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**FIXED-BED GASIFIER AND CLEANUP SYSTEM
ENGINEERING SUMMARY REPORT
THROUGH TEST RUN NO. 100**

By
K. Pater, Jr., Project Manager
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JUNE 1984

For
U. S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

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ABSTRACT

The state-of-the-art of high-pressure, fixed-bed gasification has been advanced by the many refinements developed over the last 5 years. A novel full-flow gas cleanup system has been installed and tested to clean coal-derived gases. This report summarizes the results of tests conducted on the gasifier and cleanup system from its inception through 1982. Selected process summary data are presented along with results from complementary programs in the areas of environmental research, process simulation, analytical methods development, and component testing.

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1.0 SUMMARY

1.1 OVERVIEW

In 1963, an options analysis by the forerunner to the U.S. Department of Energy (DOE) Morgantown Energy Technology Center (METC) indicated that fixed-bed gasification of coal could be a promising technology for utilizing U.S. coals. Evaluation of existing technologies indicated a clear need for the development of useful generic fixed-bed technology and its applicability to U.S. coal feedstocks and utilization patterns (Synthetic Natural Gas (SNG), combined cycle).

In 1968, testing commenced on a one-ton-per-hour, pressurized fixed-bed coal gasifier in Morgantown. Since then, system development and test strategy have developed in four phases:

<u>Phase</u>	<u>Period</u>	<u>Description</u>
I	1967-1974	Gasifier shakedown and tests on U.S. coals.
II	1975-1978	Additional gasifier tests with a side-stream cleanup system to define the potential characteristics of a novel gas cleanup system, in anticipation of the need for enhanced environmental controls.
III	1978-1979	Mechanical shakedown tests of full-flow novel gas cleanup system developments and selected gasifier tests.
IV	1980-1982	Environmental characterization, partial characterization of the full-flow cleanup system and Stretford sulfur removal system debugging.

METC expanded the facility to evaluate and develop environmentally sound fuel gas cleaning processes and fuel gas utilization systems (e.g., combined cycles, fuel cells, SNG). METC initiated this activity by first developing and testing a sub-scale gas processing train. Successful operation (Phase II) led to the construction and operation of a full-flow gas cleaning system in 1979. A unique, pressurized Holmes-Stretford desulfurization unit was integrated into the cleanup system in 1980. This fully integrated gasification/gas cleaning system has been used to provide clean, low-Btu (British Thermal Units) gas to a high-temperature, gas turbine material test facility for the evaluation of erosion and corrosion of advanced, ceramic gas turbine materials by actual coal-derived fuel gas combustion products. A simple schematic in Figure 1 shows the current configuration of the system and describes individual unit operations.

The METC fixed-bed gasification program is well integrated within DOE's fixed-bed gasification research and development program, providing DOE with the broad capability of addressing alternative and advanced gasification and clean-up technologies. The overall program also includes the University of North

FIGURE 1. METC FIXED-BED GASIFIER AND FULL-FLOW CLEANUP SYSTEM PROCESS FLOW DIAGRAM

Dakota Energy Research Center (UNDERC, formerly Grand Forks Energy Technology Center) process development unit, the General Electric (GE) gasification system, and the Mining and Industrial Fuel Gas Group (MIFGA) program. The MIFGA program utilizes a 6.5-foot inside diameter Wellman Galusha atmospheric pressure gasifier at Minneapolis/St. Paul, Minnesota, to test a variety of coal fuels and to evaluate the combustion characteristics of the produced low-Btu gas. A tar removal system has recently been installed for use in testing a small skid-mounted Stretford desulfurization unit.

UNDERC is investigating the advanced slagging mode gasifier which offer potential for significantly increasing capacity and reducing steam requirements, both of which improve economics. It also supports integrated wastewater treatability research. The GE gasifier is somewhat similar to METC's except that it is completely refractory lined and is uncooled. GE's gas cleanup configuration follows the more conventional deluge gas-washing approach in contrast to METC's "dry tar" removal concept. GE and METC are experimenting with collecting and reinjecting coal fines and recovered tars into the gasifier to improve the process. METC is taking the lead in oxygen-blown operation of the dry ash fixed-bed gasifier along with a multi-faceted gasifier and cleanup system development program.

Whenever possible, projects related to the METC fixed-bed gasification program are integrated with other government organizations such as: the Environmental Protection Agency (EPA) and the National Institute of Occupational Safety and Health (NIOSH); Oak Ridge, Argonne, Sandia and Brookhaven National Laboratories; and industry-sponsored organizations such as the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI).

A balanced approach has been adopted at METC towards extracting research and development (R&D) information from the test facility. In keeping with its lead role in surface gasification, METC has taken a systems analysis approach in defining the data needs and tests for the METC fixed-bed gasification system. Therefore, research is conducted not only on the gasifier but also in the related areas of novel gas cleanup processes, product gas utilization, and environmental control; areas where improved efficiencies through new R&D could lead to enhancement in the overall feasibility of large coal conversion plants. Fixed-bed gasification spinoffs from such research and development activities can also help other gasification technologies. An overview of the program with its key components is shown in Figure 2. A detailed description of the METC facility is included in Section 3.0. Section 5.0 summarizes the results of the 100 test runs conducted from 1967 through 1982. Key complementary programs which operate in conjunction with the METC facility are described in Section 4.0. The principal direct recipients of information from the METC Fixed-Bed Gasification Program are the METC Gasification Technology Data Base, R&D divisions of other government agencies, and the private sector.

1.2 PROGRAM ACCOMPLISHMENTS

Each phase of the gasification program has drawn upon the lessons learned from the tests which preceded it. Table 1 highlights the major accomplishments for each phase of the gasification program and indicates the "building block" development of METC'S Full-Flow Cleanup System (FFCUS). Phase I gasifier system

FIGURE 2.. METC FIXED-BED PROGRAM OVERVIEW

TABLE 1. SUMMARY OF ACCOMPLISHMENTS AND GOALS FOR METC FIXED-BED GASIFICATION PROGRAM

1967 Phase I 1974	1974 Phase II 1978	1978 Phase III 1979	1980 Phase IV 1982	1983 Goals 1984
Runs 1 - 82	Runs 83 - 90	Runs 91 - 94	Runs 95 - 100	Runs 101 - 104
<ul style="list-style-type: none"> • Tested gasification of 15 types of coal of varying coal sizes • Tested gasification at pressures from atmospheric to 300 psig • Developed hydraulic grate drive • Developed improved coal feeding techniques • Developed nuclear level detector. 	<ul style="list-style-type: none"> • Tested various configurations to develop optimum cleanup system • Demonstrated humidification "dry-tar" removal • Tested erosion/corrosion of gas turbine blade materials • Characterized gasification by-product • Developed aerosol sampling techniques 	<ul style="list-style-type: none"> • Tested full-flow dust cyclone • Improved design of coal feed system • Installed continuous monitoring of erosion device on dust cyclone • Developed stirrer-mounted thermocouples • Tested alternative humidifier spray nozzles • Tested tar separator techniques • Hydraulic stirrer drive installed • Successfully measured aerosols in gas stream • Developed on-line alkali metals monitor • Tested Venturi scrubber removal of low molecular weight tars from gas • Installed ADACS 	<ul style="list-style-type: none"> • Tested full-flow cleanup system • Tested Stretford sulfur removal system; performed improvements • Provided 1000 hours of gas supply to ceramic materials corrosion/erosion test facility • Demonstrated coal fines utilization by feeding coal briquettes • Characterized trace metal levels in process streams • Characterized major/minor hydrocarbons in process streams • Performed health and safety analysis of facility • Characterized plant emissions • Performed simulations using computer models • Updated control systems • Improved component reliability • Documented METC program test results 	<p><u>Process Development</u></p> <ul style="list-style-type: none"> • Operate oxygen blown gasifier and cleanup system using lignite and other coals • Complete characterization and long-term evaluation of the Stretford system • Characterize performance at varying system throughputs • Characterize fines recycle and briquette gasification using air • Perform process dynamics and control studies for gasifier and FFCUS <p><u>Environmental Development</u></p> <ul style="list-style-type: none"> • Environmental characterization of oxygen blown operation • Environmental characterization using briquettes • Perform environmental systems analysis • Perform comparative analysis for dry and deluge quenches • Complete high pressure, high temperature desulfurization tests using zinc oxide based materials <p><u>Sampling and Analysis</u></p> <ul style="list-style-type: none"> • Refine precision of advanced analytical instruments both on-line and laboratory instruments • Develop and test new analytical techniques <p><u>Components Development</u></p> <ul style="list-style-type: none"> • Complete testing of Peerless Separator and ESP • Complete development of hardened stirrer <p><u>Modeling and Simulation</u></p> <ul style="list-style-type: none"> • Perform process simulation of oxygen-blown operations • Improve process models for direct cooler, Stretford system and humidifier • Perform dynamic simulation and validate with transient data • Test scenarios for alternative operation

testing began in Morgantown in 1967 and ended as a separate program in 1976 when development of the cleanup system began. Over this period, 81 test series were run on 15 different coals and coal mixtures ranging in size from 2-inch to run-of-mine.

This first phase of testing demonstrated the operability of the gasifier, and its capability for continuous operation at pressure on a wide spectrum of coals, including highly-caking coals. The coals tested ranged from anthracite to lignite. The only coal which created operating problems was North Dakota lignite which, as anticipated, suffered severe decrepitation and resulted in high dust loadings in the product gas. During this period, a fixed back-pressure orifice was utilized and consequently, pressure and flow were not independent. In the present setup, a control valve permits control of back-pressure independent of gas flow. This provides closer control of bedflow velocities and attendant reduction of dust carryover.

An initial performance data base was established for near-atmospheric and pressure operation. Tar- and dust-free gas heating values were generally in the range of 130 to 150 British thermal units per Standard Cubic Foot (Btu/SCF). Calculated cold gas efficiencies were generally in the range of 60 to 80 percent. (Uncertainty in this value was a result of the inability to accurately measure product gas flows directly at that time, because the gas could not be cleaned to a level consistent with reliable instrument accuracy. This capability is now developed and is an example of a means for upgrading the data base).

Improving the reliability of the gasifier system which includes auxiliaries such as coal receiving, handling, and lockhopper feeding, ash letdown and disposal, air and steam supply systems, and fuel gas incineration, has been a major concern and effort. Many design modifications have been engineered and successfully demonstrated. Some of these design improvements are listed below.

- Development of an hydraulic grate drive system for controlled ash removal from the gasifier. This feature facilitated the maintenance of an established ash level, critical to process stability.
- Development of an improved coal feeding system featuring metering valves and screw feeders, which gave a positive means of transporting batch-weighed coal into the gasifier at a constant rate. Consistent output gas properties are contingent on constant uniform coal feeding. The screw feeders also permit use of coal fines since they eliminate coal hangup and the inevitable resulting blockages due to tar formation.
- Development of a nuclear detector system for measuring bed depth and void formations. This non-intrusive capability provided the information needed to maintain stable bed levels, critical to a consistent gasification process.
- Development of valid sampling and analysis procedures that function in a complex and/or harsh environment.

In Phase II testing and prior to embarking upon a program for construction and evaluation of a full-scale gas cleanup train, METC fabricated and tested a side-stream cleanup system capable of processing 20 percent of the gasifier output gas. This testing started in June 1976 and was completed in 1978. During this phase, nine series of tests were completed in more than 750 hours of operation. In addition, a preliminary gas turbine materials erosion/corrosion test on cleaned low-Btu gas was performed at METC in cooperation with the General Electric Company. The combustion and turbine simulators were operated on cleaned low-Btu gas for a total of 144 hours. While encouraging, the short-term results were not conclusive and it was determined that longer-term testing was required.

Various gas cleanup configurations were tested and evaluated for their effectiveness in cleaning high-volatile bituminous coal product gas streams to suitable levels for end users. Product gas, byproducts, and effluent data were characterized for the various configurations tested. Based on this information, component designs and an initial configuration for the full-flow gas cleanup train were selected. A key accomplishment in Phase II testing was the demonstration of the feasibility of the "dry tar" removal concept. This permitted the condensation and removal of the high-molecular-weight tars without the need for costly water/tar separation equipment that is associated with commercial deluge-quench systems.

Phase III testing, evaluation of the FFCUS, began in September 1978. Initially, only the upstream cleanup train components, i.e., the dust cyclone, humidifier, and tar separator were utilized. Once these units were evaluated and the necessary modifications were made to ensure satisfactory operation, the remaining downstream components were sequentially added. Accomplishments in the first three test series in this phase included:

- The redesigned screw feeder bearing and seal assemblies were proven to be successful and eliminated one of the major causes for run interruptions.
- The type and sizing of single-phase humidifier nozzles were established for full-flow conditions. These nozzles were arranged in a multiple array, using filtered recycled sour water and cascade controlled on the basis of humidifier outlet gas temperature. Two-phase nozzles, using nitrogen or eventually using recompressed product gas as the propellant, were economically and performance-wise inferior to the single-phase type, particularly at higher pressures. A technically and economically viable gas quenching operation was crucial to the dry-tar feature for removing high-molecular-weight tars and to the ensuing continued development of the sequential gas cleanup system.
- A new stirrer drive was installed and tested. It provided controlled, trouble-free operation. This added substantially to system reliability and enhanced gas properties through improved bed-density control.

- A cyclone-type tar separator was selected as the most efficient means of removing the high-molecular-weight tars exiting the humidifier. A number of alternative schemes were tested (including several baffle arrays, orifice-impact plate arrangements, and a settling chamber), but proved less desirable.

In Phase IV, the Stretford Sulfur Removal System was added to the FFCUS, giving METC the potential to produce relatively large quantities of clean, nearly sulfur-free, fuel gas. System testing is presently in this phase. The current cleanup system configuration, in sequential order, consists of a cyclone particulate separator, humidifier featuring single-phase spray atomization nozzles, a cyclone-type tar separator, a venturi scrubber, a direct contact cooler, an electrostatic precipitator (ESP), a Stretford system for sulfur removal, and a final water scrub column. The ESP was relocated from upstream to downstream of the direct cooler in the hope that it would operate more effectively in this less hostile environment and reduce hydrocarbon levels entering the desulfurizer. All components have been developed and tested through an initial phase and have been found to perform satisfactorily, although some mechanical refinement of the ESP and the Stretford system are in progress.

During Phase IV, highly-caking Pittsburgh No. 8 coal has been processed to produce an ultra-clean, low-sulfur fuel gas of approximately 170 Btu/SCF. Six test series have been run to date for a total operating time exceeding 8000 hours. Test Run 98, conducted in July and August 1981, logged 733 hours of operation with an availability of 93 percent. Accomplishments during this phase included:

- The Corrosion/Erosion Test Facility was supplied with fuel gas for 1000 hours in three test phases. This was in support of high temperature (2600 degrees Fahrenheit or °F) dynamic and static screening tests of candidate advanced ceramic turbine materials.
- Tar/Fines utilization capability was successfully demonstrated in a test using briquettes made from coal fines and high-molecular-weight tars extracted by the cleanup system. The quantity of extracted tars used in this test was shown to be adequate to bind the 50 percent of coal fines (<1/4-inch size) associated with run-of-mine coal. This is important to users unable to gasify coal fines. More definitive follow-on system characterization tests are presently scheduled.
- System automation activities have favorably impacted economic and operational factors. Manpower requirements have been halved while data quality, resulting from more stable operating conditions, has dramatically improved. The operators have been relieved of numerous mundane, repetitive duties and consequently can more effectively address the basic process parameters and test goals. Automated control functions include coal handling, bed height, system pressure, process temperatures, air-steam ratio, ash level/removal, data acquisition and processing.

- Environmental health and safety (EH&S) research and results are being compiled into a detailed report. Substantial work has been accomplished in characterizing process and effluent streams to help assess potential hazards to personnel or the environment. Findings and accomplishments in these areas include:
 - Preliminary pollutant production characteristics have been developed based on comprehensive environmental characterization during Runs 97 and 98.
 - The workplace air space does not constitute an extraordinary environmental hazard when reasonable guidelines are followed for operating procedures, protective attire, and selective use of respirators.
 - Ash properties from the fixed-bed gasifier meet Resource Conservation and Recovery Act (RCRA) guidelines for disposal through landfill techniques. This resolves major logistical and environmental concerns for large plants generating similar ash.
 - Substantial wastewater analytical data have been generated in support of external wastewater treatment programs.
- Modeling activities have been extensively supported through cooperative system operations and the resulting data acquisition. The models are essential in characterizing systems and components for economical and technical purposes. Predictions of performance, through extending actual performance data as well as scaling parameters in future plants, are important elements of the gasification data base. Although this activity is separately reported, the associated areas addressed and accomplished include:
 - The models of the gasifier by Wen, the humidifier by Physical Sciences Inc., and the Stretford system by METC have been used to develop an integrated Advanced System for Process Engineering (ASPEN) simulation of the fixed-bed gasifier and cleanup system.
 - The Wen gasifier model has been upgraded and used to predict operating parameters for oxygen-blown operation of the METC fixed-bed gasifier.
- System reliability and operability have been demonstrated during more than 2,300 hours of Phase IV testing. The following areas of accomplishment contributed significantly to improved operations.
 - A slotted, Bosh (wear) ring design has been successfully developed and tested that does not suffer any of the thermally induced warpages experienced frequently in the old design. Warpage of this ring, located in the grate area, results in channeling of inlet air. This channeling results in hot spots, uncontrollable fire zone size and location, thermal damage to grate area components, and eventual shutdown for repairs.

- Surface hardening technology has been successfully applied to components suffering severe abrasion and erosion damage. A diffusion coating of boron carbide processed to a depth of approximately .020 inch has dramatically extended the useful life of the tar separator cyclone. Development testing is still ongoing with extremely encouraging results. Stirrer arms have been hardened using a 1/8-inch thick weld overlay coat of Titanium Carbide/-Stellite 6 and a subsequent diffusion coat of boron carbide. The stirrer arm configuration has also been redesigned to reduce torque requirements, improve bed agitation, and reduce manufacturing costs. Although long-term evaluation is ongoing, these design changes, coupled with surface hardening, have virtually eliminated concerns about stirrer abrasion.

Table 2 summarizes general run parameters and accomplishments achieved during Phases III and IV of the test program.

1.3 GOALS FOR FISCAL YEARS 1983 AND 1984

The desired near-term goals of the fixed-bed gasification program can be broadly distributed among the major program components shown in Figure 1. These goals, based on at least four additional test runs, are enumerated in five separate categories (summarized in the last column of Table 1).

A primary objective of these test runs will be to generate data from the gasifier and cleanup system in the oxygen-blown mode. This will be performed in the following sequence: first, test the functional capability of the new hardware; second, conduct tests comparing the gasifier performance with oxygen to the many tests conducted using air and Pittsburgh seam coals; and last, conduct complete characterization of the gasification of North Dakota lignites. R&D activities will be conducted in the areas of: process design; environmental health and safety; computer simulation; analytical sampling techniques and on-line analysis; and process components development.

An environmental characterization will be performed to resolve several issues related to dry-bottom fixed-bed gasification systems such as the Great Plains Gasification Project. Comprehensive information will also be obtained to compare the environmental differences between air- and oxygen-blown operation. Light and heavy hydrocarbon liquids will be sampled (especially during lignite runs) for comprehensive biological analysis. In addition, the Stretford Desulfurization Process will be characterized from the standpoints of pollutant capture, liquor chemistry, and development of process design criteria. Development of advanced analytical techniques will continue, partly in conjunction with the environmental R&D effort. Furthermore, this effort will include the continued testing of laser-induced, on-line concentration measurement techniques. Computer models will be used to assist test planning and, in turn, test data will also be used for model verification. These include models of fixed-bed gasifiers (dry-bottom) using lignite coal, the Stretford desulfurization unit, rigorous models of the METC direct cooler and transient/-dynamic models of the gasifier. METC's Test-Data Data-Base (part of the METC Gasification Technology Data Base Project) will also be used to store and analyze the data. Finally, the performance of new and/or improved hardware components will be evaluated in upcoming test runs. Several of these (e.g., the gasifier stirrer) will be designed with hardened surfaces to study resulting increase in operating life.

TABLE 2. METC STIRRED FIXED-BED GASIFIER AND FULL-FLOW CLEANUP SYSTEM RUN SUMMARY

	RUN NO.	COAL TYPE	PRESSURE (PSIG)	ELAPSED TIME (HOURS)	GASIFIER MODIFICATIONS	CLEANUP SYSTEM MODIFICATIONS	HOLMES-STRETFORD DESULFURIZATION	COMMENTS
	91/92	Pittsburgh #8 (Arkwright)		91		Tested system through tar separation; high-efficiency dust cyclone failed rapidly		Tested various dust cyclones and tar separators
Phase III	93	"	118	304		Tested nozzles in humidifier		"
	94	"	131	206	Hydraulic Stirrer Drive	Venturi scrubber added, short humidifier, alternate tar separators, sidestream COS conversion		Upper limit of 60 MSCFH in humidifier; alkali level in gas measured by "Ames" meter
	95	"	211	608	Single-arm stirrer	Direct cooler added, enlarged humidifier, single-phase nozzles	Startup, system upsets	Humidifier and nozzles acceptable; HSDU reduced H ₂ S to 10 ppm
	96	"	200	170	Instrumented stirrer excellent for bed control	Piping changes to eliminate upsets, ESP startup	Startup mode, operational problems	First phase of ceramic materials exposure completed; HSDU reduced H ₂ S to 10 ppm
	97	"	140	383	Automatic coal feed	Multi-clone tar separator, fume vent system	Startup mode, operational problems	HSDU sulfur removal acceptable; effluents/ industrial hygiene data, wastewater collected
Phase IV	98	Kitanning (low Sulfur)	100	733	New stirrer design	Continued ESP tests	Not operated	Effluents data and wastewater collected; EPA/radian sampling
	99	Pittsburgh #8	160-200	300	Tested new stirrer coatings, automatic ash removal	ESP relocated downstream of direct cooler	Performance testing gave H ₂ S removal to 400 ppm with acceptable carryover; sulfur produced	Gas to HSDU acceptable; effluents/ industrial hygiene data collected
	100	"	150	96	Tested automatic coal feed controlled by gasifier bed level; tested gasification of briquettes	Added droplet separators in Stretford piping	Tested enlarged sieve tray holes in absorber; near design sulfur removal achieved at design liquor flows	Stirrer shaft seal excessive leakage

These tests have been integrated into a comprehensive plan. Each research project will be conducted in a staged manner to allow the experience gained from each test to direct the parameters of study for the next test run. Figure 3 presents the test schedule for Test Run 101, next in the current series of tests. The elements of the test schedule are:

- Anthracite coal will be used for initial "Light-Off" to warm up the system and avoid condensation of tars in the cold equipment.
- Characterization of the Stretford Tray hydraulics will be conducted at varying gas velocities.
- Arkwright, a locally available Pittsburgh #8 seam coal, will be used for stabilization of the system and for oxygen gasification check-out tests.
- Briquettes made of crushed coal and a binder of gasifier tar will be tested to determine the fate of the tars when recycled and how well briquettes hold up inside the gasifier.
- Blacksville coal (used to manufacture the briquettes) will be tested to quantify differences between the two feedstocks.
- Transient analysis studies will be conducted to provide dynamic behavior data of the system for validation of computer simulation programs.
- Tests will be conducted to determine the dynamic effects of alternate stirrer operating modes on gas quality.
- Tests will be conducted to verify the efficiency of the ESP at hydrocarbon mist removal.
- The Peerless Separator, a commercially-manufactured tar separator, will be tested to determine the effectiveness of a multiclone device for separating tars.

