits easy enclosure in a pressurized vessel. Can be easily cleaned by pulsating jet.	System tends to delaminate at bonded joint. This problem may be corrected with glazing bonds.
3. Ceramic Bag Filter**								
3a. Felted Bag Filter**	Very high	Very high	Moderate	Pilot Scale	Westinghouse with Acurex	Near absolute filtration.	Not known	Difficult to clean using pulsating jet. History of bag failure in pilot plant tests.
3b. Woven Ceramic Bag Filter**	High	High	High	Acurex tests continue at 800°F and atmospheric pressure. Westinghouse tests done at 165 psia and temps. of 1500 to 1600°F.	Westinghouse, Acurex, 3M, Buell and Envirotech	Filtration efficiency of 99.9% attained on PFBC ash.	High filtration efficiency. Low pressure drop operating at conventional velocity. Filters can be easily cleaned by pulsating jet.	One incidence of bag failure occurred in early tests. A seam rupture was corrected using Nextel thread in lieu of J.P. Stevens astroquartz thread. NOTE: 3M is developing a seamless bag; not tested yet.

NOTES: * DOE Sponsored
 ** DOE and EPR: Sponsored
 *** EPR: Sponsored Only

TABLE 6-5
SUMMARY OF SULFUR REMOVAL SYSTEMS

	CALCIUM-BASED SORBENTS (Includes limestone, CaCO_3 , and dolomite, $\text{CaCO}_3 + \text{MgO}^3$)	IRON-BASED SORBENTS (Includes Iron Oxides FeO and Fe_2O_3)	ZINC-BASED SORBENTS (Includes Zinc Oxide, ZnO , and Zinc Ferrite, $\text{Zn}(\text{FeO}_2)_2$)
PHYSICAL PROPERTIES	<ul style="list-style-type: none"> • Porosity varies from 1-18% • Attrition fair • Kinetics adequate 	<ul style="list-style-type: none"> • More durable than calcium sorbents with respect to attrition and reaction kinetics. 	<ul style="list-style-type: none"> • Slowest desulfurization kinetics of the three sorbents. • Attrition durable.
CHEMICAL CAPABILITIES AND STABILITY	<ul style="list-style-type: none"> • Limestone is a poor sulfur sorbent unless in calcined state CaO. • Dolomite is an adequate sulfur sorbent in either its calcined or uncalcined state. 	<ul style="list-style-type: none"> • FeO is stable in reducing atmospheres. • Fe_2O_3 is stable in oxidizing atmosphere. • Tests show that iron carbonates tend to be unstable. 	<ul style="list-style-type: none"> • Very potent in scrubbing sulfur from gases. • Zinc ferrite decomposes into zinc oxide.
THERMODYNAMICS AND DESULFURIZATION	<ul style="list-style-type: none"> • Desulfurization can be achieved to levels <100 ppm up to 1300°C. • Sulfation reaction for limestone: $\text{CaCO}_3 + \text{H}_2\text{S} \rightarrow \text{CaS} + \text{CO}_2 + \text{H}_2\text{O}$ • Sulfation reaction for dolomite: $\text{CaCO}_3 + \text{MgO} + \text{H}_2\text{S} \rightarrow \text{CaS} + \text{CO}_2 + \text{H}_2\text{O}$ 	<ul style="list-style-type: none"> • Restricted more by thermodynamics than by calcium sorbents. • FeO can achieve desulfurization levels of 100 ppm between 200°C and 343°C. • Fe_2O_3 can only achieve desulfurization levels of 1000 ppm & does not comply with NSPS acceptable limits. • Sulfation reaction for Fe_2O_3: $\text{Fe}_2\text{O}_3 + 2\text{H}_2\text{S} \rightarrow 2\text{FeS} + 2\text{H}_2\text{O}$ 	<ul style="list-style-type: none"> • Zinc oxide can effectively desulfurize the gas to levels of 100 ppm up to 1300°C. • Desulfurization of <1 ppm can be achieved using zinc-based sorbents at a moderate temperature of 650°C.
REGENERATION	<ul style="list-style-type: none"> • Both calcium sorbents are only partially regenerable using CO_2 and steam: $\text{CaS} + \text{H}_2\text{O} + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{S}$ • Regeneration is carried out at 1 atm at >975°C or at 15 atm at >1150°C. • If temperature is maintained below 700°C at 15 atm, regeneration can yield a maximum of 3 mole percent sulfur. 	<ul style="list-style-type: none"> • Regeneration of iron oxide sorbents can be done in two ways: with steam or by sulfide oxidation over a broad temperature range of 400 to 1300°C at high or low pressures. Reaction is exothermic. • Steam regeneration: $2\text{FeS} + 2\text{H}_2\text{O} \rightarrow \text{Fe}_2\text{O}_3 + 2\text{H}_2\text{S}$ • Sulfide oxidation: $4\text{FeS} + 7\text{O}_2 \rightarrow 2\text{Fe}_2\text{O}_3 + 4\text{SO}_2$ • Only Fe_2O_3 can be regenerated by steam at temperatures >500°C; this regeneration can yield a maximum of 30 mole percent H_2S. • Iron oxides are regenerable over multiple cycles. 	<ul style="list-style-type: none"> • Can easily be regenerated by oxidation over a broad range of pressure (1 to 15 atm) and temperature (400 to 1300°C) while simultaneously producing a tail gas with >10 mole percent SO_2. • Regeneration reaction for ZnO: $\text{ZnS} + 1.5(\text{O}_2) \rightarrow \text{ZnO} + \text{SO}_2$ • In testing, regeneration of zinc ferrite was maintained over three cycles using a 1:1 ratio of steam and air.
RECOMMENDATIONS	<ul style="list-style-type: none"> • Since attrition rate is fair and material is abundant and not expensive at \$8/Ton, dolomite is the best choice for once-through fluidized-bed sulfur removal systems. • Because their regenerative capabilities are severely limited, calcium-based sorbents are not good candidates for regenerative sulfur removal processes because neither sorbent can be regenerated over multiple cycles due to its porosity and fair resistance to attrition. 	<ul style="list-style-type: none"> • Because of versatile and durable regenerative capabilities displayed by iron oxides in bench scale testing, they are recommended for further development and use in pilot-scale fluidized-bed processes. • Because the regeneration process is very exothermic, the fluidized-bed dynamics can better control potential temperature spikes better than fixed or entrained beds. By controlling the temperature, sintering of the sorbent with subsequent deactivation of the sorbent is avoided by the fluidizing action. • Although some attrition was noted in coke oven gas cleaning testing at Appleby-Frodingham, sulfur removal and regeneration was successful with iron oxide sorbents. • U.S. Bureau of Mines found that by mixing iron oxide sorbents with fly ash, the temperature of the process can be controlled within a fixed-bed, while successfully removing sulfur from the hot product gas and simultaneously regenerating the sorbent. 	<ul style="list-style-type: none"> • Researchers recommend that zinc-based sorbents be used as gas polishers because these regenerable sorbents can effectively scrub hot product gas to high efficiencies at high temperatures removing not only H_2S, but also greatly reducing the potential for formation of sulfated alkaline salts which further prevents corrosion of turbine hardware. • The only drawback to implementing zinc-based sorbents in desulfurization processes is the cost: \$120 to \$150/ft³ of material. If the regenerable hybrid sorbent, zinc ferrite, is used, scrubbing efficiencies are maintained at a reduced cost.

TABLE 6-6
SUMMARY OF ALKALI REMOVAL SYSTEMS

	BAUXITE	EMATHLITE (FULLER'S EARTH)	DIATOMACEOUS EARTH
PHYSICAL PROPERTIES	<ul style="list-style-type: none"> • Ore of aluminum • Nontoxic • Noncombustible • Large surface area 	<ul style="list-style-type: none"> • Porous, colloidal aluminum silicate • Sticky; clay-like • Nontoxic • Noncombustible 	<ul style="list-style-type: none"> • Soft material made up mainly of silica. Composed of skeletons from prehistoric, aquatic algae-like plants (diatoms).
SORPTION CAPACITY	<ul style="list-style-type: none"> • Weak, non-dissociative chemisorption at 1.1 gms Na/100 gms bauxite. • Sorption capacity increases with high gas concentrations. • Performs best between 315-900°C. 	<ul style="list-style-type: none"> • High sorption capacity • Sodium and water vapor combine to form a molten glass phase around the getter particle making it sticky. • Reaction rate lower than for bauxite 	<ul style="list-style-type: none"> • Higher sorption capacity than for bauxite. • Reaction rate slows as diffusion-limiting product layer grows inward.
IRREVERSIBILITY OF SORPTION REACTION	<ul style="list-style-type: none"> • Partially reversible by exposure to hot, salt-free gas. 	<ul style="list-style-type: none"> • Irreversible; sodium will not be released if getter is exposed to low-salt gas. 	<ul style="list-style-type: none"> • irreversible
KINETICS	<ul style="list-style-type: none"> • Affected by film and pore diffusion limitations. 		
COST	<ul style="list-style-type: none"> • \$0.50/Kg 	<ul style="list-style-type: none"> • Inexpensive at \$0.10/Kg 	<ul style="list-style-type: none"> • Less costly than bauxite but more than emathlite.
REQUIREMENTS FOR CLEANING	<ul style="list-style-type: none"> • Can be cleaned via water leaching. 		
PLUGGING POTENTIAL	<ul style="list-style-type: none"> • Possible 	<ul style="list-style-type: none"> • Probable from molten glass phase and dust trapping 	<ul style="list-style-type: none"> • Not likely; is not sticky
DEFLUIDIZATION POTENTIAL	<ul style="list-style-type: none"> • Possible 	<ul style="list-style-type: none"> • Probable 	<ul style="list-style-type: none"> • Not likely
OTHER LIMITATIONS	<ul style="list-style-type: none"> • Possible release of alkali, along with loss of pressure and generation of dust in a fluidized bed. 	<ul style="list-style-type: none"> • The sticky molten glass phase and its clay-like characteristics make it unlikely that emathlite will fluidize. It would tend to cause plugging in either a fluidized bed or in a GBF scheme during blowback of the stationary filter or while in motion in a moving bed. 	
ADVANTAGES		<ul style="list-style-type: none"> • Low getter consumption & efficient cleaning 	
RECOMMENDED FOR USE IN PACKED BED	<ul style="list-style-type: none"> • Not especially 	<ul style="list-style-type: none"> • Yes-molten phase no problem in a packed bed. 	<ul style="list-style-type: none"> • Perhaps (if emathlite fails)
RECOMMENDED FOR USE IN FLUIDIZED BED	<ul style="list-style-type: none"> • Not at all 	<ul style="list-style-type: none"> • Not at all 	<ul style="list-style-type: none"> • Perhaps (if emathlite fails)
RECOMMENDED FOR USE IN ENTRAINED BED	<ul style="list-style-type: none"> • Yes by General Electric 	<ul style="list-style-type: none"> • Not at all 	<ul style="list-style-type: none"> • Perhaps
RECOMMENDED FOR INTEGRATION WITH GBF*	<ul style="list-style-type: none"> • Yes in both stationary and moving beds. 	<ul style="list-style-type: none"> • Not at all 	<ul style="list-style-type: none"> • Yes in Moving GBF system

*Granular Bed Filters

SECTION 7.0

LABORATORY SUPPORT STUDIES

7.1 INTRODUCTION

Coal gasification support studies represent a continuing effort to extend an understanding of gasification phenomena and to provide the information necessary to complement integrated plant tests, permitting a basis for gasifier design and scaleup. Studies were conducted at the Westinghouse Research and Development Center in support of process development unit (PDU) operations, systems analysis, and scaleup. Specific areas for study were selected based on the need to investigate proposed design or operating parameter modifications for the PDU, to interpret plant data, to model gasifier performance, and to develop criteria for scaleup. Work performed this period was in the areas of:

- Gas-Solids Flow Phenomena
- Coal Behavior
- Ash Agglomeration
- Deposit Control
- PDU Operations Analysis

7.2 GAS-SOLIDS FLOW PHENOMENA

Gas and solids behavior, associated with the two-phase jet that introduces oxidant and fuel into the KRW gasifier, are of particular interest. An understanding of jet phenomena is required to model agglomeration and reaction processes within the gasifier. Experimental and analytical modeling was conducted to investigate jet interaction, the effect of elevated temperatures on fluidization velocity, and mixing and residence times of fines in a fluidized bed.

The jet interaction studies were experimentally investigated using a 12-inch diameter semicircular Plexiglas cold flow model at the Westinghouse Research and Development Center. A 6-inch diameter high-temperature quartz testing unit was installed to measure the minimum fluidization velocity of sand particles at different bed temperatures.

The history of coal particles, or fines, entering the gasifier is also important in order to understand where specific reaction processes (e.g., devolatilization, char combustion, gasification) occur. Tests were performed in a modified 12-inch diameter cold flow model using tracer particles to determine mixing characteristics and residence times of the coal feed. High-temperature effects on different bed materials represent the other area of study.

7.2.1 Jet Phenomena

The objective of this task was to study the structure of jets (i.e., jet penetration length, jet half-angle) in a fluidized bed for different jetting regimes and to characterize the associated entrainment of gas and adjacent solids into the jets as a function of flow variables, such as jet injection velocity and fluidizing properties of the main bed material.

Preliminary results from the high-temperature, minimum fluidization experiments for 20 to 30 mesh Ottawa sand obtained at ambient conditions and at 500°F and 900°F were analyzed. The data showed the expected trend, i.e., the minimum fluidization velocity decreased with increasing bed temperature. A detailed account of these experiments is reported in Quarterly Progress Report FE-19122-28.

7.2.2 Fine Particle History

The objective of this task was to study the mixing and residence time of fines injected either concentrically or radially into the gasifier as a function of reactor flow field characteristics. Such knowledge is essential for the design of fines recapturing and recirculation systems that accompany an operating fluidized-bed reactor and will enable prediction of fines consumption and reactor performance through identification and proper scale-up.

The approach, reported in FE-19122-28, involved the construction and assembly of an air-humidity control and monitoring system for the 12-inch diameter cold flow model. Early shakedown tests for the fine particle history program indicated unsatisfactory mass balances for fines injected into the bed. In addition, most of the earlier tests were performed at a relative humidity, near 60 percent. At this humidity, droplets of condensed water were found in the flow meters as well as around the jet nozzle inside the bed due to inefficiency in humidification. Four tests were designed to investigate the whereabouts of the fine particles and the effect of humidification. The tests were performed at the highest relative humidity, about 45 percent in this case, at which the flow meters showed no evidence of condensed water droplets. Results are reported in FE-19122-28.

Earlier shakedown tests for the fine-particle history program indicated unsatisfactory mass balances for fines injected into the bed. After the installation of a bag filter and modification of the cyclone dipleg, the fines injection for each test was increased from 50 g to 200 g to reduce the experimental error. The fine-particle material balance was then satisfactory for all test runs. In most cases, the fine-particle material balance could be closed to within 3 percent. Details are reported in Quarterly Progress Report FE-19122-41.

7.2.3 Solids Circulation

Data on coal particle history from the semicircular laboratory unit were analyzed to determine solid circulation rates. Experimentally-measured profiles of tracer particle concentration inside the fluidized bed were employed to calculate rates of bed-solid circulation induced by the presence of a central jet and by slug motion. Lagrangian minimization and direct pattern search techniques were used to determine the solids transfer rates which would minimize the error in the tracer particle mass balance while satisfying the bed solid mass balance. Time averaged steady-state mixing of bed solids and upstream weighting of tracer concentrations were employed in the formulation of the minimization scheme.

Quantitative information on solid circulation for three nominal jet velocities of 52, 37, and 25 m/s was presented in Appendix A of Quarterly Progress Report FE-19122-37. The increase in the computed solid circulation rates with increasing jet injection velocity agreed with prior observations of improved solids mixing with increasing jet injection velocity. The computed solid circulation rates show that there is a region of high solid circulation around the jet and a region of lower solid circulation induced by the slug motion. Moreover, the results indicated that with an increase in jet injection velocity and a corresponding higher superficial gas velocity, the role of slugging in enhancing bed-solid circulation becomes more prominent.

7.2.4 Char/Ash Separation

The objective of this task was to determine the effect of different particle characteristics on the rate and effectiveness of particle separation. An added objective this year was to evaluate the efficiency of particle separation in the PDU.