2.0 INTRODUCTION

The purpose of this report is to summarize the development of the METC high-pressure fixed-bed gasifier and cleanup system. This report documents the system's evolution since its inception through the end of 1982, and presents data representative of its performance. For complete information concerning any given test run, inquiries should be addressed to METC. Reports covering major activities of this program are planned for the near future. A synopsis of major program accomplishments was included in Section 1.0 with the highlights of testing planned for 1983 and early 1984. Section 2.0 details the background and program objectives of the fixed-bed gasifier and cleanup system. A detailed description of the function and operation of each component of the facility appears in Section 3.0. Section 4.0 describes many of the complementary programs implemented in conjunction with the system. A discussion of the results of system testing, including complementary programs,

FIGURE 3. METC FIXED-BED GASIFICATION PLANT TEST SCHEDULE FOR RUN 101

is contained in Section 5.0. Section 6.0 is a glossary of acronyms and abbreviations, Section 7.0 is a list of reference documents, and Appendix A gives dates, coal tested, and operational hours for each of the 100 test runs conducted through 1982.

2.1 BACKGROUND

The low-pressure gas producer concept for coal gasification is a proven method of producing a usable gas fuel. Numerous producer plants were operational in the United States as recently as the 1950's. However, the completion of interstate natural gas pipelines in the 1950's introduced clean, low-cost natural gas to wide areas of the nation and doomed the gas producer industry. In fact, the availability of lower-cost natural gas is still the major impediment to a revival of the low- and medium-Btu gasification industry. The recent rapid escalation in natural gas prices and uncertainties in the long-term availability of natural gas are significantly changing this situation. However, a favorable economic climate vis-a-vis natural gas prices will not in itself guarantee a swift changeover to coal gasification by American industry. A secure and reliable fuel source is vital to industry, and there are still many uncertainties associated with coal gasification. These uncertainties stem from potential problems with present-day U.S. environmental requirements, the lack of data on large-scale gasification plant performance and reliability, and the lack of adequate and pertinent operational experience.

Recognizing that industry's concerns could seriously delay the implementation of this technology, DOE has embarked on programs that sponsor the development of improved technology to a proof-of-concept stage and the development of a data base on the full range of coals and environmental effluents. In 1967 a coal gasification test unit was installed in Morgantown and the capabilities were developed to generate data over a wide range of operating conditions and coal feeds. The METC gasification system has been expanded so that it can now gasify the entire spectrum of U. S. coals from lignite to anthracite, and can clean and desulfurize the resulting fuel gas so that it is available for testing various applications. This unique test facility has made significant contributions to the publicly-available fixed-bed gasification data base in the United States.

This report presents the objectives and accomplishments of the METC fixed-bed gasification program, describes the evolution and present physical configuration of the gasification and gas cleanup system, discusses the results of the various test phases of the program, and describes complementary projects in the areas of process modeling and environmental characterization projects. It also outlines METC's goals and future plans for this facility.

2.2 GASIFICATION PROGRAM OBJECTIVES

Fixed-bed gasification represents the most highly developed of all gasification technologies. It is potentially the most efficient gasification process, and it presents environmental problems. The major drawbacks of commercial European fixed-bed gasifier technology have probably been the lack of a demonstrated ability to process highly-caking coals, and the inability to clean the product gases so that they can meet end-use and environmental requirements. These problems were recognized at Morgantown when plans were made in 1963 to construct a nominally one-ton-per-hour fixed-bed coal gasifier. The heart of this facility, a 3.5-foot-diameter, pressurized gasifier, is capable of gasifying all ranks of U. S. coals, including the highly-caking eastern coals.

In 1976 METC began construction of a gas cleanup facility in order to evaluate environmental problems associated with fixed-bed coal gasification plants and to develop improved cleanup systems. The construction and preoperational testing of this FFCUS was completed during the fall of 1980; the METC facility can now gasify all U. S. coals and remove particulates, tars, oils, sulfur-containing gases, and alkali metals from the resulting fuel gas streams.

Since installation of METC's gasifier in 1967, gasifier operation has been tested and evaluated on all major ranks of U. S. coals. The purposes of the initial testing phase were to demonstrate operation at pressure on highly-caking coal, develop a data base on a wide range of U. S. coals, and improve the operability and performance of the gasifier and the coal feeding system design. The first phase of the program originally proceeded gradually, at a rate consistent with modest funding levels and consistent with the absence of a major drive towards this technology. This situation changed in the mid-70's as the U.S. became aware of its limited oil and natural gas supplies, and began to appreciate the need to safeguard the environment. Cost studies indicated that combined-cycle gas turbine and fuel cell plants powered by coal-derived synthetic fuels could compete economically with conventional power systems. The prospect of greater thermal efficiencies was seen with advanced cycle design. Thus, the stage was set for an increasing interest in gasifier development and an adequate system for cleaning the fuel gas stream.

Gas stream cleanup testing at METC began in June 1976. The purpose of this testing phase was to clean the fuel gas to the low impurity levels required by some of the more advanced power generating systems then under development, and to accomplish this in a manner consistent with concerns over protecting the quality of the environment. In pursuing these goals, novel techniques of gas cleaning which had not been tried in earlier low-pressure gas producers were evaluated. These techniques may not require as extensive a waste water treatment as that needed with existing commercial deluge-quench techniques. These methods provide a more complete separation of coal gasification by products, thus, potentially improving economics. The advanced power system concepts under development include combined-cycle systems which burn cleaned coal-derived fuel gas in gas turbines, and fuel cell combined-cycle power plants which convert fuel gas energy directly into electrical power via electrochemical reactions. Both of these concepts require ultra-clean fuel gas, since even extremely low levels of particulates and alkali metals can cause erosion and corrosion damage to gas turbine blades. Concentrations of sulfur and ammonia gas impurities as low as one part per million can produce unacceptable degradation in fuel cell power plant output. The improved gas cleaning techniques are also potentially applicable to oxygen-blown (medium-Btu) gasifiers which provide feed gas to synthetic natural gas and liquid fuels plants.

The above technical and environmental issues form the basis for a specific set of objectives for the METC gasification system, which are as follows:

- Develop Technical Data Base - Provide a publicly available data base for industry on a fixed-bed gasifier and gas cleaning system operating on wide ranges of U.S. coals, feed rates, and pressures. Develop and demonstrate reliable gasifier performance for this spectrum of coals including the highly-caking coals. Investigate the effects of operating conditions on system efficiency, component performance, by-products, and effluents.

- Test Novel Cleanup System - Develop and demonstrate reliable performance of a novel gas cleaning system that sequentially removes particulates, tars, oils, sulfur-containing gases, and other gas contaminants while producing a clean, environmentally acceptable fuel gas. This process is an alternative to the deluge-quench systems currently used commercially, and has potential economic and environmental advantages.
- Perform EH&S Safety Research - Address the EH&S aspects of the fixed-bed gasification system. Identify the type and quantity of gaseous and liquid contaminants that may pose hazards to workers or the environment. Quantify worker exposure to hazardous materials and minimize these potential hazards by developing safer effluent handling systems and operational techniques.
- Support Downstream Testing - Provide a source of coal-derived fuel gas for various end-use testing. The sequential cleanup system can provide gas in varying stages of cleanliness up to a turbine-quality fuel. As such, it can support a wide variety of testing including combustion studies; turbine blade materials evaluations for corrosion and erosion, development of control systems and instrumentation, and testing and evaluation of mechanical components and operational procedures.
- Develop and Test New and Improved Sampling and Analytical Techniques - Conduct on-line/in-situ characterization of major/minor gas phase species as well as carryover of contaminants, i.e., particulates, hydrocarbons and heavy metals.
- Support and Apply Computer Modeling - Conduct computer-aided modeling and simulation of the fixed-bed gasifier and FFCUS to predict the performance of the facility at varying conditions and with a multiplicity of feed coals. Validate these models through the interpretation of test run data.

The program is presently in Phase IV of the development and evaluation sequence. The phases are somewhat overlapping since the testing of new ideas and components in all systems is an ongoing process. The reason for adopting this methodical "building-block" approach was to maximize the quantity of information and data gathered with respect to the amount of funding invested in the program. For instance, rather than move immediately from gasifier to FFCUS testing, METC chose to develop a small-scale side-stream gas cleanup train. The amount of gas processed in this side-stream cleanup train was approximately one-fifth of the total gas flow stream. This procedure enabled METC to evaluate and test process components and cleanup train arrangements of small size and at relatively low cost before making a commitment to the larger and more expensive process units and configurations. In like manner, the FFCUS had to reach a certain minimum level of gas cleaning performance before the sulfur removal system was added to the gas cleanup train.

3.0 GASIFICATION SYSTEM DESCRIPTION

The current configuration of the METC fixed-bed gasification system has evolved since its inception in 1967 to the current process configuration (see Figure 1 in Section 1 of this report). The following discussion describes the configuration and function of each component of the system as it currently stands and also explains its evolution through the "building-block" phases of the test program.

3.1 GASIFICATION SYSTEM DESCRIPTION

Figure 4 shows the plant coal handling and gasifier systems. Coal crushed to less than two inches is delivered by truck, unloaded into a truck unloading hopper, and conveyed via a belt conveyor and a bucket elevator to two enclosed storage silos. The smaller silo has a capacity of 25 tons and is used to store anthracite coal. Anthracite coal is used to start the gasifier since it contains very little volatile matter and avoids fouling the system with tars and oils which might condense on the cold downstream components and piping. The large silo has a storage capacity of 100 tons and stores the normal operating coals. This storage capacity is sufficient to carry the gasifier through a weekend at maximum operation capacity.

Coal feed for the gasifier is discharged from the bottom of the silo onto a belt conveyor. The coal drops onto a weigh cell, the output of which is utilized to record feed rate; the coal is then conveyed by bucket elevator to a dual, pressurized coal feeding system. The coal feed system is shown in Figure 5. The dual feed system was selected in order to provide redundancy and to avoid potential operating interruptions brought about by malfunctions in this sensitive area of the process. Each feed train is capable of providing a coal flow of approximately one ton per hour to the gasifier.

The gasifier and coal feeding system are designed to operate at pressures up to 300 pounds per square inch gauge (psig). The coal is fed through the two pressurized lockhoppers equipped with pressure isolation ball valves. When the lockhoppers are filling, the lower ball valves are closed, isolating the gasifier. Nuclear level detectors are utilized to determine when the hoppers are empty.

When coal is charged into the gasifier, the upper lockhopper valves are closed, isolating the gasifier system feed hopper. The coal is metered by a rotary feeder and driven into the gasifier by a screw conveyor. The rotary and screw feeders provide a continuous coal feed to the gasifier. The rotary feeders are adjusted to maintain the desired gasifier throughput (as determined by the bed level). The screw feeders form a high-speed, positive displacement device which transports the coal from the metering device to the reactor bed fast enough to preclude the swelling and devolatilization problems associated with bituminous coals. Experience has shown that a continuous feed will avoid the wide temperature and constituency fluctuations in the product gas caused by intermittent charging of coal.

As the coal passes down through the gasifier, the volatile matter and carbon are consumed and the remaining ash passes through the grate and is collected in the bottom of the gasifier. This ash buildup is periodically discharged

FIGURE 4. METC PRESSURIZED GASIFIER AND COAL HANDLING SYSTEM

from the gasifier into the ash letdown hopper. The ash letdown hopper functions similarly to the coal feed lockhopper, although in reverse. Pressure isolation valves on either end of the ash hopper allow ash to be introduced into and discharged from the hopper by gravity while at all times maintaining pressure isolation of the gasifier vessel.

Figure 6 shows an early version of the gasifier with a gravity coal feed, ash hoppers, and isolation valves. The gasifier has a 3.5-foot inside diameter and an overall length of nearly 28 feet. The upper surface of the grate is located 12 feet above the gasifier ash pit discharge flange. Air and steam are introduced below and flow up through the grate. A water-cooled stirrer arm is rotated in the coal bed above the grate. The arm also moves vertically through the coal bed and normally traverses a path from one to four feet above the grate.

A current, more detailed sectional view of the gasifier is shown in Figure 7. The lower portion of the steel gasifier shell is water-jacketed, while the upper section is expanded and lined with a refractory to the same inner diameter. The coal bed is normally controlled at a fixed depth (typically in the range of six to eight feet) and is supported by an eccentric rotating grate. The periodicity of the intermittent grate rotation controls the rate at which ash is removed from the bed and, consequently, the rate at which coal must be introduced in order to maintain a constant bed level. The eccentricity of the grate plates acts to crush any ash clinkers that may form in the gasifier between the grate and a Bosh ring protecting the steel gasifier walls.

The stirrer consists of a vertically mounted rotating shaft with horizontal arms. Both the shaft and arms are water-cooled. The purpose of the stirrer is to ensure a uniform gas distribution in the coal bed, both eliminating the formation of channels within the coal bed and breaking up any soft agglomerations which are typically formed when operating with caking coals. Coal swelling and agglomerating conditions, existing inside the gasifier, tend to plug sections of the gasifier and create bridging conditions. This restricts gas flow and significantly decreases throughput, carbon conversion, and efficiency.

Pressurized air and superheated steam are mixed and injected into the lower section of the gasifier. The air and steam pass up through the grate and into the coal bed. The grate is designed to evenly distribute the air/steam flow, which in turn helps cool the grate.

The chemical reactions taking place in a fixed-bed gasifier can be more easily understood if the coal bed is divided into the different reaction zones shown in Figure 8.

The topmost part of the coal bed acts as a drying zone. As the coal is fed into the gasifier from the top, it contacts the hot gases generated below. These gases heat the coal and evaporate the moisture. The temperature of the coal, which is now dry, continues to increase as the coal proceeds further into the bed. This preheating of the coal causes the trapped and dissolved hydrocarbon gases and liquids to boil off and escape from the coal particles. This process is called pyrolysis or devolatilization. After devolatilization, the coal is predominantly char or carbon plus ash. This carbon reacts with

FIGURE 5. PRESSURIZED COAL FEEDING SYSTEM

FIGURE 6. EARLY VERSION OF FIXED-BED GASIFIER

FIGURE 7. SECTIONAL VIEW OF CURRENT FIXED-BED GASIFIER

FIGURE 8. GASIFIER REACTION ZONES

water (H_2O), hydrogen (H_2), and carbon dioxide (CO_2) in the gasification zone to produce fuel gas products which are primarily H_2 and carbon monoxide (CO) and methane (CH_4).

The gasification reactions are endothermic and ideally occur at temperatures above 1500°F . Heat input is required to bring the reactants up to temperature and to provide the reaction heat. The oxygen in the air stream combines with coal to supply this necessary heat in the oxidation zone which starts about one foot above the grate. A 12- to 18-inch layer of ash between the oxidation zone and the grate insulates the grate from the high combustion temperatures ($> 2000^\circ\text{F}$). The ash layer also serves to preheat the air and steam. Control of the quantity of steam flow to the gasifier determines the oxidation zone temperature. This control helps prevent ash slagging which can damage the grate and upset gas flow distribution. The steam also participates in the gasification process, reacting with carbon and CO to produce hydrogen. In this oxidation process, nearly all the remaining carbon is converted to CO and CO_2 .

Operation at elevated pressure aids the gasification process by increasing coal throughput for a given reactor volume. Higher pressure, greater than 3 atmospheres, also promotes methane formation by shifting reaction equilibrium points. For this reason, higher-pressure processes are favored for production of synthetic natural gas (to increase the equilibrium yield of methane), while low-pressure, atmospheric processes are favored for production of synthesis gas (H_2 and CO).

Either oxygen or air can be utilized as the source of oxidant for the gasification reaction. In the case of air, the major difference is the effect of nitrogen dilution of the product gas, which reduces the specific heating value of the dry gas by approximately 50 percent. Industrial heating applications and potential combined-cycle gas-turbine combustion applications, which are not significantly affected by the nitrogen dilution of the gas, can utilize ordinary air. This eliminates the expense and complexity involved in supplying pure oxygen. Gasification systems employing oxygen are primarily those utilizing the H_2 and CO in the gas as a reactant in downstream chemical processes.

As the coal is heated in the gasifier, the entrapped hydrocarbon gases and liquids boil off and are swept out of the gasifier with the fuel gas stream. If the product gas is to be cooled for transport, compression, and/or sulfur removal, these heavy hydrocarbons will condense as tars and oils. To avoid plugging and fouling of downstream equipment, the fuel gas must be cooled and the tars and oils must be removed and collected in a careful and controlled manner. In addition to the tars and oils, the fuel gas contains potentially toxic substances including phenols, ammonia, and sulfur gases which must be separated and disposed of properly. The development of process systems, equipment, and procedures to accomplish this in an efficient and cost effective manner is the subject of Section 3.2. Data description is provided in Section 5.4 and pollutant production synopsis is given in Table 39.

3.2 GAS CLEANUP SYSTEM DESCRIPTION

Gas produced by coal gasification processes has many potentially attractive uses, such as: industrial process and space heating fuel, gas turbine fuel for combined-cycle power generation, fuel cell reactant feed, and chemical feedstock to generate ammonia, methanol, and a wide range of other chemicals.

Preparing the gas for the above applications is complicated by the fact that the raw product gas leaving the gasifier contains gaseous, liquid, and solid contaminants, any or all of which may be unacceptable to the end user. A listing of the recognized contaminants follows:

- Particulates -- ash and unburned coal
- Condensable tars and oils
- Ammonia
- Phenols
- Sulfur gases -- hydrogen sulfide (H_2S), carbonyl sulfide (COS), carbon disulfide (CS_2), etc.
- Alkali metals -- primarily sodium and potassium
- Heavy metals -- primarily vanadium

Only the simplest combustion processes can use the raw, coal-derived gas directly, and only when the combustion process is closely coupled with the gasifier and is not restricted by limitations in the flue gas sulfur content. If the combustor is located at a distance from the gasifier, the raw gas will cool and tars will condense, plugging gas lines and burner equipment. Tars produced in the coal gasification process cover a wide spectrum and include high-melting, high-boiling, semi-solid, pitch-like materials. Analysis of these materials is presented in Section 5.3.1. Obviously, if the gas is to be transported and distributed for any distance, the tars and oils must be removed. For potential gas turbine use, stringent limitations have been placed on allowable particulate loadings in order to control turbine blade erosion. The presence of alkali metals in the gas stream presents corrosion problems for high-temperature turbine materials. Gas turbine industry fuel specifications, when translated to a 150 Btu/SCF fuel gas, make it necessary to hold the alkali metal concentration to less than one part per million. Fuel cell uses similarly require very low particulate loading and the removal of ammonia and sulfur to levels below one part per million. The phosphoric acid cell is sensitive to ammonia, and the molten carbonate cell is sensitive to sulfur. Table 40 compares the limits for advanced technology applications with the levels currently measured in the gas stream.

3.2.1 Side-Stream Cleanup System

METC is engaged in investigating and developing gas cleaning systems and techniques that will apply to all of the above uses. Initial gas cleanup tests used conventional gas processing components, and the ability to clean a

side-stream of the main gas stream was demonstrated. The side-stream cleanup train processed approximately 20 percent of the total gas flow. This approach, utilizing small-scale components for the initial development and testing, was adopted in order to minimize equipment costs and the turnaround time associated with the trial-and-error testing of various cleanup train configurations. The purpose of this testing was to demonstrate that the gas could be cleaned to the exacting levels demanded by some of the advanced applications being considered for coal-derived fuel gases, and also to provide a basis for designing the FFCUS.

Several cleanup system configurations were tried. In all of these configurations, the main gas flow stream passed through a particulate removal cyclone to a flare stack.

First Side-Stream Cleanup System Configuration. The first side-stream cleanup train configuration is shown in Figure 9. Data and a discussion of the results of these tests is included in Section 5.2.1. The cleanup train consisted of a humidifier and disengagement chamber (tar separator), a venturi scrubber and cyclone, and a valve-tray scrubber and knock-out drum. The side-stream then joined the main gas stream to the flare stack. In this configuration, gases flowed directly from the gasifier to a humidifier where once-through water was sprayed. The water evaporated into the gas stream, lowering the temperature so that it approached the saturation point. The condensing tar droplets were carried with the gas stream out of the humidifier into the disengagement chamber or tar separator. This tar separator vessel provided a volume where the tar droplets could coalesce and drop out of the gas stream. In the process of evaporating the spray water, the gas stream was cooled from the 800-1200°F level to approximately the 320-360°F level.

At the latter temperature range, the heavy tars condensed out of the raw gas stream. The gas then entered the venturi scrubber where additional water cooled it to 110-120°F. The remaining tars and most of the light oils condensed at this temperature. The gas was dewatered by cyclone separation before passing through a four-plate valve tray scrubber for final polishing with additional water. The gas exited the tray scrubber at approximately 85°F, at which point the majority of all the tars, oil, and particulates were removed. The synopsis of these data are provided in Section 5.4.2.

Preliminary Gas Turbine Combustion Tests Configuration. A preliminary program was conducted on a turbine simulator test rig in order to evaluate the combustion characteristics of coal-derived low-Btu gas in a prototype gas turbine combustor, and in order to determine the erosive and corrosive potential of the combustion gases on turbine materials. A schematic of the test rig is shown in Figure 10. This test program was performed in cooperation with the General Electric Company (Day 1977).

The objective of this program was to provide engineering data on the performance of selected gas turbine nozzle and bucket materials in low-Btu combustion gas environments. Natural gas was burned in the preheater to heat air to 570°F, simulating gas turbine conditions. This preheated air was burned with cleaned low-Btu gas in the combustor section, raising the temperature to between 1750° and 1830°F. The combustion gases flowed through the inside of the combustor section and passed over the cooling pins, sensors, and turbine element test specimens.

FIGURE 9. FIRST SIDE-STREAM GAS CLEANUP TRAIN CONFIGURATION

FIGURE 10. TURBINE MATERIALS - COMBUSTION TEST RIG

Second Side-Stream Cleanup System Configuration. The second series of side-stream tests incorporated several major changes in the cleanup system configuration (Figure 11):

- The low-Btu gas path included the particulate removal cyclone to reduce dust loadings input to the humidifier.
- The venturi scrubber and downstream cyclone were removed from the cleanup train in order to simplify the system and investigate the potential of performing the entire light tar and oil removal function with the valve-tray scrubber/knock-out drum configuration.
- The waste water decanter system was upgraded to collect all the scrubbing water streams so that this water could be filtered and recycled back to the process units.

Data from these tests are described in Section 5.2.3.

Third Side-Stream Cleanup System Configuration. The third series of side-stream tests used the same basic configuration as the second series, with one change and one addition:

- A two-phase nozzle was installed in the humidifier. The nozzle used nitrogen to attempt to atomize the scrubbing liquor, with the intent of producing droplets one to five microns in size.
- A packed-column scrubber using a once-through water wash was added downstream of the knock-out drum. The purpose of this scrubber was to demonstrate removal of trace quantities of alkali metals, namely sodium and potassium, to levels required for gas turbine operation.

Data from these tests are described in Section 5.2.4.

3.2.2 Full-Flow Cleanup System

The FFCUS configuration was designed on the basis of prior side-stream testing and is being developed as an alternative to conventional deluge-quench gas cleanup technology. The METC approach is novel compared with conventional coal gasification gas cleaning because it features sequential removal of particulates, tars, oils, sulfur, alkali metals, and other trace contaminants in the order shown in Figure 12. By producing individual effluent streams, the level of dust/tar/oil/water separation and subsequent processing that current commercial deluge-quench technology entails is dramatically reduced. A key development in the METC process is the humidifier vessel which removes the high-molecular-weight hydrocarbons in a manageable "dry-tar" state. A study comparing the two systems on a process technology and economic basis was sponsored by METC. The study was based on the commercial-scale application of the METC "dry-tar" gas cleanup system using raw gas from an air-blown fixed-bed gasifier using Pittsburgh seam coal. This study concluded that the METC system was a viable and possibly a superior alternative to the conventional

FIGURE 11. MODIFIED SIDE-STREAM CLEANUP CONFIGURATION

FIGURE 12. CURRENT CONFIGURATION OF FIXED-BED GASIFIER AND FULL-FLOW CLEANUP SYSTEM

deluge-quench gas cleanup system. The study also found the METC system approach appears to be better environmentally and to have more operational flexibility when considered on a total facility basis. The basic system is described below, and the development and test results of this system are described fully in Section 5.3.

As shown in Figure 12, raw gas from the gasifier at approximately 1000°F and up to 300 psig enters a low-velocity cyclone where 85 to 90 percent of the entrained particulates, primarily char, are separated from the gas. Removal of this dust reduces the viscosity of tars condensing downstream by reducing the solids loading to a manageable state. The dust is recovered through a lockhopper and if agglomerated, is available for recycle to the gasifier. The cyclone outlet gas is next treated in the humidifier vessel.

In the humidifier (see Figure 1 in Section 1 of this report) recycle water (atomized by single-phase spray nozzles) is used to cool the incoming gas stream (approx. 1000°F) to a temperature that is 25-50°F above its dew point (300-400°F). This results in the condensation of high molecular weight tars. A viscous tar stream exits the system through a lockhopper in a "dry-tar" state that is fluid at >200°F but solidifies at room temperature. Before the present configuration was determined, this process step was the subject of extensive development activities involving vessel size parameters, development and testing of two-phase atomization nozzles, and a study of the suitability of a spinning disc atomizer. The vessel size was expanded to feasible limits to provide adequate cooling, but did not provide adequate tar removal. The nature of the tar aerosol formed as a result of the temperature reduction in the humidifier is such that simple gravity separation does not fully separate the droplets from the gas. Consequently, a separator was added downstream from the humidifier to remove tar droplets not captured in that vessel. Various configurations of droplet separators were evaluated for facilitating tar removal performance (see Section 5.3.1). A cyclone-type design was selected as adequate for this severe service. The effluent tar stream is removed through a lockhopper.

The gas then flows to a venturi scrubber where a very fine tar mist, not removed by the humidifier or tar trap, is separated from the gas stream. This process utilizes recycled venturi scrubber water (liquor) which is separated from the tar stream in a pressurized decanter vessel. The effluent tar stream contains some lighter oils and consequently, this tar remains liquid at room temperature.

After the venturi scrubber, the gas stream flows to a direct cooler operating with recycled water (liquor) and is cooled to approximately 100°F. This is the only nonadiabatic step in the process. This cooling step condenses and removes the unconverted steam fed into the gasifier, the water atomized in the humidifier, and the condensable light oils from the gasification process. This gas cleanup system approach results in the liquid condensate from the system being accumulated at system pressure in the direct cooler decanter. A major virtue of this approach is that the mid-level of this decanter liquor is sufficiently "water-like" to be directly recyclable without any of the depressurization or treatment steps required in "conventional" systems. The recycle water is pumped from the decanter mid-level through indirect coolers (shell and tube heat exchangers) wherein the heat energy originally extracted from the gas is transferred to process water and leaves the system. There are

three small byproduct liquid flows from the decanter. The largest is "surplus" water which is actually the fraction of steam introduced to the gasifier that was not converted into product gas. This is the only wastewater stream that must be treated, and the treatment scheme requirement is dictated by the disposition (e.g., in-plant re-use, sanitary discharge). The other two streams are still smaller in volume and are highly fluid, water insoluble, low-boiling-point oils with specific gravities above and below that of the water-like liquor. This method of operation produces a wastewater that is potentially more easily treated than that produced by a deluge-quench system. This is because of the reduction in contact time of the waste waters with the heavy tars, reducing the level of water-soluble hydrocarbons such as polynuclear aromatics (PNAS) in the effluent stream.

Next, the gas flows through an electrostatic precipitator (ESP) in order to reduce any remaining hydrocarbon mists, since the Holmes-Stretford desulfurization unit (HSDU) is sensitive to a buildup of contamination by hydrocarbons. The gas then goes to the desulfurization unit (see Section 3.2.3) where the major sulfur-containing constituent in the gas stream, hydrogen sulfide (H_2S), is removed. Following desulfurization, the gas stream passes to a water scrub column for removal of trace alkali metals that may have been introduced during desulfurization, since these materials can produce severe corrosion and erosion damage in gas turbines.

3.2.3 Holmes-Stretford Sulfur Removal System

In the coal gasification process, most of the sulfur in the feed coal is converted to hydrogen sulfide and to lesser amounts of carbonyl sulfide and carbon disulfide gases. METC has installed a Holmes-Stretford unit which will remove the hydrogen sulfide from the product gas stream. The commercially proven Stretford process can reduce the amount of sulfur in the gas stream to a few parts per million, and can convert this sulfur to an inert, solid byproduct. However, the process has not been proven in a pressurized gasification application. Successful demonstration at Morgantown will resolve one more area of technical uncertainty in coal gasification, and in addition, will provide the opportunity for generating a design data base for the integration of the Stretford process into other gasifier cleanup train systems.

The unit installed at METC was designed and fabricated by Peabody Engineering Systems. A flow schematic for the Stretford process is shown in Figure 13. The METC system utilizes a venturi scrubber to scrub the H_2S from the producer gas, as shown in the schematic. The venturi option is much smaller than the wooden-grid absorber towers normally associated with past Stretford system designs. However, it results in a somewhat larger pressure loss. For pressurized gasification systems, the higher pressure loss is usually not critical and the venturi option is generally more suitable. The venturi removes approximately 80 percent of the H_2S in the raw, low-Btu gas. Final cleanup of the gas stream to low-ppm levels is achieved in a small tray tower situated above the venturi. This absorber allows intimate mixing of the gas with the Stretford solution. In the venturi and absorber, the cooled low-Btu gas contacts an alkaline solution which contains a vanadium salt with an anthraquinone derivative. The H_2S in the gas stream is converted to elemental sulfur while the vanadium salt is reduced by the following reactions:

FIGURE 13. STRETFORD HYDROGEN SULFIDE REMOVAL SYSTEM

A delay tank located below the absorber provides the necessary residence time interval for the chemical reactions to proceed before the solution goes to an oxidizer tank. Since the oxidizer tank is vented to atmosphere, a flash tank is positioned between the delay and oxidizer tanks in METC's pressurized system. The flash tank depressurizes the solution and releases the dissolved gas from solution. These gases (typically small quantities of nitrogen or N_2 , CO , CO_2 , H_2 , and hydrocarbons or HC) are vented to the flare stack and combusted. The solution is then fed to the oxidizer where air is blown through the liquor to reoxidize the solution and separate the sulfur by flotation. In the oxidizer, anthraquinone disulphonic acid (ADA) reacts with the 4 valent vanadium, converting it back to the 5 valent form and is itself reduced:

The oxygen in the air converts this reduced ADA back to the oxidized state.

The overall simplified Stretford reaction is:

The sulfur formed in this process is a finely divided particulate which is floated to the top of the oxidizer by the rising air stream. A froth containing approximately three to eight percent sulfur forms at the top of the tank and overflows into a slurry tank. The slurry is pumped to a vacuum filter which discharges the sulfur in the form of a washed, wet filter cake.

For large commercial gasification operations, where the recovery and sale of pure sulfur is economical, the sulfur product can be heated and melted to separate the water and impurities in order to produce a commercial-grade sulfur with greater than 99.5 percent purity. In METC's operation, because of the very small quantities involved, the inert wet sulfur cake is either stored or disposed of in an environmentally acceptable manner.

The underflow solution from the oxidizer is sent to a pump tank and after heating or cooling, depending on ambient conditions, is recirculated back to the absorber, completing the cycle. Data from testing of the Stretford is presented in Section 5.3.2.

4.0 DESCRIPTION OF COMPLEMENTARY PROGRAMS

The operation and testing of the METC fixed-bed gasifier and cleanup system provides a vehicle for the implementation and testing of complementary programs both on- and off-site. These programs are important to the generation of a data base as wide as possible concerning all aspects of the technology. This Section summarizes the key programs implemented over the past few years in conjunction with the fixed-bed gasifier and cleanup system.

4.1 CONTROL SYSTEM IMPROVEMENTS AND INNOVATIONS

Throughout the development of the METC gasifier and full-flow cleanup system, improvements and innovations in the control systems have been implemented. Two areas are described below.

Automatic Data Acquisition and Control System (ADACS). As the scope of the project increased due to the large number of process systems being tested, METC determined that an automated data acquisition and control system should be installed on the gasifier and FFCUS. ADACS was first implemented in early 1978 with automatic logging of data on magnetic tape. ADACS is now an integral part of the operation and control of the entire process facility, and performs the following functions for the operating technicians and test engineers:

- Logs data at desired interval (typically 30 seconds) onto tape for post-processing and analysis.
- Stores most recent five days of data on disk. These data can be retrieved on line for historical display, statistical analysis, comparison of operating conditions, and event analysis (e.g., valve failure).
- Provides trend display of data over any period. Display can cover any time span and any range for the data retrieved (e.g., 0-100 percent, 50-75°F, 0-200 pounds per square inch or psi). Up to five data points at one time may be displayed.
- Plant mimics can be graphically displayed by the ADACS system. These are process diagrams of selected portions of the equipment including process data monitored by the computer. Either historical or current data may be displayed.
- Process calculations are performed on line by ADACS, converting millivolt readings into engineering units. In addition, complex calculations required for heat (energy) and material balance information are performed on line. ADACS is also used to perform data reduction of raw gas chromatograph information.
- Incoming data is checked against expected limits to verify that the instruments and sensors are functioning properly.
- ADACS is used during calibration of instrumentation to ensure the maximum accuracy possible for test data.
- ADACS provides statistical evaluation of data during testing to assist plant engineers with rapid evaluation of test conditions.
- ADACS calculates key parameters for comparison with actual operating data to determine if a process is functioning properly (e.g., Btu output, efficiency).

Integrated Control System. Operation of the FFCUS required the installation of additional instrumentation not required in the early phases of the gasification program. METC determined that a single control system should be constructed in order to consolidate the controls for the gasifier with the FFCUS. The new instrumentation is electronic (versus pneumatic) and is more compatible with the ADACS system. Installation of the controls and the transfer of the gasifier control to the new system was a major task. The nuclear level detectors on the gasifier were upgraded and other control instrumentation improvements were provided.

The major goals of Test Run 95 in the fall of 1980 were to test the new control system, tune the instrumentation for proper control element response, and acquaint the operators with the new system prior to initiation of the corrosion/erosion program.

The new instrumentation is versatile and can easily be modified as test program criteria warrant. The integration of the control instrumentation with the ADACS computer system has eased calibration and hastened modifications. The control instrumentation and ADACS are interrelated but not interdependent. Failure of the computer does not jeopardize plant operation. Similarly, the failure of a control component can be compensated for by monitoring its status on the computer. This redundancy provides a high measure of security for plant operation.

Other innovative activities more fully discussed in Section 5.1 include:

- The automation of coal feed, ash removal, and dust removal (including voice synthesizers for operator alarms). Automation of these batch systems relieves the operator of the need to concentrate so much attention on the hardware as previously required. This allows more time to monitor other operating parameters and assures smooth running conditions. A voice synthesizer was installed to provide status annunciation for the batch feeders without the distraction created by numerous bells, beepers, and hooters (see Section 5.1.1).
- The development and implementation of gasifier bed level control utilizing nuclear detectors. This was developed so that the coal feed rate could be adjusted to maintain a consistent bed level, regardless of changes in the gasifier operating parameters (see Section 5.1.2).
- Cascade control of the humidifier spray system. Humidifier outlet temperature control requires careful attention to controlling the spray water flow to each of four separate spray nozzles. Flow to each nozzle is only permitted from 50 percent to 100 percent of design to insure proper atomization of the spray water for optimum cooling. A control system to automatically maintain flow to each nozzle within the specified range and maintain constant humidifier outlet temperature, regardless of system throughput, was developed.
- Development and implementation of ash level control by means of temperature measurement on the rotating stirrer arms. Maintaining ash level at a constant depth is a key to uniform operation of the gasifier. Measurement of temperature within the moving bed is a difficult

assignment which required extensive developmental effort. This has been perfected to a reliable procedure which accurately denotes ash level within the gasifier (see Section 5.1.4).

- Development of a stirrer internal torque measurement technique to determine the resistance imposed on the stirrer arm inside the gasifier. Accurate measurement of actual stirrer torque will allow detailed information on the resistance of the reactor bed separated from the seals, bearings, etc. This information can be used to provide design data for other systems.
- Fabrication of a ramp-rate generator for implementation of transient analysis studies. The ramp-rate generator is used to provide a smooth set point change at a fixed rate in a process variable. This relieves the operator of the responsibility for manually adjusting a controller meticulously between two set points. The smooth ramp provides a cleaner input signal for subsequent data analysis.

4.2 ENVIRONMENTAL HEALTH AND SAFETY (EH&S) RESEARCH

The commercial acceptability of coal gasification technology mandates that plants operate in a manner that jeopardize neither the health and safety of the worker nor the environment of the surrounding area. DOE has a responsibility to identify and characterize those effluents and emissions that pose hazards to the worker and the environment. Once such parameters have been identified, corrective engineering designs, if necessary, can be implemented and tested. An active R&D program exists at METC in the area of environmental management and workplace health and safety. Activities related to the fixed-bed gasifier and FFCUS have increased significantly since 1979 (Test Run 95). Information acquired for on-site EH&S compliance also complements process R&D characterization efforts. The following discussion describes these EH&S activities. Results from these programs are included in Section 5.4.1.

4.2.1 Environmental Characterization and Systems Analysis

The METC system provides an excellent opportunity to conduct environmental research related to pollutant production, characterization, and environmental control technologies. Ongoing projects include:

- Environmental characterization of process streams for air-blown gasification of coal and briquettes and for oxygen-blown coal gasification.
- Development of mass balances around selected unit operations and the overall system for environmentally significant species.
- Development of thermodynamic data, reaction kinetics, and mass transfer coefficients for environmentally significant species.
- Identification, characterization, and estimation of fugitive emissions.
- Development of data in support of environmental systems analyses and modeling (models for environmental control and for vapor-liquid/liquid-ionic equilibria).

- Environmental characterization of the Stretford system.
- Comparative analyses of the METC "dry-tar" and conventional deluge-quench processes.
- Wastewater characterization and ageing studies.
- Joint data development with on-site environmental compliance activities.

Environmental Characterization and Mass Balances. In order to understand both the production and distribution characteristics of pollutants related to fixed-bed gasification, environmental characterization has been performed in streams that are internal to the process. These streams do not actually discharge into the environment, but environmental analysis of these process stream samples yields useful insight into control technology needs. To date, this effort has been restricted to air-blown coal gasification, but will encompass air-blown gasification of briquettes and oxygen-blown operation. Compilation of these characteristics requires combining detailed overall heat and mass balances with comprehensive environmental characterization information. This combination of stream flowrates and pollutant concentrations provides definitive information on distribution patterns for respective pollutants, and also an estimation of environmental loadings in the wastewater, gaseous, solid, and heavy hydrocarbon liquids streams. The degree of closure of mass balances also provides a measure of data integrity. Calculations of normalized pollutant production estimates (pounds of pollutant/ton of moisture and ash free or MAF coal) are performed to provide a meaningful basis for comparison of these data with those from other facilities. In order to better understand the basis of pollutant production and distribution, environmental characterization data and mass balances must be augmented by the development of thermodynamic parameters (distribution coefficients, reaction kinetics information, and other rate effects). This is in addition to the normal overall process data available from the system provided by ADACS.

The fundamentals of H_2S absorption and Stretford liquor chemical interactions that convert the absorbed H_2S (or HS^- ion) to elemental sulfur are not well understood. Work is underway to study these reactions in detail and to assess the basic role of vanadium, ADA, and chelating agents in the Stretford liquor. In addition, the disposal and recycle options for spent Stretford liquor will be investigated.

Additional R&D projects fall in the area of wastewater ageing studies, identification of previously undetected compounds (e.g., hydantoins), development of advanced environmental sampling and analytical techniques, and joint data development with on-site compliance programs. In keeping with the overall engineering theme of this document, detailed reports on the above activities are published separately. A summary description of results is included in Section 5.4.1.

Environmental Systems Analysis. Computer modeling tools are being developed to assist environmental systems analysis. They require actual pollutant production and distribution data for validation and improvement. The METC system provides the information for developing certain model parameters and

also provides a data base against which models developed elsewhere can be validated. An example of this is the input into the ASPEN simulation of the METC fixed-bed gasification system. The simulation is complete in that both process and environmental information are included. This detailed environmental characterization yields data for the validation of electrolyte simulation capability in ASPEN, which enables modeling of ions in the liquid phase along with molecules in the vapor and liquid phases. Such information is then useful for simulating environmental control unit operations. A synopsis of these results is given in Table 39 and in Figure 26.

4.2.2 Byproduct Characterization and Environmental Management

Gaseous, aqueous, and solid products of the gasifier are characterized to determine their potential impact on the environment. Through process-related monitoring, gas composition and quantity of gas released to the environment are determined. Ambient air monitors, located upwind and downwind of METC, have been sited using approved dispersion modeling techniques in order to measure the impact of gaseous emissions on ambient air quality. Criteria pollutants are continuously monitored.

Gasification wastewater is generated through two major sources: process condensate and ash quench water. Each stream has been characterized to determine the principal components significant in treating these wastewaters. Monitoring efforts at the gasifier, initiated with Test Run 96, have provided data used to define influent water quality parameters. These parameters will be used in the design of a wastewater treatment system at the METC site, scheduled for construction in FY84. Unit operations will include equalization, ammonia stripping, solvent extraction, activated sludge biological treatment, and metals coagulation and sedimentation.

Solid byproducts from the gasification system include bottom ash, devolatilized coal dust, light oils, liquid tars, solid tars, and sulfur. Each byproduct stream has been characterized for toxicity, as defined by the RCRA. Process-related information (such as viscosity and boiling point) has been coupled with data acquired from toxicity tests required by EPA (EP for metals, ignitability, corrosivity, and reactivity) in order to determine the toxicity of solid byproducts from the METC gasifier. Results are illustrated in Section 5.4.1. Solid waste management techniques have been implemented to maximize recovery of the byproducts for re-use or sale. Non-salable byproducts are treated as potentially hazardous materials and are handled accordingly.

4.2.3 Workplace Health And Safety

The major goal of the health and safety program is to characterize and quantify material hazards associated with the operation of a synthetic fuels facility. Once hazards have been quantified, appropriate administrative or engineering controls can be implemented in order to minimize these hazards. To determine the exposure effects on workers during the operation of the gasifier, medical personnel have conducted periodic blood and urine sampling and testing. Area testing for carbon monoxide and hydrogen sulfide is regularly conducted to identify potentially hazardous locations.

A health hazard assessment (HHAS) was conducted in order to: provide a profile of the METC gasifier workplace environment for comparison with occupational safety and health standards; determine the chronic and acute occupational health effects related to the METC gasifier operation; and to help create a data base of potential contaminants found at coal conversion facilities of this type. The HHAS was initiated by METC during gasifier Test Run 96. Because of the expertise acquired by NIOSH in performing HHAS at other coal conversion facilities, METC requested that NIOSH participate in the effort at METC.

4.3 CHEMICAL ANALYSIS DATA BASE

The operation of the METC fixed-bed gasifier and FFCUS provides a laboratory for the gathering of a chemical process data base for characterization of the process streams. Design of gasification plants has generally been hampered by a lack of knowledge on the disposition of trace materials from the feed coals processed in the gasification facility. This was not a problem in past years when raw gas was directly fired in crude equipment and untreated waste water was dumped into sewer systems or directly into nearby streams. Today's designer requires far more data in order to properly design waste treatment systems, and the high-technology potential end uses of the gas (i.e., turbines and fuel cells) are far more sensitive to impurities.

Sampling and analysis of a gasification stream is a complex task, and requires the development of new equipment that can reliably measure the components of the gas stream. The METC program has provided a ready location for the development of sampling techniques and new analytical equipment. Work on these programs has been a cooperative effort by experienced analytical personnel working at METC with outside research organizations. Several of the programs developed include:

- In-house process stream characterization studies.
- Atomic emission analysis studies for alkali and heavy metals in the gas phase.
- High- and low-temperature aerosol analysis.
- Coherent Anti-Stokes Raman Spectroscopy (CARS) for direct measurement of gas composition in hot and dirty streams such as the gasifier raw product gas stream.
- Laser-Induced Breakdown Spectroscopy (LIBS) for direct measurements of clean gas streams, such as the final product gas.

Results from these activities have been used where applicable for analysis of system performance. A description of the results obtained from these analyzers is presented in Section 5.4.2. The concentrations of environmental species are given in Section 5.4.1.

4.4 TEST SAMPLES FOR OTHER PROGRAMS

Many programs funded by the government and/or industry deal with the utilization of product gas, component testing, and disposition and treatment of waste/byproduct streams associated with coal gasification facilities. R&D such as these require adequate amounts of suitable materials upon which to conduct tests. The operation of the gasifier and FFCUS provides a ready source of material exhibiting the characteristics of actual coal gasifier operation which cannot be synthesized in a laboratory.

The disposition and treatment of streams emanating from gasification facilities has been an area of concern regarding the commercialization of many proposed gasification facilities. The development of new techniques for treating these streams, using samples from the METC gasifier and cleanup system, may provide improvements in these areas.

4.5 VALVE TEST PROGRAM

The gasification and valve testing programs have co-existed for several years to the mutual benefit of each program. METC maintains a program to test and develop valves, obtained from various manufacturers, suitable for withstanding the harsh environments associated with coal gasification and combustion processes. Selected valves which have been successfully screened under this program are utilized on the fixed-bed gasifier and FFCUS. This provides useful feedback on the working life of these valves in actual, non-simulated environments. Counters have been installed that track the number of cycles undergone by the coal and ash lock valves. This assists in the development of a wider data base for "mean time between failure" analyses.

Lockhopper valves currently used on the gasifier are Kaymr 10-inch ball valves. These are designed as a Class 300, 316 stainless steel body, flame spray coated ball, with stellite seats, rated at 720 psig at 650°F. Typical life experienced by these valves is 4500 cycles. The most common failure is scoring of the ball and seats which results in a failure to hold pressure. Data from the valve test program pertinent to the fixed-bed gasifier are given in Section 5.4.4.

4.6 COMPUTER-AIDED PROCESS MODELING AND SIMULATION

Computer-aided modeling of unit operations and process simulation of the overall integrated system play a key role in the overall fixed-bed gasification test program at METC, especially during Phase IV and beyond, when mechanical operational problems have essentially been overcome and the system can be used to extract process characterization information. The simulation can be performed for both steady-state and dynamic modes. The complexity of unit operation models can range from simple "black-box" models to fairly detailed, first-principle models that are usually quite large and require considerable computer resources. The current emphasis is on steady-state simulation. Most of the unit operation models are at a level of sophistication above the black-

box category. These models tend to be predictive in nature within the operating range of the gasifier. ASPEN, the most-often used process simulator, is a third-generation process simulator developed especially for coal conversion processes. It was developed at the Massachusetts Institute of Technology (MIT) under the aegis of DOE and is the current state-of-the-art for this type of computer program. Both industrial and government users of ASPEN indicate that while ASPEN is a very useful and sophisticated tool, it still needs final "polishing" and debugging, which can best be achieved by attempting to correlate ASPEN with actual process data. Thus, the relationship of ASPEN with METC's fixed-bed gasification program is symbiotic. ASPEN is enhanced by comparing its predictions to actual facility data; system operation is in turn supported by ASPEN in the determination of future operating regimes most valuable for process characterization. The same philosophy can be extended to individual unit operation models of the fixed-bed gasifier, humidifier, Stretford system, and the direct cooler. A discussion of the results of the simulation activities is described in Section 5.4.3.