Material withdrawn from the gasifier char/ash separator during PDU test TP-032-2 was fluidized in a laboratory 2.75-inch diameter fluidized bed model. The fluidizing velocity was decreased in small increments and was maintained for several minutes at each incremental step to allow the particles to separate in the bed. This procedure was followed until the whole bed was inactive. The bed material was then vacuumed from the reactor, layer by layer. Each layer was about 0.5-inch of bed height. Each layer of bed material was ground to 60 mesh, and the ash content of the material was determined. Results of these tests were reported in Quarterly Progress Report FE-19122-28.

Gasifier bed material and withdrawal material from the char/ash separator, collected during TP-033-1 using North Dakota lignite, were screened into different particle size fractions, and their respective bulk density and ash concentration were measured. Preliminary observation indicated a substantial overlap in the particle-size distribution between the bed material and the ash withdrawal material, although the particles in the ash withdrawal material were generally larger. Details of these analyses are reported in FE-19122-37.

Solid samples from ten steady-states from four PDU tests conducted in 1983 were analyzed to explain the char/ash separation mechanism and the ash-agglomeration and sintering mechanisms. The feedstock used in these tests were Wyoming subbituminous coal, Pittsburgh bituminous coal, and North Dakota lignite. Three separate samples from each steady-state were analyzed: a bed sample, a sample withdrawn from the char/ash separator at the corresponding time, and a sample withdrawn from the char/ash separator taking into account the material holdup time in the separator. Each sample was sieved into eleven different size fractions (+4, -4+6, -6+8, -8+10, -10+12, -12+16, -16+20, -20+40, -40+70, -70+100, and -100 mesh), and the respective bulk density and ash concentration values were calculated.

Bulk density was determined by pouring a weighted sample into a graduated cylinder prior to additional vibration and obtaining its weight and occupied volume. The ash concentration of each sample was determined by first grinding a 0.5 g portion of the sample to -60 mesh, then placing this portion into a glazed porcelain boat and inserting it into an air-blown (3 l/min) tube furnace for 20 minutes at 1922°F (1050°C). When the sample was removed from the furnace, it was placed into a desiccator to cool and be weighed. The remaining weight was assumed to be 100 percent ash. Dividing the remaining weight by the original sample weight gave the ash concentration of the sample. Detailed results of the analyses were reported in Quarterly Progress Report FE-19122-41.

7.3 COAL/ASH BEHAVIOR

The objective of this task was to develop an understanding of the critical factors that determine gasification kinetics and ash agglomeration and to characterize coals for reactivity and ash-sintering characteristics in support of PDU operation.

7.3.1 Coal Gasification

The effect of maximum heat treatment temperature (HTT) and the holding time at maximum HTT on char reactivity was studied using Wyoming Sub-C coal. Chars were prepared separately at temperatures of 2012, 2192, and 2372°F in a gas mixture containing 7 percent hydrogen and 93 percent nitrogen in a high-temperature furnace. The holding time was about one second. A char sample was also prepared at the median temperature (2192°F) at a furnace holding time of ten seconds to study the effect of holding time.

These chars were also characterized for reactivity at standard conditions. A char sample was prepared at 1800°F on the thermogravimetric analyzer (TGA) in a gas mixture identical to that above. These tests were performed at higher HTTs than those used in earlier tests; at temperatures perceived more likely in a commercial gasifier. Test results were reported in FE-19122-28.

In an effort to characterize the effect of temperature on the reactivity of Ohio No. 9 coal, laboratory tests were performed at 1850°F and 1800°F, and average reactivities of 22.3 and 19.0 were obtained, respectively. These results compared well with a reactivity of 22.5 at 1800°F obtained for Ohio No. 9 char from the PDU gasifier. Illinois No. 6 coal and Texas and North Dakota lignites were studied to characterize midwestern and western coals for reactivity in a carbon-dioxide atmosphere. Laboratory tests were performed in a mixture of nitrogen (N₂), hydrogen (H₂), and carbon monoxide (CO), and the test material was gasified in a mixture of CO, CO₂ and N₂, where the ratio of flow rates of CO to CO₂ was unity.

For Illinois No. 6 coal, average reaction rates of $0.61 \times 10^{-2} \text{ min}^{-1}$ and $0.76 \times 10^{-2} \text{ min}^{-1}$ were obtained in two tests. The average reaction rate of Illinois No. 6 char (prepared on the TGA) in a H₂O-H₂-N₂ atmosphere, where $p_{\text{H}_2}/p_{\text{H}_2\text{O}} = 0.5$, was $4.9 \times 10^{-2} \text{ min}^{-1}$. Thus, the contribution of the C-CO₂ reaction for the gasification of Illinois No. 6 coal can be expected to be much smaller than the C-H₂O reaction.

Reactivity rates of Texas and North Dakota lignites in a carbon dioxide atmosphere at the above conditions were determined to be $39.3 \times 10^{-2} \text{ min}^{-1}$ and $50.0 \times 10^{-2} \text{ min}^{-1}$, respectively. The reactivities of these two lignites in a CO₂ atmosphere were comparable to those obtained in a steam atmosphere.

The report on the effect of char time and temperature history parameters on char reactivity was updated to include (1) the effect of pressure of char preparation, (2) the effect of holding time at maximum heat treatment temperature, (3) and higher heat treatment temperatures than those previously studied. Results of this work are presented in Appendix B of FE-19122-37.

Char fines collected in the PDU primary cyclone with Wyoming Sub-C coal feedstock (TP-034-1, SS1A) were characterized. Average relative reactivities of 149, 146, 184 and 130 were obtained in various tests giving an average value of 152. This compares very well with a reactivity of 136 obtained for Wyoming Sub-C coal (-1+0.25 mm, TP-033-2). Based on these results, it is concluded that the true kinetic rate of fines is essentially the same as that for the larger size distribution in the case of Wyoming Sub-C coal. Details were reported in Quarterly Progress Report FE-19122-38.

7.3.2 Ash Behavior

The sintering behavior of coal ash particles was studied on a hot-stage microscope facility. Ash particles were prepared by combustion at 1000°F (538°C). Coals from eastern, midwestern and western regions of the United States that were processed in the Process Development Unit (PDU) were studied. The sintering behavior of coal ashes were characterized by an initial sintering temperature that corresponds to the temperature at which the particles begin to shrink. Details are given in FE-19122-38.