4.7 CORROSION/EROSION TEST PROGRAM

The clean fuel gas produced by the gasifier and cleanup system was utilized by the Corrosion/Erosion Test Facility during Test Runs 95 through 98. The purpose of this facility was to determine the effects of cleaned, coal-derived fuel gas combustion products on the mechanical properties of candidate ceramic gas turbine components.

The Ceramic Corrosion/Erosion Studies were part of the DOE High-Temperature Turbine Technology Program. The Program's overall goal has been to advance the firing temperatures of gas turbines from the current range of 1900-2000°F to the range of 2600-3000°F. For these exposure tests, relatively clean, low-Btu gas was taken at the end of the METC FFCUS. A sketch of this facility is shown in Figure 14.

Two test units, a "dynamic" and a "static" facility, were designed and fabricated and were operated simultaneously, exposing ceramic materials to the combustion products of the coal-derived gas. The facilities were designed to burn a common low-Btu fuel gas in a controlled manner. The dynamic facility operated at a temperature of 2600°F and produced a combustion product gas velocity of 1000 feet per second (ft/sec) for a scheduled 1000 hours. The static facility operated three parallel test cells each at selected temperatures (2600°F, 2200°F, and 1850°F) for three time durations (100, 300, and 1,000 hours) at relatively "zero" combustion product gas velocity.

The dynamic test provided an indication of the combined corrosive/erosive effects while the static test provided indications of the predominantly corrosive effects. By comparing these tests, a measure of each effect on the ceramic specimens could be made. At a minimum, the tests were designed to eliminate materials unsuitable for a coal-derived combustion gas environment. Although follow-up tests may be needed, these studies were intended to identify the degradation of ceramics due to their exposure in a coal-derived gas combustion environment, and to provide input to a ceramic materials technology base for future stationary gas turbines. The results of these tests are described in Section 5.4.5.

FIGURE 14. CORROSION/EROSION TEST FACILITY

During Test Runs 96 through 98, the gasifier and cleanup system provided the Corrosion/Erosion Facility with a steady supply of clean, low-Btu gas for each phase of the Test Program. The fuel gas heating value as measured by the on-line calorimeter indicated a consistent range of gas quality values of 175 ± 10 Btu/SCF for the 1000 hours of testing.

5.0 DISCUSSION OF RESULTS

The development of the METC fixed-bed gasifier and cleanup system was built upon the experience gained during each phase of the test program. This section of the report presents the results of each phase of testing and describes the evaluation of the system components from their initial installation to their present configuration. The improvements performed on the hardware during the course of development have made the METC fixed-bed gasifier and cleanup system into a highly reliable test unit capable of operating during sustained periods. This has prompted use of this system as a field laboratory for additional activities such as development of advanced analytical on-line analyzers and collection of baseline environmental health and safety data. The results of the work from these and other complementary programs are described in Section 5.4.

5.1 GASIFIER SYSTEM DEVELOPMENT

The initial testing phase of the gasifier development program took place from December 1967 to May 1976. The test configuration is shown in Figure 15. The auxiliary steam and air supply systems are not shown. Air was supplied at 200°F, and steam was provided at 400°F (75°F superheat). During this period, the only gas cleaning component used was the cyclone dust separator. The development and test program focused on checking out the gasifier, demonstrating operation at pressure on highly-caking coals, and generating basic performance data on the broad spectrum of U. S. coals.

During this period 81 test runs were made; useful performance data were gathered in all but six of these. A major objective of these test runs was to improve the reliability of the gasifier. The gasifier operated at pressure levels ranging from near-atmospheric to 300 psig. Although sized coal was normally used, a crushed run-of-mine coal was also tested in the gasifier. The gasifier operated on a complete range of U.S. coal feeds from lignite to anthracite, including highly-caking coals such as Pittsburgh No. 8 and Upper Freeport. This Section includes a summary of these data, comparing the primary process data from a cross section of the test runs. Table 3 presents analyses of the coals tested. The gasifier performance was least satisfactory when operated on the North Dakota lignite. Lignite possesses an extremely fragile structure; severe decrepitation of the coal was experienced, and large amounts of dust were entrained in the raw, low-Btu gas. A total of 4,626 operational hours were logged by the pilot plant during Phase I of the test program.

FIGURE 15. GASIFIER TEST CONFIGURATION - PHASE I

TABLE 3. PHASE I OF TEST PROGRAM-ANALYSES OF COALS TESTED

Analysis, percent	Non-Caking	Low Caking			Medium Caking			High Caking				
	Anthracite	W.D. Lignite	W.M.	Montana Rosebud	Ill. #6	Wy. #9	Oh. #3	L. Cedar Grove	Middle Kittann.	Pittsburgh Seam Loveridge	Arkwright	Upper Freeport
Ultimate:												
Carbon	85.0	41.1	50.8	52.2	65.7	64.5	70.3	80.9	79.4	74.2	75.9	66.8
Hydrogen	2.0	6.9	5.1	6.1	4.8	5.5	5.0	5.2	5.7	5.7	5.7	4.4
Nitrogen	1.0	.6	1.6	0.8	1.7	1.7	-1.1	1.4	1.3	1.4	1.4	1.2
Sulfur	.5	.7	1.0	0.8	3.7	3.9	4.3	.7	1.1	2.9	2.7	3.8
Oxygen	.5	44.5	8.5	32.6	12.9	4.0	11.2	6.2	2.2	3.0	4.9	2.5
Ash	10.0	6.2	24.2	7.5	11.2	15.4	8.1	3.7	8.3	7.5	8.3	20.3
Proximate:												
Moisture	1.0	36.7	8.8	24.3	5.2	5.0	4.3	1.9	2.0	5.3	1.1	1.0
Volatile Matter	4.9	26.6	31.3	28.6	36.1	34.0	40.2	34.7	29.1	35.1	36.8	51.8
Fixed Carbon	84.1	30.5	35.7	39.6	47.5	45.6	47.4	59.7	60.6	52.1	53.8	26.9
Ash	10.0	6.2	24.2	7.5	11.2	15.4	8.1	3.7	8.3	7.5	8.3	20.3
Btu/lb ¹	14,305	6,890	8,900	8,945	11,750	11,450	12,900	14,375	14,000	13,755	13,675	11,590
FSI ²		2	2	2	4-1/2	4-1/2	5	7	7	8	8	8-1/2
Ash Fusion Temp., ³ °F												
Initial Deformation	2,410	2,240	2,510	2,265	2,230	2,080	2,135	2,600	2,195	2,150	2,237	2,080
Softening Point	2,520	2,280	2,660	2,285	2,350	2,165	2,200	2,675	2,360	2,240	2,345	2,190
Fusion Point	2,645	2,320	2,600	2,370	2,440	2,280	2,260	2,760	2,490	2,370	2,370	2,240

1. British Thermal Units per pound
2. Free Swelling Index
3. Ash Fusion Temperature = AFT

Ref.: METC/RI-78/12

Table 4 shows the performance of the gasifier during pressurized operation with various coal feeds, operating pressures, air and steam feed rates, gas yield and compositions, gas heating values, and cold gas efficiencies. The product gas heating value is based on measurement of the gas constituents. The calculated heating value was generally in the range of 130 to 150 Btu/SCF, which is typical of air-blown gasifiers where the dust, tar, and oils are not included in the heating value. The calculated cold gas efficiencies were generally in the range of 60 to 80 percent. These efficiencies are slightly lower than would be expected in commercial-size gasifiers. Due to their smaller size, pilot units inherently demonstrate higher heat losses which are reflected as efficiency penalties. In the case of the METC gasifier, the heat loss to the water-cooled wall was two to three times greater than that assumed for a larger unit. Cold gas efficiency does not credit the sensible heat in the gas stream, or the heating value of the entrained dust, tar, and oil. Making use of these additional heat energies can theoretically raise the overall thermal efficiency of this type of coal conversion system at a commercial size to over 90 percent.

Attempts were made to measure product gas flow directly; however, contaminants in the gas stream frequently fouled the measuring equipment and made this direct measurement unreliable. Consequently, the product gas flow determination was arrived at indirectly by means of a nitrogen balance.

The basis for calculating the nitrogen balance was to total the incoming nitrogen:

$$(\%N_2 \text{ in Air} \times \text{Air Mass Flow}) + (\%N_2 \text{ in Coal} \times \text{Coal Flow}) = \text{Nitrogen Mass Flow}$$

The volumetric flow of air was readily determined from an orifice meter. Coal samples were periodically sampled and analyzed, and coal feed rates were recorded. These items constitute the necessary input data. Outlet gas flow was calculated by first subtracting the weight of nitrogen removed with the ash, dust, tars, etc., and then analyzing the product gas for nitrogen content.

$$\frac{\text{Mass Flow N} - \text{N in byproducts}}{\%N_2 \text{ in product Gas}} = \text{Mass Flow Product Gas}$$

This procedure should be reasonably accurate, assuming careful sampling and analysis. With the FFCUS in operation, it is now possible to measure the clean, product gas flow directly. This permits a double check on the calculated cold gas efficiency. Also, the installation of an on-line calorimeter in the final product gas line accounts for small quantities of hydrocarbons that are not measured by the on-line gas chromatograph. This provides more accurate determinations of the product gas heating values used in efficiency calculations. The average heating value recorded for recent test runs using Pittsburgh seam coal has been approximately 170 Btu/SCF.

Representative performance data obtained on various coals for atmospheric and pressurized operation during Phase I are given in Table 5. The gas compositions and heating values and the corresponding efficiencies resulting from operation at higher pressure are comparable with low-pressure operation. The key advantages of operating at pressure are the increased throughput and/or reduced component size and cost at equivalent capacity. This increase in throughput with pressure can be seen in Table 5.

TABLE 4.

PHASE I OF TEST PROGRAM - GASIFIER PERFORMANCE UNDER PRESSURIZED CONDITIONS ON VARIOUS COAL FEEDS

Coal	Non-Caking	Low Caking			Medium Caking			High Caking				Upper Freeport
	Anthracite	N.D. Lignite	Mont. Rosebud/Anthracite	N.M.	Ill. #6	Ky. #9	Oh. #8	L. Cedar Grove	Middle Kittann.	Pittsburgh Seam Loweridge	Arkwright	
Pressure, psig	80	80	133	145	144	207	80	80	80	90	144	119
Input, lb/hr ¹			*									
Coal	540	985	1,228	1,800	1,401	1,987	1,382	1,229	1,414	1,330	1,440	1,196
Air	1,991	3,062	3,733	4,583	3,894	5,708	4,594	4,594	4,381	4,419	4,725	4,033
Steam	320	505	1,015	763	668	987	600	650	436	641	540	501
Input Ratios, lb/lb ²												
Steam: Coal	.6	.5	.8	.4	.5	.5	.4	.5	.3	.5	.4	.4
Air: Coal	3.7	3.1	3.0	2.6	2.8	2.9	3.3	3.5	3.1	3.3	3.3	3.4
Output, lb/hr												
Ash	76	87	86	330	154	243	105	76	97	132	105	135
Cyclone Dust		54	16	86	23	18	9	15	0	20	2	16
Gas	2,923	5,310	4,879	5,784	4,965	8,096	7,460	6,630	5,873	5,705	6,193	5,375
Tar			2	53	35	21			42	52	71	19
Water				889		348			462	481	524	182
Gas Yield												
MSCFH ³	38.0			77.7	76.9	101.4	97.0	86.2	86.4	83.2	91.3	74.7
SCF/lb Coal, ⁴ as rec. basis	70.4			43.4	54.8	54.4	70.2	70.1	61.1	61.1	63.4	64.7
Gas Analysis, Vol. %												
CO	24.7	13.4	15.3	15.3	18.2	18.1	20.4	22.7	22.9	19.8	21.7	22.5
CO ₂	6.4	12.4	12.9	12.7	10.6	11.0	6.8	6.9	7.7	9.5	7.8	7.1
N ₂	53.8	58.2	50.3	59.3	52.3	54.4	54.7	54.7	52.3	52.0	53.7	53.6
H ₂	13.4	14.7	16.7	10.7	15.6	13.3	14.0	13.7	14.5	15.8	11.0	14.0
CH ₄	.9	1.3	1.7	2.1	2.4	2.0	2.0	1.7	2.4	2.9	2.8	2.5
C ₂ H ₆			.0	.0	.0	.2			.2	.0	.0	.0
H ₂ S			.2	.2	.7	.9			.1	.2	.5	.3
O ₂	.9		.0	.0	.0	.1	1.1	.0		.0		.0
Heating Value Btu/SCF	130	100	132	104	138	128	148	135	149	144	139	142
Cold Gas Efficiency %	64			50	65	57	81	66	65	66	64	77

* Diluted with anthracite for turbine material tests

NOTE: THESE DATA ARE NOT NECESSARILY REPRESENTATIVE OF THE CURRENT OPERATIONAL CONFIGURATION

Ref.: METC/RI-78/12

1. Pounds per hour
2. Pounds per pound

3. Thousands of Standard Cubic Feet per Hour
4. Standard Cubic Feet per Pound

TABLE 5. GASIFICATION PERFORMANCE DATA OPERATING AT ATMOSPHERE
AND PRESSURE FOR ASSORTED TEST GOALS

Coal	Anthracite		N.D. Lignite		Illinois #6	
Pressure, psig	80	0	80	0	80	0
<u>Input, lb/hr</u>						
Coal	540	224	985	725	1,401	1,030
Air	1,991	613	3,062	2,550	3,894	2,550
Steam	320	130	505	320	668	322
<u>Input Ratios, lb/lb</u>						
Steam: Coal	.6	.6	.5	.4	.5	.3
Air: Coal	3.7	2.7	3.1	3.7	2.8	2.3
<u>Output, lb/hr</u>						
Ash	76	11	87	140	154	69
Cyclone Dust			54	67	23	28
Gas	2,923	1,230	5,310	3,900	4,965	3,322
Tar					35	23
Water						242
<u>Gas Yield</u>						
MSCFH	38.0	16.0			76.9	44.2
SCF/lb Coal, as rec. basis	70.4	71.4			54.8	47.0
<u>Dry Gas Analysis, Vol % *</u>						
CO	24.7	18.5	13.41	15.3	18.2	21.8
CO ₂	6.4	9.5	12.4	14.1	10.6	6.9
N ₂	53.8	56.5	58.2	54.1	52.3	51.5
H ₂	13.4	13.7	14.7	15.3	15.6	17.8
CH ₄	.9	.5	1.3	1.2	2.4	2.0
C ₂ H ₆					.0	.2
H ₂ S					.7	.2
O ₂	.9	1.2			.0	.0
Heating Value Btu/SCF	130	107	100	110	138	153
Cold Gas Efficiency, %	64	53			65	56

Ref.: METC/RI-78/12

*Volume percent

In addition to the above performance results, the gasification program has demonstrated and is continuing to develop innovative design and operational concepts that are aimed at improving the reliability and operability of components within the gasification system.

5.1.1 Coal Feeding System

The original design simply used lockhoppers, isolation valves, and gravity to feed coal to the gasifier. When the gasifier required coal, the lower ball valves opened and coal fell down through the feed pipe and into the gasifier. Although inert gas pressurizing was used during coal feeding, feed-system plugging problems were experienced. This was caused by tar condensation and coal caking in the feed pipes and hoppers due to the long residence time of the bituminous coal in the hot environment and occasionally by leaking valves. These problems were corrected by modifying the design as shown in Figure 5 (see Section 3 of this report), to include a rotary feeder and screw feeder in each feed leg. These components feature variable-speed drives and allow for relatively continuous coal feed to the gasifier.

The operation of the coal feed system has been automated to allow "one button" feeding of coal from the storage silos to the gasifier. This system, first tested during Test Run 98, uses a dedicated microprocessor controller to control the operation sequence of the various belts, feeders, bucket elevators, and valves in the coal feed system. Utilization of this system has promoted more uniform coal feed and allows the operator more time to attend to other factors affecting plant operation and performance.

5.1.2 Bed Level and Voids Sensing

The McDowell-Wellman gasifier is designed to use poke rods to sense bed levels when operated at atmospheric pressure. This procedure is impractical for measuring bed depth on a pressurized gasifier.

METC has installed and demonstrated nuclear sensing devices based on gamma ray densitometry for measuring and controlling coal level in the pressurized coal hoppers and the fixed-bed gasifier. The output of the sensors are utilized as a means to control the coal feeding system. A sketch showing the arrangement of the nuclear sources and detectors is shown in Figure 16. In addition to sensing bed level, the nuclear gauges are also used to monitor bed density in order to detect the occurrence of voids in the bed. The presence of voids in the bed can severely affect gas flow distribution, with detrimental effects on gas production, gas quality, and gasifier efficiency. Once the voids are recognized and located, the condition can be corrected by using the stirrer to break up and redistribute the coal in the bed and reestablish normal operating conditions.

5.1.3 Bed Stirrer

The rotating arm or stirrer is essential for operating a fixed-bed gasifier with highly caking coals. The original design used three horizontal arms, two for bed stirring and the top arm for bed leveling; the stirrer cooling water and the gasifier jacket cooling water were a single system. The cooling systems were separated to afford better control and reliability.

FIGURE 16. METC FIXED-BED GASIFIER - NUCLEAR LEVEL DETECTION DESIGN

During the past several runs, many improvements have been made in the operation and maintenance of the stirrer and its drive mechanism. The stirrer design, which evolved from three diametral arms to two widely-spaced radial arms, was selected to reduce drag and cooling losses. The principal reason for this change was that the shallow helix angle traversed resulted essentially in overstirring of the bed by the diametral arms. Each arm of the stirrer was equipped with three thermocouples which could indicate bed temperature zones. After approximately 400 hours of testing, inspection of the stirrer revealed that it had become bent. To correct this problem, a subsequent design incorporated a diametral arm at the bottom and maintained the wide spacing and the singular radial upper arm. This design eliminated the unbalanced vertical load and the resultant bending, and was used for 730 hours during Test Run 98. In order to decrease the stirrer vertical cycle time period and also to increase stirrer effectiveness, a configuration was developed that incorporated three radial arms with reduced vertical spacing. This present array (see Figure 7 in Section 3 of this report), was used successfully in Test Runs 99 and 100. Concurrently with these configuration and operational modifications, abrasion of the arms was also addressed. Abrasion damage had caused the non-scheduled termination of several tests and accordingly, was of major concern. Each arm of the stirrer is now specially hardened to resist abrasion. A 1/8-inch-thick weld-overlay coating of a mixture of titanium carbide-tungsten carbide-Stellite #6 powders, specially pre-mixed and carburized, was weld-overlaid on the shaft. Additional treatment involved the application of a diffusion coating of boron carbide. This combination has performed excellently in resisting abrasion and erosion; long-term evaluation is continuing.

The stirrer drive was modified from the original McDowell-Wellman design to a hydraulic mechanism. A hydraulic motor was used to power the rotation and a hydraulic cylinder was used to raise and lower the shaft. A hydraulic power skid provided the motive fluid for the system. The hydraulic system has been much more reliable and trouble-free than the the original mechanical system, which required constant maintenance.

5.1.4 Grate Temperature Control

A layer of ash approximately 12 inches deep is used to insulate and protect the metal rotating grate from the hot combustion zone. Measurement and control of the ash layer thickness is accomplished in commercial low-pressure gasifiers by a procedure called rodding or poking. This procedure calls for opening a port in the top of the gasifier and inserting a metal rod through the bed to the grate. The rod is left in place for a given time period, usually five minutes, and is then withdrawn. The location of the combustion zone is readily determined by the cherry-red color of the poking rod, and the distance between the red zone and the end of the rod is the depth of the ash layer. When the ash layer is too shallow, the grate speed is slowed, and conversely, when the layer is too thick, the grate speed is increased. While this poking method is relatively reliable, it is inherently limited to steady-state operations and is unsuited to pressurized operation. It is also unattractive from manpower efficiency and health and safety standpoints. METC

designed and tested a system whereby thermocouples on and above the grate indicated the adequacy of the ash layer. Several thermocouples were required to provide the necessary area coverage. This arrangement proved unsatisfactory for several reasons. The slow grate motion inherent in normal ash removal precluded the acquisition of sufficient ash-zone temperature data and, as a result, ash-zone depth could not be adequately determined. Subsequent operation also resulted in thermal damage to the thermocouples and grate components.

A superior method of sensing ash zone depth was developed by using data from thermocouples installed in the lower stirrer arm. The temperature spike associated with the combustion zone and subsequent fall in temperature as the stirrer entered the ash zone has been very effectively used to determine ash zone height. The controls and instrumentation have been extended to automatically control grate speed. The thermowells in the arms are of a rugged design which provide extended service within the harsh gasifier environment. The temperature signals are relayed via an FM radio transmitter to facilitate communication between the rotating stirrer shaft and the fixed platform for relay to the control room and ADACS system.

5.1.5 Grate Drive

The original grate, supplied by McDowell-Wellman, was provided with an intermittent electric/mechanical drive mechanism. This design made control of the ash level difficult because it had inadequate speed control. The original mechanism was changed to a continuous hydraulic drive with a wide speed range but also capable of running at low speeds. Greatly improved operation and controlled ash removal rates have been achieved. The hydraulic system powers a cylinder which drives a rack and pinion mechanism. This mechanism transfers the power to the grate drive pinion.

The grate is housed within a device known as the "Bosh ring", which forms a collar around the grate and serves to guide the downward ash flow. Upon examination following a test run, the Bosh ring was often warped or loose. Typically, it would have to be straightened and welded into place prior to the next test run. A new ring was manufactured with slots cut in the sides to allow for thermal expansion. Implementation of this design has eliminated "Bosh ring" problems.

5.2 SIDE-STREAM CLEANUP SYSTEM TEST RESULTS

Phase II of the test program consisted of three series of side-stream tests, run in the period from 1975 to 1978. The thrust of the side-stream gas cleanup program was to demonstrate that raw, low-Btu gas generated from highly volatile, highly-caking coal could be cleaned to exacting standards using a novel sequential cleaning approach coupled with conventional gas cleaning technology. The program also provided operating experience and data for determining the configuration and component designs for the full-flow cleanup train. A preliminary evaluation was made on the effects of actual coal-derived fuel gas on gas turbine materials.

5.2.1 First Side-Stream Cleanup Test Series

During the summer of 1976 the side-stream gas cleanup configuration was run initially with Illinois No. 6 coal and later with a mixture of Montana Rosebud and anthracite. Montana Rosebud is a sub-bituminous coal that is easily^o gasified but presents materials-handling difficulties because of its fine ash properties. The gas heating value is also lower than that obtained with a bituminous coal. For these reasons, Rosebud coal was blended for testing with 25 to 37 percent anthracite to achieve increased heating values of approximately 132 Btu/SCF (as required for a test series using a gas turbine combustor).

The system configuration, showing locations of material sampling points, is illustrated in Figure 9 (see Section 3 of this report). The scrubbing system operated for 135 hours on gas derived from the Illinois No. 6 coal and 210 hours on gas derived from a mixture of Montana Rosebud and anthracite. The average cleanup system operating pressure for the Illinois No. 6 testing was approximately 80 psig while the Montana Rosebud/anthracite tests were run at approximately 120 psig.

In this first test series, once-through water was used to clean the gas. No attempt was made to recycle the dirty wash liquor. Approximately 20 gallons per minute (gpm) were used to contact the gas at four locations. Up to one gpm was used in the humidifier, 1.5 gpm in the disengagement chamber (tar separator), 9 gpm in the venturi scrubber, and 9 gpm in the valve tray scrubber. The waste water and entrained material from these units were collected in a decanter (see Figure 9). The discharge from the decanter was then pumped into a holding pond for storage, study, testing, and treatment.

The particulates removed from the raw, low-Btu gas stream by the cyclone separator, and the tars and solids collected in the disengagement-chamber lock hopper, were sampled and analyzed. These analyses are presented in Table 6. Significantly more tars were collected in the Illinois No. 6 bituminous coal tests than in the sub-bituminous/anthracite testing.

Table 7 gives the concentrations of contaminants measured in the once-through wash water from both the disengagement chamber and the valve tray separator for Illinois coal.

5.2.2 Preliminary Gas Turbine Materials Combustion

The purpose of this series of tests, performed in conjunction with the first series of side-stream tests, was to provide engineering data on the performance of selected gas turbine nozzle and bucket materials in gas environments expected from the combustion of coal-derived low-Btu gas. A turbine simulator test rig was used which included a fuel combustor, nozzle vane cascade, air-cooled nozzle, and bucket simulation pins. A schematic of the gas turbine simulator is shown in Figure 10 (see Section 3 of this report). The pins contained cooling holes simulating selected cooling air hole sizes, and patterns potentially applicable to airfoil cooling for high-temperature operation.

TABLE 6. SOLIDS ANALYSIS FROM FIRST SIDE-STREAM TEST SERIES - TEST RUNS 82 TO 84

Sampling Point	Illinois No. 6				Montana Rosebud/Anthracite			
	Coal	Bottom Ash	Entrained Dust	Tar	Coal	Bottom Ash	Entrained Dust	Tar
Sampling Point	1	2	3 and 7	6	1	2	3 and 7	6
Total Carbon lb/hr	903.4	25.9	16.7	27.1	804.5	11.5	9.2	1.6
H lb/hr	66.0	0.5	0.4	1.6	55.9	0.0	0.4	0.2
S lb/hr	50.9	0.8	0.5	0.9	11.0	0.2	0.2	0.0
N lb/hr	15.1	0.0	0.0	0.4	9.4	0.0	0.1	0.0
O lb/hr	114.1	0.0	1.0	2.4	96.1	0.0	0.0	0.2
Moisture lb/hr	71.5	0.5	0.4	0.0	133.3	0.0	0.0	0.0
Ash lb/hr	154.0	126.3	4.0	2.6	119.9	74.7	6.2	0.0
Heating Value Btu/lb	11,750	2,260	11,230		11,696	1,500	9,090	14,440

Ref.: METC/RI-78/12

The gas turbine combustor and the turbine simulator test rig were operated in a series of runs for a total of 144 hours on gas derived from two coal types. Sixty-four hours of combustor operating time were accumulated on Illinois No. 6 coal. The second coal used was a mixture of 63 percent Montana Rosebud and 37 percent anthracite. Eighty hours were logged by the combustor on this mixture. The coals were chosen to include a wide range of sulfur and alkali levels. Illinois No. 6 is a low-sodium, high-sulfur coal while Montana Rosebud is a low-sulfur, high-sodium coal.

The tests were conducted at two atmospheres of combustor pressure. In operation, 800 to 1100 standard cubic feet per hour (SCFH) of natural gas were burned in approximately 100,000 SCFH of air in the preheater to raise the air temperature to 570°F. The heated air stream was then burned with approximately 28,000 to 33,000 SCFH of cleaned, low-Btu gas to generate a 1750-1830°F combustion gas. Table 8 lists the average values for measured emissions in the combustor exhaust. CO and HC levels were quite low, indicating satisfactory combustion. No evidence of erosion or corrosion was visible to the naked eye after the 144 hours of operation. The pins were subjected to metallographic examination which showed penetration of about 1 mil. Although this depth is quite shallow, it was significant due to the short operating time and relatively low combustion temperature. This fact, and preliminary analytical evidence of sodium and potassium contaminants in the cleaned, low-Btu gas, indicated that the metal parts of the hot gas path experienced the beginnings of hot corrosion.

5.2.3 Second Side-Stream Cleanup Test Series

The second series of side-stream tests were conducted from December 1976 to August 1977. The objectives of the second side-stream cleanup test series were:

- Better control of tar condensation, separation, and removal in the humidifier/disengagement section.
- Recycling and cooling of the wash water to minimize water usage and wastewater treatment requirements.
- Decanting of the wash water under pressurized conditions with a suitable level of separation to allow recycling of the water in the process.
- Determination of alkali metal content in the product gas stream.
- Characterization and quantification of the sulfur compounds in the product gas stream.

To accomplish these objectives, a number of major changes were made in the cleanup system configuration shown in Figure 11 (see Section 3 of this report). The raw, low-Btu gas source to the side stream was relocated downstream of the cyclone separator in order to reduce the particulate loading of the gas input to the humidifier. Second, the system was fitted with a pressurized decanter connected to the scrubber water effluent line. The decanter was designed to separate out low-boiling tars and particulates from the wash

TABLE 7. CONTAMINANT LEVEL IN ONCE-THROUGH WASH WATER
OPERATING WITH ILLINOIS NO. 6 COAL - TEST RUNS 82 AND 83

Parameter	Disengagement Chamber	Separator to Decanter
COD (mg/l) *	33,250	31,250
Phenol (mg/l)	3,780	930
NH ₃ (mg/l)	414.8	61.2
CO ₃ (mg/l)	0	0
HCO ₃ (mg/l)	1,160	1,600
Cl (mg/l)	68.0	36.2
S (mg/l)	4.2	3.9
SCN (mg/l)	10.8	6.4
CN (mg/l)	2.5	2.7
Na ₂ O (mg/l)	35.3	34.2
K ₂ O (mg/l)	3.6	2.7
pH	8.2	6.8

* milligrams per liter

TABLE 8. MEASURED EMISSIONS IN GAS TURBINE SIMULATOR
COMBUSTOR EXHAUST - TEST RUNS 82 TO 84

Species	Coal Type	
	Illinois No. 6	Montana Rosebud/ Anthracite
Total Hydrocarbons *	3.5 (ppm) **	8.8 (ppm)
CO *	52.8 (ppm)	64.5 (ppm)
NO *	13.6 (ppm)	10.4 (ppm)
O ₂	11.4 (%)	11.2 (%)

*Measured by continuous gas chromatograph

** parts per million

water. Pumps for recycling water back to the humidifier, disengagement chamber, and valve tray scrubber were connected to the water leg. The venturi scrubber was removed from the cleanup train for the remainder of the side-stream test series. Four small indirect water-cooled shell and tube heat exchangers were installed to cool the recycled scrubbing water.

The recycled wash water contained light oils, phenols, and ammonia scrubbed from the producer gas. A bleed stream from the decanter limited the buildup of these constituents to maintain the effectiveness of the recycle-water scrubbing liquor.

A Pittsburgh No. 8 (Arkwright) bituminous coal was used in this and all subsequent test series. This coal has a free swelling index of eight and is typical of highly-caking eastern coals. This coal was selected as a baseline for the cleanup system testing because it was locally available, representative of coals difficult to gasify, heavy in tar production, and high in sulfur. A gasification cleanup system capable of generating clean, low-Btu gas from this coal should be capable of processing most of the coals in the United States.

The results of this test series demonstrated that recycling of scrubbing liquor could be achieved with reasonable operability, and that the liquor could be effectively used to cool and remove tars and oils from the raw, low-Btu gas. Control of humidifier exit temperature was not achieved.

This test series provided a wealth of data. Samples of the major flow streams were taken at periodic intervals. The analyses of samples collected during Test Run 87 (June 1977) are given in the following tables.

Table 9	<ul style="list-style-type: none">● Analysis of Pittsburgh No. 8, Arkwright Coal● Analysis of Bottom Ash● Analysis of Cyclone Dust● Analysis of Tar
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Table 10	<ul style="list-style-type: none">● Analysis of Raw Gasifier Gas● Analysis of Cleaned Product Gas● Measured Concentration of Sulfur Compounds in Raw and Cleaned Product Gas
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Table 11	<ul style="list-style-type: none">● Analysis of Recycle and Decanter Liquor
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5.2.4 Third Side-Stream Cleanup Test Series

This series of tests was primarily designed to determine the equipment requirements for the FFCUS configuration. Two modifications were made to the system:

- A dual-phase (inert gas) nozzle was installed in the humidifier. This nozzle was designed to atomize the scrubbing liquor to droplets one to five microns in size. The objective of this two-phase nozzle test was to improve the controllability of the humidifier exit-gas temperature and to minimize water flow requirements.

TABLE 9. GASIFICATION DATA, STATISTICAL ANALYSIS OF SIX SAMPLE
SAMPLE PERIODS, PITTSBURGH NO. 8-ARKWRIGHT COAL - TEST RUN 87

	COAL	BOTTOM ASH	CYCLONE DUST	TAR
Proximate Analysis - wt% *				
Moisture	0.87 + 0.07	0.15 + 0.09	1.28 + 0.25	-----
Ash	8.88 + 1.26	81.31 + 3.74	9.68 + 1.25	0.21 + .12
Volatile Matter	32.73 + 0.56	-----	-----	-----
Fixed Carbon	57.53 + 1.47	-----	-----	-----
Ultimate Analysis - wt%				
Hydrogen	5.01 + 0.12	0.01 + 0.01	0.99 + 0.16	6.08 + 0.15
Carbon	76.37 + 1.34	16.70 + 3.84	82.44 + 1.86	82.37 + 1.52
Nitrogen	1.36 + 0.05	0.44 + 0.25	0.83 + 0.08	1.73 + 0.17
Oxygen	5.00 + 0.52	-----	3.17 + 1.09	8.08 + 1.80
Sulfur	2.53 + 0.22	1.34 + 0.91	1.62 + 0.27	1.53 + 0.32
Fusability °F				
Initial Deformation (IT)	2311 + 78	2308 + 51		
Softening (ST)	2433 + 43	2411 + 60		
Fluid (FT)	2476 + 44	2492 + 56		
Caloric Value				
Btu/lb	13,327 + 119	2302 + 544	12,719 + 147	15,515 + 254
Free Swelling Index				
	6 + 1/2			
Ash Analysis - wt%				
SiO ₂	39.49 + 4.14	42.93 + 1.80		
Al ₂ O ₃	22.19 + 3.19	23.18 + 1.86		
Fe ₂ O ₃	17.24 + 1.37	17.47 + 1.28		
CaO	8.86 + 3.17	9.44 + 4.18		
MgO	1.54 + 0.41	2.03 + 0.52		
Na ₂ O	0.82 + 0.11	0.69 + 0.16		
K ₂ O	1.09 + 0.05	0.94 + 0.45		
P ₂ O ₅	0.37 + 0.06	0.45 + 0.01		
TiO ₂	1.16 + 0.15	1.15 + 0.09		
SO ₃	6.24 + 2.41	1.44 + 0.35		

*Weight percent

TABLE 10. GAS ANALYSIS (AVERAGE OF 5 SAMPLES)-TEST RUN 87

Species	Gas Exiting Cyclone		Clean Gas Exiting Side-Stream	
	On-Line GC	Lab GC	On-Line GC	Lab GC
H ₂ (vol %)	16.74 ± 0.68	16.58 ± 0.68	16.35 ± 0.50	16.20 ± 0.24
CO ₂ (vol %)	8.98 ± 1.07	9.14 ± 0.94	8.18 ± 1.09	7.16 ± 3.67
C ₂ H ₆ (vol %)	0.29 ± 0.03	0.30 ± 0.07	--	0.34 ± 0.08
H ₂ S (vol %)	0.40 ± 0.04	0.39 ± 0.03	0.40 ± 0.00	0.35 ± 0.40
N ₂ (vol %)	49.46 ± 0.75	50.00 ± 1.04	50.73 ± 0.49	50.72 ± 0.54
CH ₄ (vol %)	2.58 ± 0.61	2.54 ± 0.59	2.53 ± 0.22	2.76 ± 0.21
CO (vol %)	21.30 ± 1.35	20.46 ± 0.98	21.35 ± 1.82	20.52 ± 1.19
O ₂ (vol %)	--	0.47 ± 0.09	0.65 ± 0.08	0.58 ± 0.08

	Gas Exiting Cyclone	Clean Gas Exiting Side-Stream
Species	Lab GC	Lab GC
COS (ppm vol)*	190.0 ± 6.0	187.0 ± 5.5
CH ₃ SH (ppm vol)	15.5 ± 4.5	11.7 ± 1.6
CS ₂ (ppm vol)	15.8 ± 1.0	17.3 ± 2.4
Thiophene (ppm vol)	18.5 ± 0.8	22.3 ± 3.0

Species	Clean Gas Exiting Side-Stream
	Alkali Metals by Wet Test Method
Na (ppm wt)**	0.37 ± 0.07
K (ppm wt)	0.10 ± 0.07

*Parts per million by volume

**Parts per million by weight

TABLE 11. ANALYSIS OF RECYCLE AND DECANTOR LIQUOR -
TEST RUN 87

		Recycle Liquor	Decanter Liquor
Tar Solids wt%		2.1	10.4
<u>Tar-Free Basis:</u>			
pH		8.1	8.3
Ammonia (Free)	mg/l	3,658	4,740
Bicarbonate	mg/l	11,240	9,060
Carbonate	mg/l	3,360	4,940
Chloride	mg/l	473	391
Cyanide	mg/l	60	58
Phenol	mg/l	1,160	1,140
Sulfur (total)	mg/l	547	550
Sulfide	mg/l	262	191
Thiocyanate	mg/l	10	10
COD*	mg/l	56,000	44,500
BOD**	mg/l	10,855	6,420

*Chemical Oxygen Demand

**Biological Oxygen Demand

- A 20-inch-diameter packed column was added at the tail end of the side-stream cleanup train. The purpose of this unit was to investigate the feasibility of using water to scrub the cleaned, low-Btu gas to remove trace levels of alkali metals.

The two-phase nozzle effectively controlled gas temperature and removed tars. However, further development was needed in order to refine control methods and optimize inert gas pressure and flow requirements. The tar particles condensed in the humidifier did not all separate from the gas stream in the humidifier and disengagement chamber. Some particles were carried into the tray scrubber and caused fouling of tray valves. It was concluded that a much more effective tar separator located after the humidifier would be essential for the FFCUS.

Because of mechanical problems with the scrubbing water feed and some contamination of the packings with carryover tars and oils, the trace alkali-metal scrubber column was not operated long enough to provide meaningful data.

Test samples and analyses made during this series were consistent with the previous tests. A typical sample analysis for the solid, gaseous, and liquor constituents is given in Table 12.

5.3 FULL-FLOW CLEANUP SYSTEM TEST RESULTS

Early testing of the FFCUS was devoted to developing the "dry-tar" removal system and to identifying any unexpected effects from scale-up. The test program was planned to begin with testing and verification of only the upstream components, i.e., the cyclone, humidifier, and tar separator. Once the satisfactory performance of these components was established, the remaining components were installed in the process train for testing and performance verification. Improvements to the gasifier bed-level monitoring, bed-temperature sensing, and total system pressure control were also tested.

Figure 17 shows the initial components of the full-flow cleanup train configuration used in Test Runs 91 through 93. All of the raw, low-Btu gas flowed through the dust cyclone, humidifier, and tar separator. After the separator the gas was divided, with the major portion going to the flare and approximately 20 percent going to the side-stream through a tray scrubber, knock-out drum, and alkali metal scrubber, and then being discharged in the flare.

The primary objective of this series of test runs was to establish component configurations and operating conditions that would result in satisfactory removal of the bulk of the entrained particulates and heavy tars in the raw, low-Btu gas stream. Once this was accomplished, the downstream components were to be added to the full-flow cleanup train in order to remove the remaining tars, light oils, and sulfur gases, yielding a clean fuel gas suitable for gas turbine and other types of burner testing.

The above test series eventually produced a relatively particulate- and tar-free gas. Many operating problems were experienced, resulting in substantial component and system modifications.

TABLE 12.
TYPICAL SAMPLE ANALYSIS FROM THE
THIRD SIDE-STREAM TEST SERIES - TEST RUN 90

Solids, wt %	Coal	Bottom Ash	Cyclone Dust	Tar
Moisture	1.06	0.41	0.89	0
Ash	8.01	76.51	10.34	0.22
Sulfur	2.61	0.91	1.95	1.99
Hydrogen	5.23	0.09	1.32	6.83
Carbon	76.36	22.00	82.92	84.35
Nitrogen	1.47	0.08	1.38	1.56
Oxygen (diff.)	5.26	0	0	5.05
Heat Content (Btu)	13,530	2,610	12,720	15,600

Cyclone Exit Gas	Volume %
Hydrogen	16.77
Carbon monoxide	20.85
Carbon dioxide	8.54
Nitrogen	49.57
Oxygen	0.69
Methane	2.38
Ethane	0.23
Propane	0.19
Butane	0.09
Ethylene	0.13
H ₂ S	3,994 ppm
COS	241 ppm
CS ₂	13 ppm
NH ₃	17 ppm

Scrubbing Liquor	mg/l
Ammonia	3,502
Bicarbonate	11,310
Carbonate	1,750
Chloride	67
Cyanide	43
COD	54,455
Hardness	20
Phenol	30
Suspended Solids	12
Dissolved Solids	3,170
Sulfur (total)	610
Sulfide	400
Thiocyanate	15.4
Sodium	2.8
Potassium	1.7
pH	7.85
Alkalinity	13,060
Tar solids (wt %)	1.3
Conductivity (mho/cm)*	26,000
Specific Gravity	1.0099

mho/cm=*Conductivity units as mhos per centimeter

FIGURE 17. INITIAL FULL-FLOW CLEANUP TRAIN CONFIGURATION WITH SIDE-STREAM - TEST RUNS 91 TO 93

5.3.1 Phase III of the Test Program - Initial Testing of Full-Flow Components

The first new component of the FFCUS to be tested was a new, high-efficiency dust removal cyclone which had been installed for Test Run 91. This cyclone was a commercially designed and fabricated unit with a predicted capability for 90 percent removal of particles over 5 microns at a gas inlet velocity of 120 ft/sec. Testing during Run 91 was hampered by the rapid erosive failure of this commercial dust cyclone. Erosion at operating velocities of between 115 and 170 ft/sec experienced during Run 91 was sufficient to result in vessel failure within 24 hours. The cyclone was patched and the testing continued for another day. It was determined that the use of a high-velocity cyclone designed to achieve high removal efficiencies was probably not feasible; it also appeared to be unnecessary for humidifier and tar separator operability. METC fabricated a new low-velocity cyclone with a design point of 50 ft/sec. This new cyclone provides excellent reliability and adequate dust removal.

The operation of the humidifier and tar trap was to have been the central focus of this series of test runs. Various single-phase and two-phase spray nozzle designs and configurations were tested during this period. The intent of this testing was to identify a nozzle that would provide a high degree of atomization for the small liquid flowrates under consideration (typically 0.5 to 2.5 gpm). Atomization of the mist to droplets of less than 50 microns was desired to ensure rapid and complete evaporation of the spray water within the confines of the humidifier vessel. Larger droplet sizes require a larger pressure vessel to ensure complete evaporation. To achieve this degree of atomization with single-phase nozzles at these flow rates requires pressuring water through very small holes. It was feared that these nozzles would be prone to plugging when recycle liquor was utilized as a cooling medium. For this reason, two-phase nozzles were investigated.

Finding a two-phase nozzle that would provide a high degree of atomization when operated under a system pressure of 100 to 300 psig was difficult. The two most promising spray nozzles were a two-phase nozzle from Sonic Development Corporation, and a single-phase nozzle from Bete. None of the vendors of commercially available two-phase spray nozzles who were questioned had data or experience with operation under pressurized conditions. Various types of nozzles were tested based on their performance at atmospheric conditions.

Actual performance of the humidifier indicated that under the higher pressure conditions, data did not correlate well with the atmospheric data available, nor did the humidifier lend itself to the normal pressure-ratio scaling laws. Although the two-phase nozzles functioned well, their excessive use of nitrogen as an atomization medium was calculated to be prohibitive in a high-pressure, commercial installation. Studies made to determine the economic viability of this type of atomization indicated that the use of cleaned and compressed recycle product gas would be technically feasible in a commercial facility but would add noticeably to the system complexity. As a consequence, emphasis was placed on the single-phase nozzle approach.

Computer models of the humidifier design have been formulated to assist with optimization. Nozzle testing and humidifier development were test objectives for Test Runs 91 through 96. In addition, analysis of humidifier test data

from Test Run 94 indicated that the vessel was undersized. The length of the vessel was increased from 10 to 30 feet prior to Run 95, in order to provide increased residence time for full droplet evaporation at the design, i.e., of 120,000 SCFH gas throughput at 200 psig. Testing of single-phase nozzles providing droplet size in the 100- to 200-micron range, when a pressure of 200 to 300 psi was applied across the nozzle, determined that liquor would sufficiently evaporate within the vessel. To ensure that the orifice in the nozzle would not plug, filters were provided upstream of each nozzle.

Humidifier operation was considered essential to the operation of the balance of the cleanup system. As a result of testing efforts described earlier, the humidifier is now an effective, reliable cooling device capable of operating in an automatic control mode at the desired operating temperature set points. The humidifier operates reliably and controls gas temperature between 375 and 400°F. Humidifier data developed during Run 96 closely followed behavior predicted from Run 94. Table 13 compares analytical results with predicted values.

The humidifier currently uses four Bete single-phase nozzles of differing capacities. The nozzles resemble spark plugs and are shielded from the incoming raw gas in order to preclude deposits (and possible plugging) on the nozzle. Each nozzle operates with a differential pressure of between 200 and 300 psi, and spray water flow is separately controlled in order to maintain droplet size between 100 and 200 microns. Flow to each nozzle must be controlled between 50 to 100 percent of design flow to maintain proper droplet size. To achieve the desired set point exit temperature at any operating humidifier throughput, the proper number of nozzles must be utilized within their permitted flow range. For this reason, an automatic control system has been installed to sequentially activate the appropriate number of spray nozzles and control their flows, and maintain the desired operating temperature.

During the humidifier testing, various methods of collecting the tar in the tar trap were tried. The tar trap was designed as a large pressurized vessel in which various internal configurations could be tested. Unacceptable results were obtained using baffle- and vane-type internals. The highest tar removal occurred when an impact plate was used, and velocities were increased by manually throttling across the inlet valve to the tar trap. As a result of the pressure drop, greatly increased velocities were measured across the separator. This improvement indicated that higher-velocity removal devices should be tested in subsequent runs. A cyclone-type device was developed for testing in Run 95 (see Section 5.3.2).

The side-stream tray scrubber had been modified for this run by replacing the valve trays with simple sieve plates having 1/4-inch-diameter holes. Tar fouling had occurred in the valve trays during the previous test. This unit was operated and evaluated during Test Run 92. No fouling was experienced with this design modification.