APPENDIX A

GASIFIER HEAT AND MATERIAL BALANCES - TP-035-3

TABLE A-1

SUMMARY OF OPERATING DATA FOR MODIFIED GASIFIER TEST TP-035-3

Test Run Date and Time	Unit	Hours	Hours	Hours	Hours	Hours	Hours	Hours	Hours	
		6/10/84 0030-0945	6/10/84 0945-1530	6/11/84 0400-1030	6/17/84 1615-2115	6/18/84 1030-2000	6/18-19/84 2200-0230	6/19/84 1300-2230	6/20/84 0630-1230	6/20/84 1230-1930
		1A	1B	2A	2A-1	3A	3B	4A	4A-1	4A-2
Measured Gasifier Parameters										
Freeboard temperature	°F	1921	1917	1909	1850	1843	1845	1807	1784	1800
Gasifier bed temperature	°F	1929	1927	1926	1785	1768	1783	1749	1807	1836
Ash annulus temperature	°F	357	357	434	456	451	426	424	434	438
Average bed height**	feet	12.54	12.80	12.51	12.13	14.67	12.38	12.30	12.24	12.37
System pressure	psig	100	100	160	160	229	230	230	230	230
Average gasifier bed density	lb/ft ³	15.84	15.27	14.11	13.16	13.71	13.66	14.21	14.24	14.21
Average annulus density	lb/ft ³	24.22	24.66	21.97	22.00	20.93	20.99	16.60	16.39	16.36
Freeboard gas velocity	fps	1.89	1.86	1.60	1.38	1.12	1.13	1.05	1.17	1.25
Oxidant tube velocity	fps	180.11	176.19	138.23	120.61	99.93	99.13	89.59	99.81	105.21
Oxygen concentration	%	67.75	67.68	70.58	64.58	65.26	66.65	71.38	70.26	71.80
Coal feed material		PGH No. 8	PGH No. 8	PGH No. 8	PGH No. 8	PGH No. 8	PGH No. 8	W. VA.	W. VA.	W. VA.
Coal feed rate	lb/hr	1307	1313	1505	1089	1216	1261	1112	1236	1315
Carryover to water system*	lb/hr	184	195*	148	115	91	112	104	105	165
Ash withdrawal rate	lb/hr	86.5	88.6	166	82	105	85	64	48	48
Product Gas Analysis, Dry Basis										
Carbon monoxide	%	48.62	46.87	44.73	48.49	40.69	43.84	43.79	42.27	45.54
Carbon dioxide	%	24.22	24.51	25.65	30.28	35.30	31.82	33.00	32.89	28.36
Methane	%	1.90	1.83	1.72	1.75	1.53	1.62	1.62	1.72	1.56
Nitrogen	%	0.47	0.66	0.47	0.58	1.88	1.15	1.41	1.08	1.51
Sulfur	%	1.41	1.39	1.46	1.15	0.93	1.23	0.72	0.87	0.83
Hydrogen	%	23.38	24.75	22.96	17.74	19.67	20.34	19.46	21.19	22.19
HHV, dry basis (gas chromatograph) Btu/scf		251	249	244	230	209	223	220	221	233
Overall Process Rates										
Carbon mass velocity*	lb/hr-ft ²	355.2	356.8	404.5	294.1	326.5	365.1	321.3	354.7	377.4
Gas make/coal	scf/lb	37.81	37.75	39.91	40.22	37.11	34.87	35.95	36.91	38.87
Steam/coal ratio, MAF**	lb/lb	0.32	0.32	0.31	0.42	0.42	0.38	0.37	0.36	0.34
Oxygen/coal ratio, MAF	lb/lb	0.93	0.91	0.94	1.00	1.03	0.97	1.06	1.05	1.07
Total moisture/coal ratio, MAF	lb/lb	0.34	0.33	0.33	0.43	0.43	0.39	0.39	0.38	0.36
Recycle gas/coal ratio, MAF	lb/lb	1.25	1.18	1.37	2.28	2.51	2.33	2.59	2.59	2.39
Solids Analysis										
Ash content - fines	%	22.97	19.34	22.49	23.16	23.64	22.24	12.36	--	10.90
Ash content - feedstock	%	9.48	9.48	9.73	8.56	8.83	5.03	4.88	5.01	5.01
Ash content - bed	%	35.10	35.73	34.28	35.20	28.16	26.34	19.65	22.56	23.73
Ash content - agglomerate	%	85.42	85.42	86.71	83.63	92.16	85.47	87.05	87.19	91.79

+ Estimated from isokinetic probe or ash samples

++ Moisture and ash free.

* Referenced at the 20" ID section.

** From jet inlet to top of bed.

B2689A.039

Figure A-1 . Heat and Material Balance Flow Schematic

TABLE A-2

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1A

STREAM NO.		1	2	3	4	5	6
STREAM DESCRIPTION		STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL	LB/HR	0.00	372.00	0.00	58.00	274.70	524.43
TEMPERATURE	F	0.0	469.0	0.0	112.0	166.0	588.0
GAS	LB/HR	0.00	372.00	0.00	58.00	274.70	524.43
SOLID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	18.016	0.000	44.011	25.831	25.831
CO	VOLUME %	0.00	0.00	0.00	0.00	48.88	48.88
CO2	VOLUME %	0.00	0.00	0.00	100.00	24.25	24.25
H2	VOLUME %	0.00	0.00	0.00	0.00	23.28	23.28
CH4	VOLUME %	0.00	0.00	0.00	0.00	1.26	1.26
N2	VOLUME %	0.00	0.00	0.00	0.00	0.48	0.48
O2	VOLUME %	0.00	0.00	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	100.00	0.00	0.00	0.36	0.36
GAS CHARACTERIZATION							
	H2S PPM	0.000	0.000	0.000	0.000	14895.614	14895.614
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	0.000	0.000	0.000	15.829	95.018	181.398
HYDROGEN	LB/HR	0.000	41.627	0.000	0.000	5.928	11.317
OXYGEN	LB/HR	0.000	330.373	0.000	42.171	166.321	317.522
NITROGEN	LB/HR	0.000	0.000	0.000	0.000	1.425	2.720
SULFUR	LB/HR	0.000	0.000	0.000	0.000	5.079	9.697
ASH	LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT							
	KBTU/HR	0.000	66.528	0.000	0.424	1034.193	2042.377

TABLE A-2 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1A

STREAM NO.		7	8	9	10	11	12
STREAM DESCRIPTION		BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL	LB/HR	172.89	1785.32	1081.00	253.00	0.00	4445.01
TEMPERATURE	F	166.0	109.0	510.0	112.0	0.0	1147.0
GAS	LB/HR	172.89	478.32	1081.00	253.00	0.00	4261.01
SOLID	LB/HR	0.00	1307.00	0.00	0.00	0.00	184.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		25.831	25.831	31.862	44.011	0.000	24.726
CO	VOLUME %	48.88	48.88	0.00	0.00	0.00	42.19
CO2	VOLUME %	24.25	24.25	0.00	100.00	0.00	21.02
H2	VOLUME %	23.28	23.28	0.00	0.00	0.00	20.29
CH4	VOLUME %	1.26	1.26	0.00	0.00	0.00	1.65
N2	VOLUME %	0.48	0.48	0.00	0.00	0.00	0.41
O2	VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O	VOLUME %	0.36	0.36	0.00	0.00	0.00	13.22
GAS CHARACTERIZATION							
	H2S PPM	14895.614	14895.614	0.000	0.000	0.000	12235.980
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	59.301	1151.843	0.000	69.046	0.000	1479.509
HYDROGEN	LB/HR	3.731	71.751	0.000	0.000	0.000	132.401
OXYGEN	LB/HR	104.678	365.937	1081.000	183.954	0.000	2686.725
NITROGEN	LB/HR	0.897	24.831	0.000	0.000	0.000	21.067
SULFUR	LB/HR	3.197	45.440	0.000	0.000	0.000	72.211
ASH	LB/HR	0.000	123.904	0.000	0.000	0.000	40.719
HEAT CONTENT							
	KBTU/HR	550.891	19468.105	106.079	1.851	0.000	18321.205

TABLE A-2 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1A

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	86.50	2.59	0.00	-0.28
TEMPERATURE	F	288.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	86.50	2.59	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	7.638	1.601	0.000	5.352
HYDROGEN	LB/HR	0.026	0.005	0.000	1.431
OXYGEN	LB/HR	0.000	0.000	0.000	-3.656
NITROGEN	LB/HR	0.130	0.019	0.000	28.976
SULFUR	LB/HR	4.818	0.063	0.000	-21.573
ASH	LB/HR	73.888	0.909	0.000	6.769
HEAT CONTENT					
	KBTU/HR	138.679	23.286	2075.000	12.033

TABLE A-3

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1B

STREAM NO.		1	2	3	4	5	6
STREAM DESCRIPTION		STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 FURGE	GRID GAS	SPARGER RING
TOTAL	LB/HR	0.00	368.00	0.00	58.00	270.57	522.03
TEMPERATURE	F	0.0	465.0	0.0	115.0	174.0	588.0
GAS	LB/HR	0.00	368.00	0.00	58.00	270.57	522.03
SOLID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	18.016	0.000	44.011	25.595	25.595
CO	VOLUME %	0.00	0.00	0.00	0.00	48.15	48.15
CO2	VOLUME %	0.00	0.00	0.00	100.00	23.98	23.98
H2	VOLUME %	0.00	0.00	0.00	0.00	23.87	23.87
CH4	VOLUME %	0.00	0.00	0.00	0.00	1.24	1.24
N2	VOLUME %	0.00	0.00	0.00	0.00	0.61	0.61
O2	VOLUME %	0.00	0.00	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	100.00	0.00	0.00	0.71	0.71
GAS CHARACTERIZATION							
	H2S PPM	0.000	0.000	0.000	0.000	14417.355	14417.355
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	0.000	0.000	0.000	15.829	93.153	179.722
HYDROGEN	LB/HR	0.000	41.179	0.000	0.000	6.074	11.718
OXYGEN	LB/HR	0.000	326.821	0.000	42.171	163.747	315.921
NITROGEN	LB/HR	0.000	0.000	0.000	0.000	1.820	3.512
SULFUR	LB/HR	0.000	0.000	0.000	0.000	4.887	9.428
ASH	LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT							
	KBTU/HR	0.000	65.115	0.000	0.461	1024.997	2044.573