The venturi scrubber was first tested during Test Run 94 and has been demonstrated to be a very effective secondary device for removing tar not collected in the tar separator. The venturi scrubber operates at a nearly isothermal condition with the incoming gas from the tar separators. The successful operation of the venturi scrubber paved the way for the testing of the balance of the downstream equipment. Tar removed by the venturi scrubber is readily

TABLE 13. HUMIDIFIER PERFORMANCE COMPARISON OF PREDICTED
VERSUS ACTUAL MOISTURE CONTENT OF GAS - TEST RUN 96

Estimated Water Content	Calculated Values	Sample Probe
H ₂ O in gasifier outlet gas	16.9	13
H ₂ O in humidifier outlet gas	30.3	30
H ₂ O in Venturi outlet gas	24.7	22
Process Stream Conditions		
Temperature at the gasifier	990°F	
Temperature at the cyclone	850°F	
Temperature at the humidifier Exit	354°F	
Temperature at the venturi	255°F	
Air Flow Rate (SCFH) to gasifier	29,400	
Steam Flow Rate (lb/hr) to gasifier	813	
System Pressure (psig)	117	
Water Flow Rate into Humidifier (lb/hr)	530	

separated from the scrub water in a pressurized decanter and the water is recirculated to the venturi. The tar, which remains liquid at room temperature, is drained from the decanter on a regular basis. Makeup water is supplied from the recirculating decanter circuit. Tar removed from the gas in this manner is higher in water content than the relatively dry tar removed in the tar separator. Analyses of the tars and liquors collected from this system collected during subsequent runs are presented in Tables 18 through 21 later in this Section of the report.

5.3.2 Phase IV of Test Program - Complete Full-Flow Cleanup System Test Results

The objective of Test Runs 95 and 96 was to determine the operational capability of the complete FFCUS. Figure 18 is a schematic diagram of the fixed-bed gasifier and FFCUS. The dashed line indicates the component equipment tested during Test Run 94. The entire system was tested during Test Runs 95 through 98. Figure 19 shows the sample locations referred to in tables where data were collected during these runs. Modifications were made on the basis of test results. In addition, improvements to the gasifier ancillary hardware were tested. This strategy has succeeded, and each test run has been built upon the results and knowledge gained from the previous test. The successful completion of over 120 hours of continuous operation during Test Run 96, delivering excellent quality gas of 175 ± 10 Btu, was a milestone achievement.

During Test Runs 95 through 98, the gasifier and FFCUS operated for longer periods (250 to over 700 hours, versus typical 50 to 150 hours) and at higher throughputs than previously achieved, e.g., 2,000 lb/hr coal feed. This was due to design improvements made to the gasifier and its ancillary equipment. Steady operation during each test period was maintained for a minimum of 24 hours in order to allow samples to be collected for heat and material balance calculations. Results of these calculations have shown an acceptable closure (within a few percent). Table 14 gives the range of gas compositions measured during Test Runs 95 and 96.

Throughout this series of test runs the dust cyclone performed adequately as defined by removal of sufficient dust to avoid plugging problems in downstream equipment. Dust removal rates of approximately 80 percent of inlet levels were measured. Erosion of the cyclone walls, measured continuously by experimental sensors installed by Argonne National Labs, was acceptable, typically 0 to 2 thousandths of an inch (mil) for each period.

Table 15 presents a typical analysis of the size distribution of the dust collected by the cyclone.

Cooling of the raw, low-Btu gas causes high-boiling tars to condense. A portion of these tars was collected in the humidifier. To collect the balance, it was necessary to install a droplet separator to remove the tars from the gas stream. As a result of testing conducted during Test Run 94, it was determined that a cyclone device with velocities in the range of 150 feet per minute (ft/min) performed acceptably as a tar separator. A test cyclone was manufactured on-site to replace the large vessel used in Run 94. This

FIGURE 18. FIXED-BED GASIFIER AND FULL-FLOW CLEANUP SYSTEM RUNS 95 TO 98 -
CONFIGURATION TESTED IN RUN 94 - INSIDE DASHED LINES

FIGURE 19. SAMPLE LOCATIONS FOR FULL-FLOW GAS CLEANUP SYSTEM - TEST RUNS 94 TO 98

TABLE 14. PRODUCER GAS COMPOSITION (VOLUME PERCENT, DRY BASIS) - TEST RUNS 95 AND 96

	Raw Gas		Clean Gas	
	Volume		Percent (Vol %)	
H ₂	14.5	to 16.5	14.5	to 17.0
CO ₂	7.0	to 10.0	6.2	to 10.8
C ₂ H ₆	.26	to .35	.27	to .35
H ₂ S	.32	to .35		
O ₂	.56	to .73	.68	to .74
N ₂	47.0	to 50.0	47.0	to 50.1
CH ₄	3.0	to 3.5	2.9	to 4.6
CO	18.0	to 23.3	17.7	to 23.0

TABLE 15. SIZE DISTRIBUTION OF CYCLONE DUST - TEST RUN 96

Particle Size (microns)	Cumulative Wt % Oversize		
	Composite Sample	Grab Sample No. 1	Grab Sample No. 2
128.0	4.4	2.8	3.9
80.6	30.0	26.6	25.4
64.0	51.6	38.9	40.2
50.8	71.7	59.7	66.1
40.3	83.3	77.8	79.3
32.0	89.9	83.8	84.8
25.4	94.3	92.4	93.0
16.0	98.5	97.2	98.2
10.0	99.6	99.8	99.5
6.4	100.0	100.0	100.0
4.0			

device functioned effectively. It removed a high percentage of the incoming tar, did not plug, and erosion was minimal. The only disadvantage to this design has been the pressure drop attendant with its operation. Typical compositions of the tar collected in the humidifier and tar separator are presented in Tables 16 and 17.

As a result of the success of the single cyclone design, a commercially manufactured "multiclone" was installed to be tested during Test Run 101. This unit promises high droplet removal efficiencies at lower pressure drops than experienced with the in-house design.

The ESP was first checked prior to Test Run 95. Difficulties were encountered during pre-operational checking in maintaining proper voltage without excessive sparking. The vendor was unable to visit the site to assist METC until Test Run 96. Analysis of the system revealed several problems. The first problem was a difficulty in controlling primary voltage to the high voltage transformer, solved by installation of a powerstat on the electrical feed. The next problem was bending of the wire electrodes and their electromotively induced oscillation within the collector tubes, solved by replacing the wires with 1/2-inch threaded rods cross-connected at the bottom to reduce induced oscillation. After these problems were corrected, the ESP was readied for future testing. Further testing of the ESP was performed during Test Runs 97 and 98. A diagram of the ESP is shown in Figure 20.

Data concerning the operation of the ESP were preliminary and inconclusive. Tests to characterize its operation are scheduled for future runs.

The full-flow system direct and indirect coolers were first tested during Test Run 95. The cooling system lowered the gas stream temperature to the desired 100°F for hydrogen sulfide removal. Cooling the gas from approximately 300 to 100°F resulted in the condensation and washing of light oils from the gas stream. These oils form a distinct layer above the water in the recirculating decanter and were easily separated. A rotating sampler was developed by METC in order to determine the location of the oil layer in the decanter and for removal of accumulated oil. An analysis of the oils drained from the recirculating decanter is included in Tables 18 through 20.

The liquors from the direct cooler are collected in the pressurized recirculating decanter, separated, and a sour water fraction is constantly recycled. Portions of this water are used to supply water to the humidifier spray nozzles and makeup water to the venturi system. The separation capability of this decanter proved adequate and the resulting cleanliness level of the liquor, in terms of both particulates and oils, produced no pump problems, heat exchanger blockage, observable erosion, and required only modest filtration levels in order to maintain humidifier nozzle operability. Excess water resulting from condensation of the unreacted steam fed to the gasifier is bled to the waste pond for treatment. Table 21 provides an analysis of the recirculating decanter liquor.

Tests were run to determine the mass loading of aerosols in the gas stream and the particle size distribution of dust captured by the various process streams. These test data are shown in Table 22, and the average data are graphically represented in Figure 21.

TABLE 16. TEMPERATURE-VISCOSITY PROFILE FOR RECOVERED TAR -
TEST RUN 90

Temperature (°F)	Viscosity (cp)
203	3,010
221	2,500
234	2,005
241	1,910
259	1,555
268	1,200
279	990
284	950

TABLE 17. COMPOSITION OF RECOVERED TAR - TEST RUN 95

Percent by Weight	Humidifier	Tar Separator
Moisture	0.26	0.53
Ash	0.59	0.60
Hydrogen	5.47	5.15
Carbon	86.99	85.98
Sulfur	1.43	1.39
Nitrogen	1.21	1.19
Oxygen	4.05	5.16
Heating Value (Btu/lb)	15,369	15,528

FIGURE 20. ELECTROSTATIC PRECIPITATOR

TABLE 18. TAR AND OIL SAMPLES TAKEN DURING TEST RUN 95

Sampling Point	Venturi Scrubber		Direct Coolers	
	S13	S33	S21	S22
	Tar	Tar	Oil	Oil
<u>Wt. %</u>				
Water	3.37	2.08	1.02	0.2
Dust	8.11	6.75	0.075	0.76
Ash	0.24	0.36	0	0
Sulfur	0.62	0.60	0.26	0.22
Hydrogen	5.82	6.26	6.97	7.46
Carbon	85.99	83.29	88.25	87.33
Heat Content (Btu/lb)	15,795	14,939	18,906	16,909
Specific Gravity	1.007	1.012	1.004	1.004
Viscosity*	>100,000	28.8×10^3	5.5	5.5

Note: Samples are as-received

* by Brookfield Viscometer, Model LV. Viscosity in cp at 25°C

TABLE 19.
TAR AND OIL SAMPLES TAKEN DURING TEST RUN 96

Sampling Point	Recirculating Decanter	Venturi Scrubber
	S34	S13
	Oil	Tar
Percent Wt/Wt:		
Water	0.10	1.10
Dust	0.41	2.19
Ash	0	0.15
Sulfur	0.98	1.17
Hydrogen	7.44	6.84
Carbon	87.83	82.83
Heat Content (Btu/lb)	18,962	16,846
Specific Gravity	1.005	1.010
Viscosity (Brookfield at 24.4°C)	5.5	435

Note: Samples are as-received

TABLE 20.
BOILING POINT RANGE OF TAR AND OIL SAMPLES FROM TEST RUN 96

Sampling Point	Recirculating Decanter	Venturi Scrubber
	S34	S13
Simulated Boiling Point (°F)	Oil (wt %)	Tar (wt %)
232-352	13.59	1.18
353-424	28.92	3.86
426-472	14.08	2.89
473-510	7.10	2.63
511-552	11.74	3.85
553-568	3.29	2.29
569-651	9.04	10.43
652-937	5.46	19.73

TABLE 21. LIQUOR SAMPLES TAKEN DURING TEST RUN 95

Sample Location	S10	S22	S27
pH	8.57	8.33	7.80
Bicarbonate	1,787	22,800	2,574
Carbonate	3,693	1,331	0
Chloride	1,200	1,150	900
Cyanide	0.36	3.4	2.6
Phenol	2,700	6,750	2,700
Sulfur, total	5,520	996	910
Sulfate	13,500	1,840	2,110
Nitrogen, total	1,790	1,360	540
Thiocynate	1,820	290	255
Solids, total	31,760	32,420	18,560
Suspended Solids	860	11,420	10,360
Dissolved Solids	30,900	21,000	8,200
Specific Cond. (mhos/cm)	56,000	35,000	14,000
Specific Gravity	1.004	1.005	1.002
Na	2.5	0.07	1.6
K	2.5	0.07	1.6
Co	0.01	0.01	0.01
Mo	0.5	0.5	0.5
Hg	0.00043	0.00008	0.00019
V	0.04	0.04	0.04
Cr	0.01	0.01	0.01
Ni	0.015	0.83	0.015
Pb	0.03	0.03	0.03

All values are in mg/l except pH, Specific Conductance, and Specific Gravity. Bicarbonate and carbonate in mg/l (CaCO_3 equivalent).

TABLE 22. PARTICLE SIZE DISTRIBUTION OF DUST SAMPLES THROUGHOUT
CLEANUP SYSTEM - TEST RUN 95

	Cumulative Weight Percent Oversize											
<u>Size in Microns</u>	128.0	80.6	64.0	50.8	40.3	32.0	25.4	16.0	10.1	6.4	4.0	2.5
<u>Sample Location</u>												
Dust - S6	2.3	15.0	24.7	41.0	54.2	62.9	70.9	83.8	99.2	100.0		
<u>Aerosol Mass Loading</u> S-14												
0930-1030, 9/25/80		2.2	9.8	16.3	26.1	36.3	46.3	61.3	74.1	83.7	94.4	100.0
1117-1217, 9/25/80	24.8	33.6	40.5	47.5	53.4	57.3	61.1	70.1	89.5	100.0		
1335-1435, 9/25/80	29.4	49.5	57.9	63.9	68.3	71.4	74.1	79.4	99.1	100.0		
<u>Tar Samples</u>												
S 13	2.3	5.9	9.2	14.6	24.5	39.0	65.9	79.7	88.3	94.7	100.0	
S 33	0	0	2.3	7.9	16.9	28.9	49.5	61.6	74.2	91.0	100.0	
<u>Oil Samples</u>												
S 21	3.7	12.5	17.3	23.1	32.4	42.0	58.0	69.2	79.9	91.7	100.0	
<u>Liquor Samples</u>												
S 10	5.3	12.4	17.7	22.0	27.8	33.9	49.1	62.9	76.3	90.0	100.0	
S 11	6.3	13.7	21.9	32.3	42.8	52.9	70.1	82.3	90.8	96.5	100.0	
S 25	0	0	0.2	3.0	10.3	20.5	49.6	75.5	91.6	98.1	100.0	
S 27	4.2	12.0	18.9	26.1	33.0	39.0	53.3	67.2	82.3	94.7	100.0	
S 28	0.1	5.5	14.3	21.6	27.3	32.8	46.3	59.0	73.2	87.5	100.0	

Ref.: ITRI, December 1979, 1980, 1981, 1982.

FIGURE 21. SIZE DISTRIBUTION OF PARTICULATES IN PROCESS GAS STREAM - TEST RUN 95

The Stretford hydrogen sulfide removal system was initiated during Test Run 95. The Stretford system demonstrated its ability to remove the H_2S from the product gas to design levels for short periods of time. Product gas was cleaned by the system during approximately 100 hours of Stretford operation. Table 23 presents a summary of the sulfur removal capability exhibited by the Stretford system during this initial phase of its operation.

A fugitive flow of gas inadvertently bypassed the direct cooler and contaminated the Stretford solution with hydrocarbons during the early phases of the checkout. This contamination was suspected of causing severe foaming and entrainment of Stretford liquor in the absorber outlet gas streams during Runs 96 and 97. Various efforts to reduce the entrainment, including use of a defoaming agent, were unsuccessful. As a result of this problem, it was difficult to obtain accurate gas samples at the original sampling locations. Another problem was the inability to properly separate out the sulfur captured in the Stretford liquor. It appeared that the fine sulfur particles became coated with the contaminating hydrocarbons and were unable to grow into a filterable size. Measures were taken to address these difficulties; these are described with the test results of Runs 99 and 100 later in this Section.

The purpose of the water scrub columns is to remove trace quantities of any water-soluble contaminants which might be present in the gas stream at this point. Of particular concern was the potential presence of alkali and heavy metals resulting from carryover of alkali-based Stretford liquor. The alkali scrubber equipment has worked well. Alkali metal concentrations in the cleaned product gas have been very low. Table 24 provides a summary of the pertinent gas contaminant levels and testifies to the cleanup system performance.

The primary goal of Test Runs 97 and 98 (May through August, 1981) was to provide clean, low-Btu gas fuel for the Corrosion/Erosion Test Program (see Section 4.7 of this report). The requirement to provide 300 hours and 600 hours of testing for the second and third phases of that program were the principal objectives of these two respective gasifier tests.

The fixed-bed gasifier and FCCUS operated extremely well during Runs 97 and 98, logging a total of 1,116 test hours and maintaining an 88 percent availability. Test Runs 97 and 98 each ended due to erosion failure of the lower stirrer arm at its end caps. Subsequent improvements to the design and manufacture of the arms have eliminated this problem.

Operation of the cleanup system during Test Run 97 was troubled by continual foaming present in the Stretford system. A defoaming agent used to mitigate the problem was generally unsuccessful. For this reason it was determined that a low-sulfur coal (i.e., less than 1.2 percent) that did not require the Stretford system for emission control would be used during Test Run 98. This allowed most of the gasifier-related testing activities to continue with the Stretford inoperative while redesign activities were accomplished. A Lower Kittanning coal was consequently tested during Test Run 98. Table 25 shows the chemical analyses for the coals used during Test runs 97 and 98, while Table 26 presents the respective ash analyses. Gasifier and cleanup system operation with Lower Kittanning coal feedstock was virtually flawless and

TABLE 23. PRELIMINARY PERFORMANCE SUMMARY OF THE STRETTFORD SULFUR REMOVAL SYSTEM - TEST RUNS 95 AND 96

Constituent	Inlet to Stretford Unit (ppm)	Outlet from Stretford Unit (ppm)
H ₂ S	3,650-4,500	0.2-50
COS	250-410	235-360
CS ₂	12-60	11-57
CH ₃ SH	1.5-4.0	<1.5
Thiophene	4-18	3-12
HCN	78	<1.0

TABLE 24. REPRESENTATIVE GAS CLEANUP SYSTEM PERFORMANCE - TEST RUNS 95 AND 96

Cleanup System Location	Particulate Loading (gm/m ³)*	Tar Loading (gm/m ³)	Hydrogen Sulfide (ppm)	Alkali Metals (ppb)**
After cyclone	-	11.0-15.0	-	-
After humidifier	0.20-0.60	8.0-10.0	-	-
After tar separator	0.05-0.50	1.0-4.0	-	-
After venturi scrubber	0.03-0.05	0.1-1.0	-	-
Before Stretford	-	-	3,600-4,500	-
After Stretford	-	-	0.2-50	-
Before alkali scrubber	-	-	-	50-100
After alkali scrubber	-	-	-	1-15

Note: The data shown above are typical and do not represent a single test run.

Note: The Stretford system has not completed its shakedown testing and performance results were preliminary.

*Grams per cubic meter

**Parts per billion

TABLE 25. ELEMENTAL ANALYSIS, HEAT CONTENT, ASH FUSION TEMPERATURE,
AND FREE SWELLING INDEX

	RUN 97			RUN 98		
Sampling Point	Coal*	Bottom Ash	Cyclone Dust	Coal**	Bottom Ash	Cyclone Dust
<u>Proximate, wt %</u>						
Moisture	0.64	0.23	0.39	0.44	0.07	0.06
Ash	8.64	69.27	11.60	9.09	78.29	12.76
Sulfur	2.20	0.70	1.50	1.02	0.10	0.68
Volatile Matter	38.67	1.13	2.40	36.46	1.03	2.37
Fixed Carbon	52.05	29.37	85.61	54.01	20.61	84.81
<u>Ultimate, wt %</u>						
Hydrogen	5.62	1.03	0.89	5.16	0.16	1.00
Carbon	77.66	28.66	83.54	75.40	20.62	82.07
Nitrogen	1.54	0.38	1.10	1.48	--	1.19
Sulfur	2.20	0.70	1.50	1.02	0.10	0.68
Oxygen (by difference)	4.34	--	1.37	7.85	0.83	2.30
Ash	8.64	69.27	11.60	9.09	78.29	12.76
Btu	14,156	4,320	12,760	13,633	2,954	12,404
FSI	7.5	--	--	7.0	--	--
<u>Ash Fusion Temperature, °F</u>						
Initial Deformation	2,200	2,200	2,210	Greater	2,690	2,671
Softening	2,210	2,250	2,250	Than	2,701	2,729
Hemispherical	2,240	2,335	2,275	2,783	2,711	2,769
Fluid	2,410	2,410	2,430		2,760	2,778

* Pittsburgh No. 8 Coal

** Lower Kittanning Coal

Note: Samples taken from respective material balance period from each test run.

TABLE 26. ANALYSIS OF ASH (HTA)* IN WEIGHT PERCENT

Component	Run 97			Run 98		
	Coal	Bottom Ash	Cyclone Dust	Coal	Bottom Ash	Cyclone Dust
SiO_2	45.52	42.85	44.11	52.39	52.02	48.45
Al_2O_3	25.74	26.48	27.92	30.25	30.69	30.17
Fe_2O_3	17.06	19.49	16.17	10.34	11.46	13.50
CaO	5.62	4.56	4.62	1.35	1.38	1.94
MgO	1.97	1.27	1.54	0.62	0.72	0.96
Na_2O	0.29	1.10	1.07	0.79	0.50	0.69
K_2O	1.02	1.08	1.18	1.46	1.57	1.64
P_2O_5	0.29	0.27	0.38	0.62	0.64	0.90
TiO_2	1.24	1.26	1.37	1.70	1.66	1.73

Samples taken from respective material balance period from each test run.

* High Temperature Ash

required little adjustment of control parameters from previous tests on Arkwright coals. The average gas analyses for these runs are given in Table 27. During each test run, a 24-hour material balance period was maintained in order to characterize flow streams. Tables 28 through 32 summarize the analytical data measured during the material balance periods for Test Runs 97 and 98. Using these analytical data, material and energy balance calculations were performed for steady-state periods occurring during the runs. These balances are summarized in Figures 22 and 23 which also include process data averaged from several stable periods of consistent operation from each test run. Data from Test Run 97 were from periods totaling 71 hours, and data from Test Run 98 were averaged from periods totaling 93 hours.

Temperature, pressure, gas composition, and flow rate data were taken from the representative periods and averaged by the ADACS data acquisition system. Where possible, obviously erroneous data were screened from the calculations to facilitate accuracy. Mass flow rate data were calculated from the operator log sheets for coal feed, tar, oil and dust removal values. These values were carefully screened to exclude times when abnormal operation might have occurred. Chemical analyses of the process streams were performed during the "24 Hour, Heat and Material Balance Period". These values were assumed to be representative for the entire calculation period.

On-line analysis of the product gas does not account for all of the constituents in the gas. Estimates of the minor components were performed from laboratory results of analyses conducted during Run 99 and engineering estimates (see Tables 34 and 35). Calculation of the heating value of the gas analysis, Table 33, yielded values within 2 percent of the measured heating value determined by the on-line gas calorimeter.

The material and energy balance was calculated and compiled in the table included in Figures 22 and 23. Gas leakage from the cleanup system to the vent system was estimated. This was done by estimating theoretical gas production through a nitrogen balance, and calculating the losses as a portion of the product gas. The primary sources of gas leakage were lockhopper operation, packing leaks, Stretford flash gas, and deterioration with time of lockhopper vent valves. This flow represents approximately 6 percent of the low-Btu gas produced.

The overall material balance for Run 97 showed agreement to within five percent when total gas leakage from the system of about 4,000 SCFH was factored into the calculations (based on the nitrogen balance); disproportionate amounts of carbon and oxygen were still unexplained. Difficulties encountered during Run 97 with the control of the ESP and the humidifier may have caused this discrepancy. Sulfur balance calculations were based on estimates because of the inability to remove sulfur product from the Stretford system.

The Test Run 98 material balance showed agreement to within less than one-half percent. The total energy balance closes to within two percent. The ability to operate within these tolerances was aided by improved performance of the humidifier, and bypassing of the ESP and Stretford system by the cleanup train.

TABLE 27. MAJOR GAS ANALYSES BY ON-LINE GAS CHROMATOGRAPH IN VOLUME PERCENT

	Run 97		Run 98	
	Producer Gas	Clean Product Gas	Producer Gas	Clean Product Gas
H ₂	15.29 ± .84	16.00 ± .53	16.43 ± .99	17.10 ± .58
CO ₂	7.84 ± .78	6.88 ± .28	8.51 ± .62	8.55 ± .75
C ₂ H ₆	0.29 ± .02	0.26 ± .03	0.26 ± .06	.25 ± .07
H ₂ S	0.35 ± .15	0.05 ± .03	0.17 ± .04	.18 ± .02
O ₂	0.58 ± .03	0.73 ± .06	0.64 ± .04	0.70 ± .04
N ₂	48.52 ± 1.45	48.57 ± .66	47.66 ± 2.05	47.56 ± 1.69
CH ₄	2.82 ± .20	2.97 ± .23	2.28 ± .57	2.37 ± .48
CO	21.28 ± .86	21.50 ± .61	21.67 ± 1.24	22.13 ± 1.00

This data averaged from reported daily averages of each respective entire test run.

TABLE 28. CYCLONE DUST, SAMPLING POINT S6 SIZE DISTRIBUTION -
CUMULATIVE WEIGHT PERCENT OVERSIZE

Run 97		Run 98	
Size in Microns (μm)		Size in Microns (μm)	
128	0.2	128	14.8
80.6	1.3	80.6	28.3
64.0	8.6	64.0	57.8
50.8	21.9	50.8	68.5
40.3	37.4	40.3	75.5
32.0	55.4	32.0	80.3
25.4	71.5	25.4	83.4
16.0	89.4	16.0	89.6
10.1	97.1	10.1	99.7
6.4	99.3	8.0	100.0
4.0	100.0	Median (μm)	72.3
2.5	--		
1.0	--		
1.0	--		
Median (μm)	34.31		

Note: Samples taken during respective test run
material balance periods

TABLE 29. COMPOSITION OF RECOVERED TAR

Sampling Point	Run 97			Run 98		
	Humidifier	Tar Sep	Venturi Decanter	Humidifier	Tar Sep	Venturi Decanter
Moisture wt%	0.52	0.48	0.88	0.53	0.60	1.15
Ash wt%	0.38	0.26	0.15	2.10	0.33	0.22
Hydrogen wt%	5.32	5.26	5.61	5.55	5.77	6.93
Carbon wt%	86.69	87.41	73.78	75.45	79.69	84.37
Sulfur wt%	1.23	1.25	1.23	0.57	0.56	0.64
Nitrogen wt%	1.41	1.57	1.43	1.63	1.87	1.22
Oxygen* wt%	4.45	3.77	16.92	14.17	11.18	5.47
Btu	15420	15710	15464	13,410	14,979	17,406
Specific Gravity	---	---	1.015	---	---	1.015

* Oxygen by difference

NOTE: (1) All results are in Wt% except Btu and specific gravity
 (2) Solid tar at S8 and S9
 (3) Samples were taken during respective test run material balance periods

TABLE 30. LIQUOR SAMPLES

	Run 97		Run 98	
	Venturi Liquor	Recirculating Liquor	Venturi Liquor	Recirculating Liquor
pH	8.58	8.60	8.29	8.50
Ammonia (Free)	9,290	9,800	14,400	9,800
Alkalinity as CaCO ₃	7,580	40,130	223,000	257,000
Chloride	1,300	1320	21,000	1,200
Cyanide	88	72	4	115
COD	94,350	68,500	216,000	102,000
Phenol	1,880	1,610	142	380
TKN (Kjeldahl Nitrogen)	10,260	12,100	18,800	19,600
Sulfur, Total	2,217	1,330	1,100	680
Sulfide	722	890	780	110
Thiocyanate	3,230	980	600	1,000
Sodium	8.5	10.5	16	4.3
Potassium	.33	3.8	2.1	0.9
Vanadium	≤0.015	≤0.015	0.5	≤0.2
Specific Gravity	1.013	1.000	1.025	1.025
**Total Solids	44,335	33,480	26,500	2,000
*Tar and Oil	33,120	3,970	5,200	5,760

* Freon Extraction

** Residue on Evaporation (ROE) at 180°C

Note: (1) All values in mg/l except pH and specific gravity
 (2) All sample composites taken during material balance periods
 of respective test runs

TABLE 31. RECIRCULATING DECANter OIL SAMPLES

Analysis	Run 97	Run 98
Water	0.22	-0-
Dust	0.001	0.91
Ash	-0-	0.10
Sulfur	0.85	0.55
Hydrogen	11.59	8.65
Carbon	86.44	85.57
Nitrogen	0.13	0.83
Heat Content (Btu)	20,438	19,000
Specific Gravity	1.015	1.006
Viscosity*	2.0	9.0

* By Brookfield Viscometer, Model L.V. Viscosity in cp at 23.3°C

- Note: (1) Samples taken during respective test run material balance periods
 (2) All results are on "as received" basis
 (3) All results are in Wt % except Btu, specific gravity, and viscosity

TABLE 32. BOILING POINT RANGE OF OIL SAMPLES FROM RECIRCULATING DECANter

Run 97		Run 98	
Boiling Range °F	Wt %	Boiling Range °F	Wt %
231-352	22.48	231-352	16.88
353-424	30.54	352-424	18.82
425-472	15.15	425-472	16.08
473-498	10.74	473-510	13.68
499-541	3.65	511-550	7.06
542-637	6.98	551-568	7.63
Above 637	1.45	569-651	8.03
		652-937	10.07

Note: Samples were taken during respective test run material balance periods

Average data period 0000 6/13/81 to 0000 6/16/81
Chemical Samples taken 0800 6/16/81 to 2000 6/16/81

6 STREAM NO.
 6 TEMP °F
 6 PRESS. (PSIG)
 6 FLOW (GPM)

	COAL FEED	AIR	STEAM	ASH	DUST	HUMIDIFIER TAR	HUMIDIFIER WATER	TAR SEPARATOR TAR	VENTURI TAR	DECANTER OIL (LESS 71.41/HR KEROSENE)	ELECTROSTATIC PRECIPITATOR L.H.	WATER TO WASTE	RAW GAS (2808 H ₂ O)	PRODUCT GAS (20.77 H ₂ O)	SHELL COOLING WATER	STIRRER COOLING WATER	INDIRECT COOLERS	ESTIMATE REMOVED IN STRETFORD	GAS LEAKAGE BY DIFFERENCE	UNACCOUNTED	% UNACCOUNTED
	1	2	3	4	5	6	7	8	9	10	11	12	13								
FLOW #/HR	1181.0	3074.1	612.0	86.26	18.8	6.38	85.67	27.14	28.08	58.9	71.8	106.4	8852.5				50.3	261.1	213.8	4.39	
MBTU/HR	16,718	108	841	373	240	99	13	428	436	1205	12	5	10,122	406	464	1040	93	693	2038	11.54	
C	917.2			24.7	15.7	5.53	0.75	23.72	20.72	50.91	0.62	1.0	639.2				5.9	43.73	84.72	9.24	
H	66.4		68.0	0.9	0.2	0.34	9.05	1.44	1.60	6.84	7.61	12.1	82.86				1.7	5.34	4.39	3.27	
N	18.2	2318.6		0.3	0.2	0.09	0.97	0.43	0.40	0.08	0.82	1.3	2152.1				20.0	146.46	13.66	.58	
O	51.2	713.1	544.0	0	0.3	0.31	72.13	1.14	4.97	0.11	60.44	96.6	932.3				8.6	63.53	67.87	5.19	
S	25.9			0.7	0.3	0.08	0.07	0.34	0.36	0.60	0.06	0.1	4.5				14.1	.47	4.33	16.72	
Ash	102.0			59.8	2.2	0.02	2.70	0.07	0.04	0	2.25	3.6	2.3						29.02	28.45	
Ar		42.4											39.4					2.0	1.0	236	
#/TON COAL				146	31.8	10.8		46.0	47.6	99.7											

FIGURE 22. TEST RUN 97 FLOW DIAGRAM AND MATERIAL AND ENERGY BALANCE

◻ STREAM NO. ◯ TEMP °F ◻ PRESS. (PSIG) ◻ FLOW (GPM)

	COAL FEED	AIR	STEAM	ASH	DUST	HUMIDIFIER TAR	HUMIDIFIER WATER	TAR SEPARATOR TAR	VENTURI TAR	DECANTER OIL	ELECTROSTATIC PRECIPITATOR L.W.	WATER TO WASTE	RAW GAS	PRODUCT GAS (27.9% H2O)	SHELL COOLING WATER	STIRRER COOLING WATER	INDIRECT COOLERS	GAS LEAKAGE	TOTAL OUTPUT	UNACCOUNTED	* UNACCOUNTED
	1	2	3	4	5	6	7	8	9	10	11	12	13								
FLOW #/HR	1560.0	3863	801.0	128.2	28.38	6.38	17.06	39.32	39.91	65.30		372.9	5181.3				320.9	6200	24.05	0.39	
MBTU/HR	21,267.0	135	1139	379	352	90	1194	593	698	1243		22	13,627	470	460	2110	845	22,083	458	2.03	
C	1176.24			26.43	23.29	5.04	.61	31.33	33.67	55.88		13.34	899.1				55.7	1144.39	31.85	2.71	
H	80.50		89	.20	.28	.37	1.56	2.29	2.83	5.65		34.08	109.4				6.8	863.28	6.22	3.67	
N	23.09	2913			.34	.10	.33	.73	.49	.54		7.31	2743				170.0	2992.83	13.25	.45	
O	122.46	896.0	712	1.06	.65	.99	14.51	4.62	2.58	2.21		17.15	1362				84.4	1790.17	-59.71	-3.45	
S	15.91			0.13	.19	.04	.01	.22	.26	.36		.25	13.80				.86	16.12	-0.21	-1.32	
Ash	141.80			100.37	3.62	.14	.04	.13	.09	.66		.77	3.07					88.89	32.91	23.21	
Ar		53.3											50.1				3.1	53.2	.01	.19	
#/TON COAL				164.4	36.38	8.56		50.41	51.17	83.72											

FIGURE 23. TEST RUN 98 FLOW DIAGRAM AND MATERIAL AND ENERGY BALANCE

Several operational problems had to be overcome during Test Runs 99 and 100:

Run 99:

- The facility steam boiler unexpectedly failed.
- The facility high-pressure air compressor developed a crack in the cooling jacket.
- The coal bucket elevator motor burned out and was out of service for repair three times in 36 hours for four to six hours each time.
- Wet and frozen coal resulted in erratic coal feed.

Run 100:

- High concentrations of toxic gas emissions resulting from excessive stirrer shaft wear and associated seal deterioration posed a possible environmental and personnel hazard which precluded continued operation of the gasifier.

In spite of the numerous difficulties listed above, analytical tests performed during Run 99 yielded some useful information, presented in Tables 34 and 35. These data are representative of the Arkwright (Pittsburgh No.8) coal tested extensively in earlier runs. They give insight into the quantities of illuminant hydrocarbons carried by the gas phase through the tail end of the cleanup system. The presence of these compounds in the gas are responsible for approximately ten percent of the total heating value of the product gas and raise the heating value from a calculated value of 155 Btu (major gas species) to approximately 170 Btu as measured by the on-line calorimeter. Recalculation of gas heating value using an estimate of illuminant concentrations has been consistent with the measured heating value.

The objectives of Test Run No. 99 were to identify the source of the problems plaguing the operation of the Stretford Sulfur Removal System. A representative from the manufacturer was sent to assess the system and assist in this effort. Prior to Run 99, the ESP was repositioned immediately downstream of the direct cooler in the cleanup train. In addition, a droplet separator was installed immediately upstream of the Stretford system. This was done to reduce the potential for trace levels of hydrocarbon carryover into the Stretford system. These changes in the process configuration can be seen by comparing the sampling diagrams in Figure 19 with those in Figure 24. Analytical test results showed that the total hydrocarbon content entering the Stretford system was within the vendor's design specifications (see Table 34). However, testing indicated that the Stretford system was unable to operate properly at the design liquor flowrate (44 gpm) to the absorber tower. Operation above approximately 10 gpm resulted in flooding of the column. Inspection of the hardware revealed that the absorber trays delivered by the vendor did not conform to the detailed design drawing. The column had been equipped with one-half the specified number of holes.

The Stretford system was, therefore, modified to be consistent with the vendor's design drawings. An alternative tray design was fabricated and

TABLE 33. LEVELIZED GAS ANALYSIS USED FOR MATERIAL
BALANCE CALCULATION

		TEST RUN 98	TEST RUN 97
		Levelized Volume %	Levelized Volume %
AVERAGE VALUES FROM ON-LINE GAS CHROMATO- GRAPH	H ₂	17.123	16.592
	CO ₂	8.228	6.885
	CH ₄	0.276	0.273
	H ₂ S	0.193	0.046
	O ₂	0.677	0.715
	N ₂	46.821	49.197
	CH ₄	2.488	3.160
	CO	22.006	21.136
ESTIMATED VALUES FROM LABORATORY ANALYSES	C ₂ H ₄	0.241	0.153
	C ₃ H ₈	0.241	0.183
	COS	0.013	0.043
	H ₂ C (1)	0.050	0.051
	H ₂ C ₇ O (2)	0.160	0.183
	AP ₆ (3)	0.741	0.631
	H ₂ O (4)	0.600	0.754
Calculated Heating Value:		174.9 Btu/SCF	174.1 Btu/SCF
Measured Heating Value:		171.9 Btu/SCF	170.8 Btu/SCF
NOTES: Data from this table used to prepare Figures 22 and 23 (1) represents all aromatics in gas (2) represents all phenolics in gas (3) estimated based on airflow to gasifier (4) from steam tables			

NOTE: TABLE 34 FOLLOWS THIS PAGE

TABLE 35. MASS LOADING OF TARS AND WATER AT CYCLONE
OUTLET (S-4) - TEST RUN 99

Date	Sampling Point	Gasifier Conditions	Tar Loadings (gm/m ³)	Water Loadings (gm/m ³)
3-19-82	S-4	Stable	16.4	77.0
3-20-82	S-4	Stable	10.5	80.5
3-21-82	S-4	Stable	18.5	82.5
3-29-82	S-4	Unstable	19.2	79.2

TABLE 34. GAS QUALITY MEASURED ENTERING SULFUR REMOVAL SYSTEM - TEST RUN 99

Hydrocarbon Loading at S-15 (Outlet ESP) Prior to the Holmes-Stretford Desulfurization Unit								
Date/Time	Gas Volume Sample (l)	Location	Weight Collected	HSDU gm/m ³	gm/m ³			
3/17/82	15 liters	S-15	.14 gm	10.0	9.3			
3/18/82	15 liters	S-15	.16 gm	10.0	10.3			
3/22/82	15 liters	S-15	.11 gm	10.0	7.3			
Solid Particulate Measured in Gas								
Sample No.	Date	On	Off	Flow Rate (SCFH)	Filter Weights (g) -			Aerosol Mass Loading (g/scm*)
					Init.	Final	D	
1 Front	3/18/82	0900	1000	60	0.144255	0.655500	0.511245	0.30
1 Back					0.142890	0.662873	0.519983	0.31
1 Composite							1.031228	0.61
S - 38 GAS TO STRETFORD SYSTEM								
Analysis of Water Phase				Analysis of Hydrocarbon Phase				
Major Compound	Percent of Total Oil		Component				Approximate Proportion	
Benzene	4.28		Phenol				55 percent	
Toluene	10.13		o-cresol				20 percent	
Xylene	7.76		m-cresol				20 percent	
			3-ethyl phenol				<1 percent	
			2-ethyl-4-methyl phenol				Trace	
			3-hydroxy benzaldehyde				Trace	
			3-hydroxy benzenethanol				Trace	
			2-propyl phenol				Trace	
			4(3-hydroxy-1-propenyl) phenol				Trace	
			3-undecylphenol				Trace	
			2-phenylphenol				Trace	
Other Compounds Detected								
Benzene	1,3,5-Trimethylbenzene				1-Ethyl-2,4-dimethylbenzene			
Toluene	1,2,4-Trimethylbenzene				2-Methyl indene			
Ethyl benzene	1,2,3-Trimethylbenzene				1-Methyl indene			
O-xylene	2-Bropenyl benzene				Naphthalene			
Ethenyl benzene	Indene				Benzothiophene			
m-xylene					2-Methylnaphthalene			
3-ethyltoluene					1-Methylnaphthalene			

*Grams per Standard Cubic Meter

FIGURE 24. SAMPLE LOCATIONS FOR FULL-FLOW GAS CLEANUP SYSTEM - TEST RUNS 99 AND 100

knock-out pots were installed to capture any inadvertent carryover from the absorber or flash tank. These modifications were all made in an attempt to alleviate absorber flooding and to achieve the design absorber flow rate as well as make the system more forgiving in the event of carryover. They were tested during Test Run 100. A comparison of the H₂S inlet and outlet gas concentrations for Test Runs 99 and 100 is presented in Figure 25. Although large improvements in performance are indicated, sufficient data to verify continued operation at these conditions were not obtained.

Test Run 100 had two primary goals: to verify the Stretford operation and to test the gasifier's fines-utilization ability by feeding coal briquettes. These activities were being tested simultaneously when the test run was prematurely terminated due to excessive leakage through the seals at the stirrer shaft penetration of the gasifier dome. Prior to the completion of the test run, data indicated a significant improvement in the performance of the Stretford system. The next test run should complete the performance determination of the Stretford system and should open the way for implementation of system testing.

5.4 RESULTS FROM COMPLEMENTARY PROJECTS

Detailed descriptions of these complementary programs and their results can be obtained by contacting the METC program office.

5.4.1 Environmental Health And Safety Research

Since Test Run 95, accomplishments of EH&S activities include implementation of compliance monitoring of all effluent streams: air, wastewater, and solid wastes. Other accomplishments include characterization of wastewaters; characterization of gasifier byproducts and development of a reuse and disposal program; completion of a workplace HHAS; and implementation of a clinical occupational medical surveillance program.

Byproduct Characterization and Environmental Management. Gaseous emissions, wastewaters, and solid byproducts generated by the METC gasifier have been characterized. Table 36 summarizes the analyses conducted at each sample point. These data are taken for process design purposes as well as for environmental characterization. Table 37 lists the data collected during Runs 85 through 100. Detailed data are available from the METC program office.

Ambient air monitoring activities have been conducted to measure the impact of effluent streams on the environment. Ambient air monitors measuring criteria pollutants have been sited upwind and downwind of METC. Continuous monitoring has shown: METC emissions are undetectable for criteria pollutants; and national air quality standards are not exceeded.

Solid byproducts from the system include bottom ash, devolatilized coal dust, light oils, liquid tars, solid tars, and sulfur. Each byproduct stream has been characterized for RCRA toxicity; data indicate that byproducts are not hazardous as defined by RCRA (Figure 26).

An HHAS was conducted to provide a profile of the METC gasifier workplace environment for comparison with occupational safety and health standards. Chronic and acute occupational health effects related to the METC gasifier

STRETFORD PERFORMANCE COMPARISON RUNS 99 & 100

FIGURE 25. STRETFORD PERFORMANCE COMPARISON - RUNS 99 AND 100

TABLE 36. SUMMARY OF GASIFIER SAMPLING POINTS

				S-1 COAL CONVEYOR BELT	S-2 GASIFIER BOTTOM ASH	S-3 GAS FROM GASIFIER	S-4 GAS FROM GASIFIER	S-5 GAS FROM GASIFIER	S-6 DUST FROM CYCLONE	S-7 GAS FROM HUMIDIFIER	S-8 LIQUOR FROM CYCLONE	S-9 LIQUOR FROM HUMIDIFIER	S-10 LIQUOR FROM HUMIDIFIER	S-11 LIQUOR TO TAP TRAP	S-12 LIQUOR TO VENTURI SCRUBBER	S-13 LIQUOR SCRUBBER DECANter	S-14 LIQUOR SCRUBBER DECANter	S-15 GAS FROM ESP	S-16 TAR FROM ESP	S-17 NI	S-18 NI	S-19 LIQUOR TO RECIRCULATING DECANter	S-20 GAS FROM RECIRCULATING DECANter	S-21 LIQUOR FROM RECIRCULATING DECANter	S-22 LIQUOR FROM RECIRCULATING DECANter	S-23 GAS TO THE ESP	S-24 GAS TO ALKALI SCRUBBERS	S-25 LIQUOR EFFLUENT FROM ALKALI SCRUBBERS	S-26 NI	S-27 LIQUOR EFFLUENT FROM ALKALI SCRUBBER NORTH	S-28 GAS FROM RECIRCULATING LINE TO ALKALI SCRUBBERS	S-29 FINAL PRODUCT POT	S-30 NI	S-31 VENTURI SCRUBBER DECANter BLOW DOWN	S-32 LIQUOR EFFLUENT FROM RECIRCULATING DECANter	S-33 GAS TO FLARE					
GAS COMPONENTS																																									
MAJOR GAS COMPONENTS ¹						X																																			
SULFUR SPECIES ²						X																																			
HYDROCARBONS ³						X																																			
NITROGEN SPECIES						X																																			
ORGANIC ⁴ (major/minor)						X												X																							
TRACE METALS						X																																			
LIQUIDS																																									
WATER QUALITY PARAMETERS ⁵																																									
TRACE METALS ⁶										X	X	X	X	X	X	X						X		X																	
PRIORITY POLLUTANTS ⁷										X	X	X	X	X	X	X					X		X																		
SYNFUEL ORGANICS																																									
DENSITY										X	X																														
VISCOSITY										X	X																														
SOLIDS AND PARTICLES																																									
PROXIMATE/ULTIMATE ⁸				X	X																																				
SULFUR TYPES																																									
TRACE ELEMENTS ⁹				X	X		X	X	X	X	X	X	X	X	X	X																									
PARTICLE SIZE DISTRIBUTION ¹⁰							X																																		
EXTRACTABLE ORGANICS ¹¹																																									
RCRA				X	X		X	X	X	X	X	X	X	X	X							X																			
SOLIDS										X	X																														

NI: Not in Use

TABLE 36. FOOTNOTES

GAS COMPONENTS

¹ MAJOR GAS COMPONENTS

H₂ O₂ N₂ CH₄ CO CO₂ C₂ - C₄

² SULFUR SPECIES

H₂S COS CH₃SH CS₂ Thiosulfate

³ HYDROCARBONS

C₂ - C₄

⁴ ORGANICS

PNA's Aerosol/Vapor phase Ag filter/Tenax

LIQUIDS

⁵ WATER QUALITY PARAMETERS

pH, specific conductance, hardness, acidity, alkalinity
bicarbonate, carbonate, COD, BOD, TOC, phenol, TIC, TS TDS,
TSS, TVS, sulfate, sulfite, sulfide, nitrate, nitrite, ammonia,
TFN

⁶ TRACE METALS

Al, Sb, As, Be, B, Ca, Co, Cu, Fe, Pb, Mg, Hg, Mo, Mn, Ni, K,
Na, Tl, Ti, V and Z

⁷ PRIORITY POLLUTANTS

129 organic compounds listed in 40 CFR

SOLIDS AND PARTICLES

⁸ PROXIMATE/ULTIMATE

Moisture	Hydrogen	Ash Fusion Temperature °F
Ash	Carbon	Free Swelling Index
Sulfur	Nitrogen	
Vol. Matter	Sulfur	
Fix. Carbon	Oxygen (by difference)	
	Ash	

⁹ TRACE ELEMENTS

SiO₂ Al₂O₃ Fe₂O₃ CaO MgO Na₂O K₂O P₂O₅ TiO₂

¹⁰ PARTICAL SIZE DISTRIBUTION

Study performed on Coulter Counter

¹¹ EXTRACT TABLE ORGANICS

PNA's

TABLE 37. SUMMARY TABLE OF ANALYTICAL ACTIVITIES FOR METC GASIFIER

	TEST RUN 85	TEST RUN 86	TEST RUN 87	TEST RUN 88	TEST RUN 89	TEST RUN 90	TEST RUN 91	TEST RUN 94	TEST RUN 95	TEST RUN 96	TEST RUN 97	TEST RUN 98	TEST RUN 99	TEST RUN 100
MAJOR GASES	X	X	X	X	X	X	X	X	X	X	X	X	X	X
SULFUR SPECIES	X	X	X	X	X	X	X	X	X	X	X	X	X	X
C ₂ - C ₄ HYDROCARBONS	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NITROGEN SPECIES	X		X	X	X		X		X	X				
ORGANIC Tracings			X						X	X				
METALS								X	X	X	X			
WATER QUALITY	X	X	X	X	X	X	X	X	X	X	X	X	X	X
METALS					X			X	X	X	X	X	X	X
PRIORITY POLLUTANTS				*			*			X	X	X		
VISCOSITY			X						X	X	X			
RCRA										X	X	X		
B.P. RANGE								X	X	X	X			
SPECIFIC GRAVITY				X				X	X	X	X			
PROXIMATE/ULTIMATE	X	X	X	X	X		X	X	X	X	X	X	X	X
SULFUR SPECIES								X		X	X	X		
TRACE ELEMENTS	X	X	X		X	X	X	X	X	X	X			
PARTICLE SIZE DISTRIBUTION				X	X	X	X		X	X	X	X		
EXTRACTABLE ORGANICS									X	X	X	X		
RCRA										X	X			
* SOLIDS				X					X	X	X	X		
BTU	X	X	X	X					X	X	X	X		
AFT									X	X	X	X		
FSI									X	X	X	X		

* Selected Parameters only

FIGURE 26. COMPARISON OF MEASURED RCRA PARAMETERS IN GASIFIER ASH WITH LIMITS FOR METC FIXED-BED GASIFICATION - RUNS 97 and 98 (BITUMINOUS COAL)

operation were determined, and a data base of potential contaminants found at coal conversion facilities of this type was begun. Workplace health activities are documented in Table 38. Findings of the HHAS indicate that parameters measured were below permissible exposure limits with one exception (personal samples for coal tar pitch volatiles as measured while tightening the stirrer shaft seal packing gland); no significant occupational clinical abnormalities were observed; and no dermatological problems existed from skin exposures to coal tar pitch volatiles during operation and maintenance activities. As a result of the HHAS, METC adopted workplace health procedures to further minimize exposures. Workplace safety and health monitoring and clinical occupational medical observations will continue in subsequent test runs.