TABLE A-3 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1B

STREAM NO.		7	8	9	10	11	12
STREAM DESCRIPTION		BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL	LB/HR	170.18	1734.64	1061.00	253.00	0.00	4366.89
TEMPERATURE	F	174.0	114.0	508.0	115.0	0.0	1145.0
GAS	LB/HR	170.18	421.64	1061.00	253.00	0.00	4171.52
SOLID	LB/HR	0.00	1313.00	0.00	0.00	0.00	195.37
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		25.595	25.595	31.862	44.011	0.000	24.451
CO	VOLUME %	48.15	48.15	0.00	0.00	0.00	40.59
CO2	VOLUME %	23.98	23.98	0.00	100.00	0.00	21.22
H2	VOLUME %	23.87	23.87	0.00	0.00	0.00	21.43
CH4	VOLUME %	1.24	1.24	0.00	0.00	0.00	1.58
N2	VOLUME %	0.61	0.61	0.00	0.00	0.00	0.57
O2	VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O	VOLUME %	0.71	0.71	0.00	0.00	0.00	13.39
GAS CHARACTERIZATION							
	H2S PPM	14417.355	14417.355	0.000	0.000	0.000	12004.146
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	58.591	1136.081	0.000	69.046	0.000	1437.203
HYDROGEN	LB/HR	3.820	71.176	0.000	0.000	0.000	135.408
OXYGEN	LB/HR	102.992	331.846	1061.000	183.954	0.000	2637.927
NITROGEN	LB/HR	1.145	25.289	0.000	0.000	0.000	28.788
SULFUR	LB/HR	3.074	44.379	0.000	0.000	0.000	69.770
ASH	LB/HR	0.000	124.472	0.000	0.000	0.000	45.775
HEAT CONTENT							
	KBTU/HR	644.697	19347.402	103.616	2.011	0.000	18016.096

TABLE A-3 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 1B

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	88.60	2.09	0.00	-0.45
TEMPERATURE	F	290.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	88.60	2.09	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	5.024	1.295	0.300	7.015
HYDROGEN	LB/HR	0.027	0.004	0.300	-1.098
OXYGEN	LB/HR	0.000	0.000	0.300	-4.330
NITROGEN	LB/HR	0.204	0.015	0.000	8.684
SULFUR	LB/HR	5.422	0.048	0.000	-21.811
ASH	LB/HR	77.950	0.747	0.000	0.000
HEAT CONTENT					
	KBTU/HR	104.991	18.788	2045.000	13.119

TABLE A-4

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 2A

STREAM NO.	1	2	3	4	5	6
STREAM DESCRIPTION	STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL LB/HR	0.00	415.00	0.00	104.00	273.36	563.09
TEMPERATURE F	0.0	486.0	0.0	119.0	153.0	588.0
GAS LB/HR	0.00	415.00	0.00	104.00	273.36	563.09
SOLID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	0.000	18.016	0.000	44.011	25.942	25.942
CO VOLUME %	0.00	0.00	0.00	0.00	50.28	50.28
CO2 VOLUME %	0.00	0.00	0.00	100.00	23.63	23.63
H2 VOLUME %	0.00	0.00	0.00	0.00	22.22	22.22
CH4 VOLUME %	0.00	0.00	0.00	0.00	1.79	1.79
N2 VOLUME %	0.00	0.00	0.00	0.00	0.57	0.57
O2 VOLUME %	0.00	0.00	0.00	0.00	0.00	0.00
H2O VOLUME %	0.00	100.00	0.00	0.00	0.19	0.19
GAS CHARACTERIZATION						
H2S PPM	0.000	0.000	0.000	0.000	13234.582	13234.582
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	0.000	0.000	0.000	28.383	95.811	197.356
HYDROGEN LB/HR	0.000	46.439	0.000	0.000	5.802	11.951
OXYGEN LB/HR	0.000	368.561	0.000	75.617	164.786	339.436
NITROGEN LB/HR	0.000	0.000	0.000	0.000	1.674	3.447
SULFUR LB/HR	0.000	0.000	0.000	0.000	4.472	9.211
ASH LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT KBTU/HR	0.000	77.568	0.000	0.915	1045.079	2227.541

TABLE A-4 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST T²-035-3, STEADY STATE 2A

STREAM NO.		7	8	9	10	11	12
STREAM DESCRIPTION		BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	2120 CYCLONE TRANS. G.	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL	LB/HR	245.45	2260.60	1254.00	262.00	0.00	5479.04
TEMPERATURE	F	153.0	111.0	509.0	119.0	0.0	1197.0
GAS	LB/HR	245.45	755.60	1254.00	262.00	0.00	5331.04
SOLID	LB/HR	0.00	1505.00	0.00	0.00	0.00	148.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		25.942	25.942	31.862	44.011	0.000	25.171
CO	VOLUME %	50.28	50.28	0.00	0.00	0.00	42.17
CO ₂	VOLUME %	23.63	23.63	0.00	100.00	0.00	22.66
H ₂	VOLUME %	22.22	22.22	0.00	0.00	0.00	20.28
CH ₄	VOLUME %	1.79	1.79	0.00	0.00	0.00	1.52
N ₂	VOLUME %	0.57	0.57	0.00	0.00	0.00	0.42
O ₂	VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H ₂ O	VOLUME %	0.19	0.19	0.00	0.00	0.00	11.66
GAS CHARACTERIZATION							
	H ₂ S PPM	13234.582	13234.582	0.000	0.000	0.000	12932.976
	CO ₂ PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	86.027	1390.563	0.000	71.502	0.000	1795.739
HYDROGEN	LB/HR	5.209	88.879	0.000	0.000	0.000	155.248
OXYGEN	LB/HR	147.959	542.171	1254.000	190.498	0.000	3360.294
NITROGEN	LB/HR	1.503	31.366	0.000	0.000	0.000	26.011
SULFUR	LB/HR	4.015	58.413	0.000	0.000	0.000	89.928
ASH	LB/HR	0.000	146.436	0.000	0.000	0.000	35.712
HEAT CONTENT							
	KBTU/HR	936.363	23253.900	122.760	2.304	0.000	21649.535

TABLE A-4 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 2A

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	142.00	3.69	0.00	-4.60
TEMPERATURE	F	333.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	142.00	3.69	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	7.853	2.260	0.000	3.412
HYDROGEN	LB/HR	0.071	0.007	0.000	1.866
OXYGEN	LB/HR	0.000	0.000	0.000	-8.993
NITROGEN	LB/HR	0.071	0.036	0.000	32.144
SULFUR	LB/HR	10.877	0.123	0.000	-32.607
ASH	LB/HR	123.128	1.265	0.000	-9.334
HEAT CONTENT					
	KBTU/HR	179.890	33.030	2265.000	12.798

TABLE A-5

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 2A-1

STREAM NO.	1	2	3	4	5	6
STREAM DESCRIPTION	STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL LB/HR	0.00	413.00	42.30	102.00	420.97	839.94
TEMPERATURE F	0.0	426.0	0.0	27.0	164.0	588.0
GAS LB/HR	0.00	413.00	42.30	102.00	420.97	839.94
SOLID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	0.000	18.016	28.588	44.011	27.996	27.996
CO VOLUME %	0.00	0.00	0.00	0.00	51.16	51.16
CO2 VOLUME %	0.00	0.00	0.00	100.00	28.16	28.16
H2 VOLUME %	0.00	0.00	0.00	0.00	16.91	16.91
CH4 VOLUME %	0.00	0.00	0.00	0.00	1.82	1.82
N2 VOLUME %	0.00	0.00	78.06	0.00	0.42	0.42
O2 VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O VOLUME %	0.00	100.00	0.00	0.00	0.41	0.41
GAS CHARACTERIZATION						
H2S PPM	0.000	0.000	0.000	0.000	11163.936	11163.936
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	0.000	0.000	0.000	27.837	146.544	292.391
HYDROGEN LB/HR	0.000	46.215	0.000	0.000	6.692	13.352
OXYGEN LB/HR	0.000	366.785	9.942	74.163	259.578	517.923
NITROGEN LB/HR	0.000	0.000	32.354	0.000	1.787	3.566
SULFUR LB/HR	0.000	0.000	0.000	0.000	5.383	10.740
ASH LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT						
KBTU/HR	0.000	65.474	-0.763	1.070	1404.805	2905.817

TABLE A-5 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 2A-1

STREAM NO.	7	8	9	10	11	12
STREAM DESCRIPTION	BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL LB/HR	257.98	1814.95	979.00	270.00	0.00	5049.03
TEMPERATURE F	164.0	121.0	512.0	127.0	0.0	1146.0
GAS LB/HR	257.98	725.95	979.00	270.00	0.00	4934.03
SOLID LB/HR	0.00	1089.00	0.00	0.00	0.00	115.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	27.996	27.996	31.862	44.011	0.000	26.741
CO VOLUME %	51.16	51.16	0.00	0.00	0.00	41.67
CO2 VOLUME %	28.16	28.16	0.00	100.00	0.00	26.01
H2 VOLUME %	16.91	16.91	0.00	0.00	0.00	15.25
CH4 VOLUME %	1.82	1.82	0.00	0.00	0.00	1.50
N2 VOLUME %	0.42	0.42	0.00	0.00	0.00	0.50
O2 VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O VOLUME %	0.41	0.41	0.00	0.00	0.00	14.08
GAS CHARACTERIZATION						
H2S PPM	11163.936	11163.936	0.000	0.000	0.000	9889.393
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	89.806	1069.350	0.000	73.685	0.000	1615.394
HYDROGEN LB/HR	4.101	67.297	0.000	0.000	0.000	124.208
OXYGEN LB/HR	159.076	528.982	979.000	196.315	0.000	3181.904
NITROGEN LB/HR	1.095	18.763	0.000	0.000	0.000	26.133
SULFUR LB/HR	3.299	35.636	0.000	0.000	0.000	60.336
ASH LB/HR	0.000	93.218	0.000	0.000	0.000	30.348
HEAT CONTENT						
KBTU/HR	860.902	17233.422	96.532	2.832	0.000	17228.426

TABLE A-5 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 2A-1

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	82.00	4.80	0.00	0.00
TEMPERATURE	F	293.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	82.00	4.80	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	9.077	2.867	0.000	4.252
HYDROGEN	LB/HR	0.016	0.007	0.000	9.753
OXYGEN	LB/HR	0.000	0.102	0.000	-2.919
NITROGEN	LB/HR	0.002	0.030	0.000	54.408
SULFUR	LB/HR	4.248	0.103	0.000	-17.491
ASH	LB/HR	58.577	1.690	0.000	-7.934
HEAT CONTENT					
	KBTU/HR	155.300	40.975	1825.000	14.711

TABLE A-6

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3A

STREAM NO.		1	2	3	4	5	6
STREAM DESCRIPTION		STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL	LB/HR	0.00	462.00	42.30	135.00	487.53	1081.95
TEMPERATURE	F	0.0	489.0	0.0	128.0	155.0	587.0
GAS	LB/HR	0.00	462.00	42.30	135.00	487.53	1081.95
SOLID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	18.016	28.588	44.011	27.946	27.946
CO	VOLUME %	0.00	0.00	0.00	0.00	45.54	45.54
CO2	VOLUME %	0.00	0.00	0.00	100.00	30.59	30.59
H2	VOLUME %	0.00	0.00	0.00	0.00	18.75	18.75
CH4	VOLUME %	0.00	0.00	0.00	0.00	1.57	1.57
N2	VOLUME %	0.00	0.00	78.06	0.00	2.11	2.11
O2	VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	100.00	0.00	0.00	0.32	0.32
GAS CHARACTERIZATION							
	H2S PPM	0.000	0.000	0.000	0.000	11163.919	11163.919
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	0.000	0.000	0.000	36.843	162.833	361.370
HYDROGEN	LB/HR	0.000	51.698	0.000	0.000	8.206	18.212
OXYGEN	LB/HR	0.000	410.302	9.942	98.157	298.812	663.142
NITROGEN	LB/HR	0.000	0.000	32.354	0.000	10.288	22.833
SULFUR	LB/HR	0.000	0.000	0.000	0.000	6.245	13.859
ASH	LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT							
	KBTU/HR	0.000	87.012	-0.763	1.444	1532.511	3537.226

TABLE A-6 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3A

STREAM NO.		7	8	9	10	11	12
STREAM DESCRIPTION		BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL	LB/HR	302.71	2088.16	1126.00	272.00	0.00	5707.63
TEMPERATURE	F	155.0	115.0	513.0	128.0	0.0	1151.0
GAS	LB/HR	302.71	872.16	1126.00	272.00	0.00	5616.63
SOLID	LB/HR	0.00	1216.00	0.00	0.00	0.00	91.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		27.946	27.946	31.862	44.011	0.000	27.341
CO	VOLUME %	45.54	45.54	0.00	0.00	0.00	36.29
CO2	VOLUME %	30.59	30.59	0.00	100.00	0.00	31.48
H2	VOLUME %	18.75	18.75	0.00	0.00	0.00	17.54
CH4	VOLUME %	1.57	1.57	0.00	0.00	0.00	1.37
N2	VOLUME %	2.11	2.11	0.00	0.00	0.00	1.67
O2	VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O	VOLUME %	0.32	0.32	0.00	0.00	0.00	10.83
GAS CHARACTERIZATION							
	H2S PPM	11163.919	11163.919	0.000	0.000	0.000	8248.225
	CO2 PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	101.103	1198.069	0.000	74.231	0.000	1769.829
HYDROGEN	LB/HR	5.095	77.062	0.000	0.000	0.000	132.782
OXYGEN	LB/HR	185.533	618.337	1126.000	197.769	0.000	3619.197
NITROGEN	LB/HR	6.388	40.293	0.000	0.000	0.000	96.755
SULFUR	LB/HR	3.877	44.976	0.000	0.000	0.000	55.513
ASH	LB/HR	0.000	107.373	0.000	0.000	0.000	23.878
HEAT CONTENT							
	KBTU/HR	951.538	19277.738	111.293	2.910	0.000	17877.842

TABLE A-6 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3A

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	105.00	3.16	0.00	3.03
TEMPERATURE	F	320.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	105.00	3.16	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	10.385	2.164	0.000	7.861
HYDROGEN	LB/HR	0.053	0.009	0.000	17.115
OXYGEN	LB/HR	0.000	0.000	0.000	-0.310
NITROGEN	LB/HR	0.053	0.021	0.000	13.667
SULFUR	LB/HR	6.353	0.077	0.000	10.172
ASH	LB/HR	88.158	0.890	0.000	-5.172
HEAT CONTENT					
	KBTU/HR	188.702	31.537	2075.000	20.893

TABLE A-7

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3B

STREAM NO.		1	2	3	4	5	6
STREAM DESCRIPTION		STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL	LB/HR	0.00	443.00	42.30	149.00	477.51	1071.18
TEMPERATURE	F	0.0	446.0	0.0	119.0	139.0	588.0
GAS	LB/HR	0.00	443.00	42.30	149.00	477.51	1071.18
SOLID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	18.016	28.588	44.011	27.596	27.596
CO	VOLUME %	0.00	0.00	0.00	0.00	45.35	45.35
CO2	VOLUME %	0.00	0.00	0.00	100.00	30.42	30.42
H2	VOLUME %	0.00	0.00	0.00	0.00	20.04	20.04
CH4	VOLUME %	0.00	0.00	0.00	0.00	1.67	1.67
N2	VOLUME %	0.00	0.00	78.06	0.00	1.04	1.04
O2	VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	100.00	0.00	0.00	0.23	0.23
GAS CHARACTERIZATION							
	H2S PPM	0.000	0.000	0.000	0.000	12530.625	12530.625
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	0.000	0.000	0.000	43.663	160.930	361.005
HYDROGEN	LB/HR	0.000	49.572	0.000	0.000	8.671	19.452
OXYGEN	LB/HR	0.000	393.420	9.942	103.337	294.624	660.914
NITROGEN	LB/HR	0.000	0.000	32.354	0.000	5.064	11.359
SULFUR	LB/HR	0.000	0.000	0.000	0.000	6.952	15.596
ASH	LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT							
	KBTU/HR	0.000	74.405	-0.763	1.310	1553.162	3625.752

TABLE A-7 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3B

STREAM NO.	7	8	9	10	11	12
STREAM DESCRIPTION	BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL LB/HR	331.58	2126.68	1142.00	267.00	0.00	5696.86
TEMPERATURE °F	139.0	111.0	512.0	119.0	0.0	1159.0
GAS LB/HR	331.58	865.68	1142.00	267.00	0.00	5584.86
SOLID LB/HR	0.00	1261.00	0.00	0.00	0.00	112.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	27.596	27.596	31.862	44.011	0.000	26.860
CO VOLUME %	45.35	45.35	0.00	0.00	0.00	39.76
CO2 VOLUME %	30.42	30.42	0.00	100.00	0.00	28.86
H2 VOLUME %	20.04	20.04	0.00	0.00	0.00	18.45
CH4 VOLUME %	1.67	1.67	0.00	0.00	0.00	1.47
H2 VOLUME %	1.04	1.04	0.00	0.00	0.00	1.04
O2 VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O VOLUME %	0.23	0.23	0.00	0.00	0.00	9.30
GAS CHARACTERIZATION						
H2S PPM	12530.625	12530.625	0.000	0.000	0.000	11128.890
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	111.748	1305.719	0.000	72.867	0.000	1831.087
HYDROGEN LB/HR	6.021	83.184	0.000	0.000	0.000	133.521
OXYGEN LB/HR	204.583	619.743	1142.000	194.133	0.000	3553.273
NITROGEN LB/HR	3.516	28.851	0.000	0.000	0.000	61.053
SULFUR LB/HR	4.828	23.827	0.000	0.000	0.000	75.505
ASH LB/HR	0.000	63.428	0.000	0.000	0.000	28.840
HEAT CONTENT						
KBTU/HR	1078.495	21098.354	112.605	2.348	0.000	19634.801

TABLE A-7 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 3B

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	85.00	2.67	0.00	4.39
TEMPERATURE	F	309.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	85.00	2.67	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	8.134	1.888	0.000	10.318
HYDROGEN	LB/HR	0.004	0.006	0.000	19.976
OXYGEN	LB/HR	0.000	0.000	0.000	2.052
NITROGEN	LB/HR	0.068	0.013	0.000	24.659
SULFUR	LB/HR	4.114	0.060	0.000	-55.615
ASH	LB/HR	72.650	0.703	0.000	-61.115
HEAT CONTENT					
	KBTU/HR	142.774	27.376	2115.300	20.423

TABLE A-8

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A

STREAM NO.	1	2	3	4	5	6
STREAM DESCRIPTION	STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL LB/HR	0.00	387.00	42.30	146.00	477.63	1038.20
TEMPERATURE F	0.0	427.0	0.0	127.0	155.0	588.0
GAS LB/HR	0.00	387.00	42.30	146.00	477.63	1038.20
SOLID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	0.000	18.016	28.568	44.011	27.957	27.957
CO VOLUME %	0.00	0.00	0.00	0.00	45.70	45.70
CO2 VOLUME %	0.00	0.00	0.00	100.00	31.31	31.31
H2 VOLUME %	0.00	0.00	0.00	0.00	18.96	18.96
CH4 VOLUME %	0.00	0.00	0.00	0.00	1.58	1.58
N2 VOLUME %	0.00	0.00	78.06	0.00	1.42	1.42
O2 VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O VOLUME %	0.00	100.00	0.00	0.00	0.32	0.32
GAS CHARACTERIZATION						
H2S PPM	0.000	0.000	0.000	0.000	7097.063	7097.063
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	0.000	0.000	0.000	39.845	161.273	350.549
HYDROGEN LB/HR	0.000	43.306	0.000	0.000	7.970	17.325
OXYGEN LB/HR	0.000	343.694	9.942	106.155	296.998	645.566
NITROGEN LB/HR	0.000	0.000	32.354	0.000	6.793	14.766
SULFUR LB/HR	0.000	0.000	0.000	0.000	3.888	8.451
ASH LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT						
KBTU/HR	0.000	61.534	-0.763	1.531	1491.907	3374.066

TABLE A-8 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A

STREAM NO.	7	8	9	10	11	12
STREAM DESCRIPTION	BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL LB/HR	359.72	1932.37	1103.00	274.00	0.00	5394.71
TEMPERATURE F	155.0	112.0	511.0	127.0	0.0	1153.0
GAS LB/HR	359.72	820.37	1103.00	274.00	0.00	5290.71
SOLID LB/HR	0.00	1112.00	0.00	0.00	0.00	104.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	27.957	27.957	31.862	44.011	0.000	27.128
CO VOLUME %	45.70	45.70	0.00	0.00	0.00	39.48
CO2 VOLUME %	31.31	31.31	0.00	100.00	0.00	29.75
H2 VOLUME %	18.96	18.96	0.00	0.00	0.00	17.55
CH4 VOLUME %	1.58	1.58	0.00	0.00	0.00	1.46
N2 VOLUME %	1.42	1.42	0.00	0.00	0.00	1.27
O2 VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O VOLUME %	0.32	0.32	0.00	0.00	0.00	9.84
GAS CHARACTERIZATION						
H2S PPM	7097.063	7097.063	0.000	0.000	0.000	6455.457
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	121.461	1169.155	0.000	74.777	0.000	1737.536
HYDROGEN LB/HR	6.003	74.183	0.000	0.000	0.000	121.943
OXYGEN LB/HR	223.680	588.400	1103.000	199.223	0.000	3397.350
NITROGEN LB/HR	5.116	29.460	0.000	0.000	0.000	70.193
SULFUR LB/HR	2.928	15.685	0.000	0.000	0.000	40.857
ASH LB/HR	0.000	54.266	0.000	0.000	0.000	19.417
HEAT CONTENT						
KBTU/HR	1123.611	18695.057	108.499	2.874	0.000	17979.437

TABLE A-8. (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	64.00	6.00	0.00	5.13
TEMPERATURE	F	313.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	64.00	6.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	8.090	4.740	0.000	8.695
HYDROGEN	LB/HR	0.038	0.017	0.000	18.004
OXYGEN	LB/HR	0.000	0.000	0.000	3.393
NITROGEN	LB/HR	0.006	0.041	0.000	20.622
SULFUR	LB/HR	0.154	0.023	0.000	-32.576
ASH	LB/HR	55.712	1.179	0.000	-40.619
HEAT CONTENT					
	KBTU/HR	120.673	68.209	2105.000	18.445

TABLE A-9

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-1

STREAM NO.	1	2	3	4	5	6
STREAM DESCRIPTION	STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL LB/HR	0.00	420.00	42.30	132.00	487.39	1205.08
TEMPERATURE F	0.0	444.0	0.0	125.0	145.0	588.0
GAS LB/HR	0.00	420.00	42.30	132.00	487.39	1205.08
SOLID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	0.000	18.016	28.588	44.011	27.590	27.590
CO VOLUME %	0.00	0.00	0.00	0.00	42.42	42.42
CO2 VOLUME %	0.00	0.00	0.00	100.00	32.55	32.55
H2 VOLUME %	0.00	0.00	0.00	0.00	21.16	21.16
CH4 VOLUME %	0.00	0.00	0.00	0.00	1.76	1.76
N2 VOLUME %	0.00	0.00	78.06	0.00	0.96	0.96
O2 VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O VOLUME %	0.00	100.00	0.00	0.00	0.25	0.25
GAS CHARACTERIZATION						
H2S PPM	0.000	0.000	0.000	0.000	8947.505	8947.505
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	0.000	0.000	0.000	36.024	162.813	402.556
HYDROGEN LB/HR	0.000	46.998	0.000	0.000	9.197	22.739
OXYGEN LB/HR	0.000	373.002	9.942	95.976	304.618	753.168
NITROGEN LB/HR	0.000	0.000	32.354	0.000	4.769	11.790
SULFUR LB/HR	0.000	0.000	0.000	0.000	5.068	12.531
ASH LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT						
KBTU/HR	0.000	70.146	-0.763	1.328	1539.015	3963.808

TABLE A-9 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-1

STREAM NO.		7	8	9	10	11	12
STREAM DESCRIPTION		BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL	LB/HR	415.92	2112.51	1215.00	270.00	0.00	5986.59
TEMPERATURE	F	145.0	108.0	512.0	125.0	0.0	1190.0
GAS	LB/HR	415.92	876.51	1215.00	270.00	0.00	5881.59
SOLID	LB/HR	0.00	1236.00	0.00	0.00	0.00	105.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		27.590	27.590	31.862	44.011	0.000	26.682
CO	VOLUME %	42.42	42.42	0.00	0.00	0.00	37.97
CO2	VOLUME %	32.55	32.55	0.00	100.00	0.00	29.54
H2	VOLUME %	21.16	21.16	0.00	0.00	0.00	19.03
CH4	VOLUME %	1.76	1.76	0.00	0.00	0.00	1.54
N2	VOLUME %	0.96	0.96	0.00	0.00	0.00	0.97
O2	VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O	VOLUME %	0.25	0.25	0.00	0.00	0.00	10.17
GAS CHARACTERIZATION							
	H2S PPM	8947.505	8947.505	0.000	0.000	0.000	7788.261
	COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS							
CARBON	LB/HR	138.938	1277.890	0.000	73.685	0.000	1913.405
HYDROGEN	LB/HR	7.848	76.856	0.000	0.000	0.000	147.178
OXYGEN	LB/HR	259.949	648.178	1215.000	196.315	0.000	3782.077
NITROGEN	LB/HR	4.069	27.116	0.000	0.000	0.000	60.431
SULFUR	LB/HR	4.325	18.879	0.000	0.000	0.000	55.541
ASH	LB/HR	0.000	61.924	0.000	0.000	0.000	17.882
HEAT CONTENT							
	KETU/HR	1313.334	20057.250	119.803	2.717	0.000	20439.346

TABLE A-9 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-1

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	48.00	5.00	0.00	4.14
TEMPERATURE	F	320.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	48.00	5.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	0.029	3.802	0.000	8.063
HYDROGEN	LB/HR	0.024	0.010	0.000	10.038
OXYGEN	LB/HR	0.000	0.000	0.000	1.921
NITROGEN	LB/HR	0.072	0.031	0.000	24.425
SULFUR	LB/HR	0.024	0.029	0.000	-36.250
ASH	LB/HR	41.851	1.128	0.000	1.716
HEAT CONTENT					
	KBTU/HR	89.236	54.541	2205.000	15.807

TABLE A-10

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-2

STREAM NO.	1	2	3	4	5	6
STREAM DESCRIPTION	STEAM TO GRID	STEAM TO AIR TUBE	AIR	CO2 PURGE	GRID GAS	SPARGER RING
TOTAL LB/HR	0.00	419.00	42.30	107.00	471.84	1240.04
TEMPERATURE F	0.0	441.0	0.0	127.0	157.0	587.0
GAS LB/HR	0.00	419.00	42.30	107.00	471.84	1240.04
SOLID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	0.000	18.016	28.588	44.011	26.610	26.610
CO VOLUME %	0.00	0.00	0.00	0.00	46.19	46.19
CO2 VOLUME %	0.00	0.00	0.00	100.00	27.85	27.85
H2 VOLUME %	0.00	0.00	0.00	0.00	22.04	22.04
CH4 VOLUME %	0.00	0.00	0.00	0.00	1.56	1.56
NO VOLUME %	0.00	0.00	78.06	0.00	1.29	1.29
O2 VOLUME %	0.00	0.00	21.00	0.00	0.00	0.00
H2O VOLUME %	0.00	100.00	0.00	0.00	0.31	0.31
GAS CHARACTERIZATION						
H2S PPM	0.000	0.000	0.000	0.000	7586.132	7586.132
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	0.000	0.000	0.000	29.201	161.008	423.145
HYDROGEN LB/HR	0.000	46.886	0.000	0.000	9.379	24.649
OXYGEN LB/HR	0.000	372.114	9.942	77.799	289.945	762.005
NITROGEN LB/HR	0.000	0.000	32.354	0.000	6.403	16.826
SULFUR LB/HR	0.000	0.000	0.000	0.000	4.313	11.335
ASH LB/HR	0.000	0.000	0.000	0.000	0.000	0.000
HEAT CONTENT						
KBTU/HR	0.000	69.385	-0.763	1.122	1627.473	4438.369

TABLE A-10 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-2

STREAM NO.	7	8	9	10	11	12
STREAM DESCRIPTION	BOOSTER GAS	COAL FEED AND TRANS. G.	OXYGEN TO TUBE	C120 CYCLONE TRANS. G	LIQUID WATER INJECTION	PRODUCT GAS
TOTAL LB/HR	401.65	2137.79	1310.00	274.00	0.00	6280.38
TEMPERATURE F	157.0	113.0	512.0	127.0	0.0	1206.0
GAS LB/HR	401.65	822.79	1310.00	274.00	0.00	6115.38
SOLID LB/HR	0.00	1315.00	0.00	0.00	0.00	165.00
LIQUID LB/HR	0.00	0.00	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT	26.610	26.610	31.862	44.011	0.000	25.899
CO VOLUME %	46.19	46.19	0.00	0.00	0.00	41.38
CO2 VOLUME %	27.85	27.85	0.00	100.00	0.00	25.77
H2 VOLUME %	22.04	22.04	0.00	0.00	0.00	20.17
CH4 VOLUME %	1.56	1.56	0.00	0.00	0.00	1.41
N2 VOLUME %	1.29	1.29	0.00	0.00	0.00	1.37
O2 VOLUME %	0.00	0.00	99.57	0.00	0.00	0.00
H2O VOLUME %	0.31	0.31	0.00	0.00	0.00	9.14
GAS CHARACTERIZATION						
H2S PPM	7586.132	7586.132	0.000	0.000	0.000	7550.466
COS PPM	0.000	0.000	0.000	0.000	0.000	0.000
ELEMENTS						
CARBON LB/HR	137.057	1328.821	0.000	74.777	0.000	2074.151
HYDROGEN LB/HR	7.984	80.527	0.000	0.000	0.000	156.821
OXYGEN LB/HR	246.813	612.385	1310.000	199.223	0.000	3859.478
NITROGEN LB/HR	5.450	30.890	0.000	0.000	0.000	91.807
SULFUR LB/HR	3.671	17.910	0.000	0.000	0.000	57.857
ASH LB/HR	0.000	65.882	0.000	0.000	0.000	29.799
HEAT CONTENT						
KBTU/HR	1385.270	21233.088	129.170	2.874	0.000	23607.094

TABLE A-10 (Continued)

GASIFIER HEAT AND MATERIAL BALANCES, TEST TP-035-3, STEADY STATE 4A-2

STREAM NO.		13	14		
STREAM DESCRIPTION		ASH WITH-DRAWAL	BED SAMPLE (SC-22)	HEAT LOSS	TOTAL CLOSURE
TOTAL	LB/HR	48.00	6.00	0.00	1.08
TEMPERATURE	F	340.0	0.0	0.0	0.0
GAS	LB/HR	0.00	0.00	0.00	0.00
SOLID	LB/HR	48.00	6.00	0.00	0.00
LIQUID	LB/HR	0.00	0.00	0.00	0.00
MOLECULAR WEIGHT		0.000	0.000	0.000	0.000
CO	VOLUME %	0.00	0.00	0.00	0.00
CO2	VOLUME %	0.00	0.00	0.00	0.00
H2	VOLUME %	0.00	0.00	0.00	0.00
CH4	VOLUME %	0.00	0.00	0.00	0.00
N2	VOLUME %	0.00	0.00	0.00	0.00
O2	VOLUME %	0.00	0.00	0.00	0.00
H2O	VOLUME %	0.00	0.00	0.00	0.00
GAS CHARACTERIZATION					
	H2S PPM	0.000	0.000	0.000	0.000
	COS PPM	0.000	0.000	0.000	0.000
ELEMENTS					
CARBON	LB/HR	3.826	4.441	0.000	3.324
HYDROGEN	LB/HR	0.053	0.013	0.000	7.401
OXYGEN	LB/HR	0.000	0.026	0.000	0.534
NITROGEN	LB/HR	0.062	0.053	0.000	-0.000
SULFUR	LB/HR	0.000	0.043	0.000	-55.525
ASH	LB/HR	44.059	1.424	0.000	-14.269
HEAT CONTENT					
	KBTU/HR	59.989	63.707	2305.000	9.867

DOE/MC/19122-2522

ADVANCED DEVELOPMENT OF A PRESSURIZED ASH AGGLOMERATING
FLUIDIZED-BED COAL GASIFICATION SYSTEM

DOE