METC gasifier wastewater streams have been characterized to determine principal components significant to treatability. Major wastewater streams include process condensate and ash quench water. Streams have been characterized to determine constituents significant to wastewater treatability. Results indicate that the process condensate is a high strength wastewater containing significant levels of phenol, cyanide, COD, and ammonia (Table 39). Ash quench wastewater is a dilute stream, with concentrations of phenol, thiocyanate, and ammonia which are typically less than 1 mg/l, 5 mg/l, and 10 mg/l, respectively. Wastewater characterization efforts initiated with Test Run 96 have provided data used to define influent water quality parameters for the design of a wastewater treatment plant for the METC site. Facility construction is scheduled for FY84.

Workplace Health & Safety. Once potential hazards are identified, engineering measures can be taken to minimize potential hazards to the worker. Appropriate industrial hygiene procedures have been instituted to reduce employee exposure to potentially harmful materials. This includes a respiratory protection program which was developed for controlling worker exposure in those environments identified as potentially hazardous. In addition, procedures have been developed for the personal use of protective clothing. Noise monitoring has also been conducted. In addition, air samples were collected to assess employee exposures and area levels of a variety of toxic gases, tar vapors, and particulate materials; urine and blood samples were tested for the metabolites of exposed materials; blood assays were made for indicators of tissue damages; skin examinations were made; and potable water was sampled.

Gasifier personnel have carried sampling monitors to measure their 8-hour time-weighted average exposure to materials such as carbon monoxide, hydrogen sulfide, xylene, benzene, toluene, o-toluidineanisidine, cadmium, arsenic, vanadium, lead, hexavalent chromium, total chromium, coal tar pitch volatiles, and a variety of aromatic amines, alcohols, and PNAs.

During monitoring for several constituents typically generated by fixed-bed gasifiers, high levels of coal tar pitch volatiles (CTPV) were identified. Levels exceeded the 8-hour time-weighted threshold limit value. It was recognized that the effluent materials in the drums below the lockhopper discharge points were releasing gases dissolved during the previously pressurized state. Accordingly, a ventilation system incorporating hoods at all

TABLE 38. WORKPLACE HEALTH ACTIVITIES

METC Gasifier Test Run #	Activities/Accomplishments
95	<ul style="list-style-type: none"> ● Conducted personal and area air sampling for vanadium, nickel, and benzene solubles; concentrations observed were below chemical detection limits. ● Initiated Health Hazard Assessment. ● Conducted personal and area samples for benzene, toluene, xylene, anisidine, o-toluidine, chromium, nickel, vanadium, cadmium, coal tar pitch volatiles and cresols. Concentrations of coal tar pitch volatiles exceeded standards. ● Biological samples were collected to assess levels of benzene metabolites in the urine of gasifier workers.
97	<ul style="list-style-type: none"> ● NIOSH was requested to assist in conducting the Health Hazard Assessment. ● Conducted personal and area samples for vanadium, nickel, cadmium, chromium, coal tar pitch volatiles, and selected aromatic hydrocarbons, aromatic amines, and aromatic alcohols. Only two exposures above the standard for coal tar pitch volatiles were observed. ● Body burden studies were conducted to determine levels of selected trace metals and benzene metabolites in the urine. Blood analyses for selected compounds and metabolites in addition to the urine analyses and clinical function tests. ● Oak Ridge National Laboratory (ORNL) tested the operation of several industrial hygiene monitoring instruments being developed by ORNL to obtain testing experience in actual field operating situations and to develop information characterizing the workplace exposure experienced at METC. The instruments involved included the Derivative Ultraviolet Absorption Spectrometer (DUVAS), the Light Pipe Luminoscope, the Spill Spotter, and a Passive Organic Vapor Sampler.
98	<ul style="list-style-type: none"> ● The health hazard assessment conducted by EG&G and NIOSH continued. Samples were collected for the same parameters as those collected for Run No. 97. ● Wipe samples were collected to define skin contamination and personal protective equipment/barrier effectiveness.
99	<ul style="list-style-type: none"> ● Area samples were collected for selected aromatic amines, aromatic alcohols, aromatic hydrocarbons, and coal tar pitch volatiles to define ambient background levels of these chemicals. ● Biological samples were collected to assess levels of benzene metabolites in the urine of METC & EG&G gasifier workers and a group of EG&G/METC controls.
100	<ul style="list-style-type: none"> ● Industrial hygiene activities were not conducted during this run due to the short duration of this run.

TABLE 39. SUMMARY OF PROCESS CONDENSATE CHARACTERIZATION AND NORMALIZED POLLUTANT PRODUCTION

Parameter (Units)	Run 85	Run 86	Run 87	Run 88	Run 94 ³	Run 95 ³	Run 97 ¹	Run 98 ²	Typical Steady-State Condition	Lbs. Pollutant per Ton of Coal ⁴
Run Period	12/7-12/16/76	3/29-4/2/77	6/17-6/18/77	8/22-8/31/77	11/28-12/9/79	9/3-10/3/80	5/27-6/18/81	7/16-8/19/81	-	-
Run Duration (hrs.)	79	96	54	170	260	608	383	733	-	-
Type Coal	Awkwright	Awkwright	Awkwright	Awkwright	Awkwright	Awkwright	Awkwright	Kittaning	-	-
Flowrate (gal/ton coal)	-	-	-	-	-	-	52.2	46.5	60	-
pH	8.7	8.8	8.3	8.7	8.0	8.0	8.4	8.4	8.4	-
Total Alkalinity	6,800	25,400	14,000	12,100	23,800	21,900	44,000	32,000	38,000	19.0
Carbonate (mg/l CaCO ₃)	4,500	10,000	4,900	5,000	-	-	10,000	3,000	6,000	3.0
Bicarbonate (mg/l CaCO ₃)	2,300	15,400	9,100	7,100	-	-	34,000	29,000	32,000	16.0
Specific Conductance (μmho/cm)	-	-	-	-	-	-	62,000	94,000	78,000	-
Total Kjeldahl Nitrogen (mg/l N)	3,470	7,740	-	-	3,200	7,000	12,000	7,800	10,000	5.0
Free Ammonia Nitrogen (mg/l N)	-	-	4,700	3,840	-	-	7,500	7,600	6,600	3.3
Sulfate (mg/l SO ₄)	-	-	-	-	-	-	30	25	30	0
Sulfite (mg/l SO ₃)	-	-	-	-	-	-	1,700	880	1,400	0.7
Sulfide (mg/l S)	-	-	190	-	-	-	2,300	470	1,400	0.7
Total Sulfur (mg/l S)	350	1,360	550	-	-	-	-	-	-	-
BOD ₅ (mg/l O ₂)	-	-	6,400	-	-	-	15,000	9,600	12,000	6.0
COD (mg/l O ₂)	87,300	-	44,500	16,900	13,400	12,800	22,000	20,000	21,000	10.5
TOC (mg/l C)	-	-	-	-	5,370	5,390	7,100	8,600	7,800	3.9
Phenols (mg/l)	1,230	2,960	1,140	2,460	2,380	3,750	4,700	5,600	5,200	2.6
Oil and Grease (mg/l)	-	-	-	-	1,490	-	930	4,200	1,000-30,000	0.5-15.0
Total Cyanide (mg/l CN)	16	40	58	110	-	-	100	290	200	0.1
Thiocyanate (mg/l SCN)	8	34	10	204	372	-	370	560	400	0.2
Settleable Solids (ml/hr.)	-	-	-	-	-	-	< 1	< 1	< 1	-
Total Solids (mg/l)	-	3,900	-	3,330	1,350	4,420	-	-	-	-
Total Volatile Solids (mg/l)	-	-	-	-	1,200	3,790	-	-	-	-
Total Suspended Solids (mg/l)	-	20	-	40	-	-	-	-	-	-
Iron, Total (mg/l Fe)	-	-	-	-	-	-	34	22	-	-
Sodium (mg/l Na)	15	4	-	5	-	-	8	37	-	-
Potassium (mg/l K)	7	2	-	5	-	-	0.4	0.9	-	-
Magnesium (mg/l Mg)	-	-	-	-	-	-	0.2	1.0	-	-
Calcium (mg/l Ca)	-	-	-	-	-	-	-	6.2	-	-
Chloride (mg/l Cl)	-	-	350	-	-	-	2,000	1,100	1,600	0.8
Fluoride (mg/l F)	-	-	-	-	-	-	12	20	-	-
Phosphorus (mg/l P)	-	-	-	-	-	-	< 1	-	0	-

1. Results from 6/16/81 sample.

2. Results from 8/4/81 sample.

3. Results from Neufeld et.al. for drummed waste from Runs 94 and 95; date of sample collection unknown.

4. Based on "Typical" steady-state concentrations and a wastewater generation rate of 60 gallons per ton of coal.

discharge points was installed to remove potentially harmful offgasses from ground level discharge points. These gases are now combusted in the incinerator. Follow-up monitoring has shown that the ventilation system is effective in significantly reducing CTPV below the required limit.

Environmental Controls Systems Analysis. Synergism of process and environmental data has resulted in several critical analyses. A detailed description of these activities will be published in a separate environmental R&D document. Table 39 shows a summary of aqueous pollutant characterizations for eight test runs along with a normalized pollutant production analysis. Such information is useful for scaleup calculations, and for loadings analysis of unit operations in downstream wastewater treatment.

Similar efforts were conducted for pollutants in the gas phase. Pollutant concentration measurements and distribution characteristics were measured. As shown in Table 40, such analyses not only provide a comparison point for compliance purposes (fourth column), but also contribute towards assessment of the feasibility of gas turbine and fuel cell technologies.

5.4.2 CHEMICAL ANALYSIS DATA BASE

Techniques have been developed at METC to characterize the major, minor, and trace components in gas streams. The identification and measurement of trace components and contaminants entailed modification and/or development of new analytical methods and their validation in the field environment. Techniques for the extractive measurement of the major and minor species were developed in phases over the past several years. METC is now examining in-situ, real-time measurement of loading and distribution of trace constituents (i.e., heavy metals, high molecular weight hydrocarbons, sulfur, and nitrogen species). Sampling techniques were first developed, then refinements were made to enhance the precision of the results. Samples collected at operating pressure were found to differ from those collected at atmospheric pressure. A complete listing of the compounds identified in the cleaned product gas at 200 psig is presented in Lamey, Kovach, and Childers (January 1983). Specifically, the higher-molecular-weight hydrocarbons contained in the clean, low-Btu gas are primarily benzenes and naphthalenes with some furans and thiophenes. Furthermore:

- Most of the components present are substituted benzenes.
- The naphthalene and substituted naphthalenes are present in only trace amounts.
- A number of aromatics contain sulfur and oxygen (thiophenes and furans).
- Several low-molecular-weight, non-aromatic gases are present.
- A series of straight chain and branched aliphatic compounds is present, from n-heptane to undecane. More than 20 compounds of these types were found. It is likely that these components are from kerosene which was added to the system to wash the electrostatic precipitator during this test.

TABLE 40. CONTAMINANT LEVELS IN THE METC FIXED-BED GASIFIER PRODUCT GAS

CONTAMINANT SPECIES	PRODUCT GAS STREAM		ALLOWABLE LIMITS		
	GASIFIER EXIT	CLEANED GAS	ENVIRONMENTAL	GAS TURBINE	FUEL CELL
Sulfur Compounds	4000 ppm	<10 ppm as H ₂ S	260 ppm as H ₂ S (EPA: for SO ₂)	--	1 ppm
Nitrogen as NH ₃	2300 ppm	<30 ppm	350 ppm NH ₃ (EPA: for NO ₂)	--	7
Total Na + K	600 ppm	<10 ppb	--	0.1 ppm	--
Hydrocarbons (Tars)	8400 ppm	<350 ppm	Various (EPA: lowest MATE**)	--	<100 ppm
Particulate	7700 ppm	<1 ppm	50 ppm (EPA: Coal Burning Plant)	≈0 ppm @ >10μm* <20 ppm @ 2-10μm*	?

* Applicable only to products of combustion, not to fuel gas

** Minimum Acute Toxic Effluent

- The largest individual components listed in descending order are:
 1,4-Dimethylbenzene > 1,3-Dimethylbenzene > 1,2-Dimethylbenzene >
 Indene > 1-Ethyl-2-Methylbenzene > 1,2,4-Trimethylbenzene.

Under contract to METC, Ames Labs of Iowa State University has developed on-line atomic emission analyzers to detect and measure alkali metals and heavy metals in the gas. The alkali metal monitor was developed and tested at METC and showed good agreement with much slower alternative methods. Testing of the so-called "Ames meter" was conducted during Test Runs 95 through 99. Very low levels of alkali were found to be present in the cleaned product gas. Current activities include modifications to allow testing at sample locations where the gas has not been cleaned. This will assist in determining the distribution of metals as they progress through the cleanup system. Further development is required to improve the sensitivity of the heavy metals analyzer.

As part of a cooperative METC program with DOE's Office of Energy Research, Lovelace Labs of ITRI developed methods for measuring high and low temperature aerosols. These aerosols were analyzed for dust and hydrocarbon content; characterization of aerosols with mean diameters below 10 microns was achieved. Results were compared with METC analytical techniques and showed good agreement. Development and further field testing will continue.

Aerosol measurements in the gas were made using techniques developed in conjunction with ITRI. Initial test work was conducted on the side-stream during Test Runs 86 through 91. These tests keyed on development and refinement of the analytical techniques. During Test Runs 91 through 94, measurements of the aerosol mass loadings were made on the side-stream and on the humidifier and tar separator outlet. High-temperature/high-pressure measurements were made during Test Run 95. During this test, the gasifier outlet, humidifier outlet, and tar separator outlet were characterized for aerosol loading. Characterization of the clean product gas was performed for aerosols and high molecular weight hydrocarbons. During Test Runs 96 through 98, aerosol measurements were primarily made in the clean product gas. The purpose of this program was to determine the ultimate fate of the aerosol components as the gas passed sequentially through the cleaning process.

The distribution and size of aerosols as they pass from the gasifier through the cleanup system and of those contained in the final product gas are represented in Figure 27. This figure summarizes the results of many of these studies. A detailed description of these data can be found in ITRI reports (December 1979, 1980, 1981, and 1982).

The CARS system is being developed and tested in conjunction with Los Alamos National Laboratory (LANL) to measure gas compositions in hot, dirty gas streams. The CARS system consists of two laser beams that can be blended to produce a third beam. This third beam is then passed through the gas stream via optical ports at the cyclone outlet. By using the two laser beams of different frequencies, CARS is able to tune onto the frequencies of the gas molecules of interest.

During Run 99, the CARS system was operated at the cyclone outlet. The tar vapor, as anticipated, had an opaqueness that resulted in scatter of the tuned laser beam; however, sufficient energy was passed through the pipe so that a

Molecular weight ranges of hydrocarbons, range of distribution parameters and mass loading penetrating the cleanup system on the Morgantown Energy Technology Center low Btu coal gasifier during December 1979 tests. ³
 *Single measurement, (a) dilution ratio unknown, (b) $4.0 \times 10^{-3} \text{ gm/m}^3$
 (c) all mass collected on final filter of cascade impactor and therefore MMAD* < $0.5 \mu m$, (d) no measurement obtained. These analyses performed by ITRI sampling and analysis systems.

*MMAD = Mass Medium Aerodynamic Diameter

FIGURE 27. DISTRIBUTION AND SIZE OF AEROSOLS THROUGHOUT PROCESS GAS STREAMS

usable signal was obtained. The CARS system determined in-situ concentrations of nitrogen, carbon dioxide, carbon monoxide, and hydrogen sulfide; these concentrations agreed with recorded gas chromatography data. This was the initial test on the METC gasifier, and the CARS results were extremely encouraging. The purge and optical access port was reconfigured to minimize deposition so that access to the process can be extended before the windows require cleaning.

The LIBS system, also being developed in conjunction with LANL, uses a single laser focused through optical windows into the gas stream to create a plasma. This plasma acts as an excitation source, and the light emitted is analyzed. From the intensity of the emitted radiation at characteristic wavelengths, the concentration of elements of interest can be determined. The LIBS system was installed on the METC gasifier to analyze the final product gas.

Testing of the LIBS system during Run 99 revealed the gas to have cleaner optical properties with no noticeable contaminants. The LIBS system operation showed no detectable concentrations of alkalis. These tests on the LIBS system were run in conjunction with METC's Ames alkali meter, which agreed with the LIBS results. The alkali levels at this point in the process stream were < 20 ppb, as determined by a bubbler train. This agreement was reached among three independent techniques. The on-line LIBS measurements have been verified.

The following conclusions drawn from the data developed as a part of this program are described in more detail in the ITRI reports (December 1979, 1980, 1981, and 1982.

- The METC cleanup system provides clean low-Btu product gas.
- Diluting and/or cooling low-Btu gas, as might happen in fugitive releases, produces a dense, respirable aerosol.
- Gasifier operating conditions have little effect on the elemental composition of cleaned gas aerosols.
- Gasifier bottom and cyclone ash are similar to coal combustion fly ash.
- Ba and Ge are enriched in small aerosol particles of the cooled and diluted coal gas aerosols.
- Cl, I, Mo and Sr are enriched in large aerosol particles ($> 5 \mu m$).
- Aerosol particle-phase organic concentration is reduced by the METC cleanup system.
- High molecular weight organic compounds present in the gasifier are primarily aromatic and alkyl-substituted aromatic compounds.
- Cooling and diluting low-Btu coal gas preferentially transfers polynuclear aromatics heavier than 182 atomic mass units (amu) from the vapor to the particle phase.

5.4.3 Process Modeling and Simulation

The process modeling and simulation program, described in Section 4.6, has provided meaningful information for the METC gasification and cleanup system. Current program activities are described below.

Gasifier and Cyclone. The Wen II gasifier model, developed at West Virginia University and enhanced with new coal kinetics data, has been the primary model utilized. It treats the gasifier as a fixed-bed, plug-flow reactor having four reactor regimes: drying (top); devolatilization; gasification; and combustion (bottom). Given coal and gaseous feeds into the reactor, raw product gas temperature, species concentrations, and solids content are predicted. Either the reactor height or the coal carbon conversion efficiency can be specified. This model can be operated as an ASPEN unit operation block or on a stand-alone basis. Other fixed-bed gasifier models are also available or are being procured (i.e., TRW, Denn-EPRI, Joseph, Scientific Design Company or SDC). The raw product gas enters a cyclone which is currently being modeled using the cyclone model from the ASPEN unit operations library. Other stand-alone cyclone models also exist (i.e., METC, GE, Research-Cottrell). The predictions by the Wen II gasifier model are used for both oxygen and air-blown gasification operations. Figures 28 and 29 are examples of model predictions for air-and oxygen-blown operations, respectively.

Humidifier. In the humidifier, water is injected to cool incoming gas to about 50°F above the dew point. This results in condensation of only heavy tar. A modified version of a humidifier model developed by Physical Science, Inc., (PSI) is being used to simulate its operation. The model uses the simultaneous evaporation of water droplets and condensation of tar droplets, taking into account variations as flow proceeds from the top to the bottom of the humidifier as well as variations along a radial direction. This model has been validated against past operating data and has been "ASPENized" (modified for incorporation into the ASPEN unit operations library). The humidifier model has been very useful in both design modification studies and process analysis.

An example of humidifier model predictions is given in Figure 30. Good comparison between measured and predicted humidifier tar removal performance is also demonstrated in Figure 31. Additional details of simulation efforts related to the METC fixed-bed gasification system will be published as a separate document in the near future.

HSDU. A steady-state model of the HSDU was developed at METC. It is a systems model since it does not account for all the complex chemical reactions occurring in the Stretford liquor. The overall HSDU model actually comprises several "sub-models" for the absorber, delay tank, flash tank, oxidizer, and the evaporator. In order to use the model, incoming gas flowrate, temperature, pressure, components concentration, liquor flowrate, equipment sizes, and design must be specified. The model predicts the degree of capture of sulfur compounds from the gas phase and the rate of those compounds after they are absorbed into the Stretford liquor by an extremely fast chemical reaction with sodium carbonate. Depending on the oxidizer operating condition, delay tank capacity, pH, and reaction kinetics, the model predicts the amount of elemental sulfur produced in the HSDU. Since the gas and liquid phase mass

FIGURE 28. PREDICTION OF PRODUCT GAST HEATING VALUE FOR METC FIXED-BED GASIFIER UNDER AIR-BLOWN OPERATION

FIGURE 29. PREDICTION OF PRODUCT GAS HEATING VALUE FOR METC FIXED-BED GASIFIER UNDER OXYGEN-BLOWN OPERATION

FIGURE 30. MODEL PREDICTION OF HUMIDIFIER WALL TEMPERATURES, TAR CONDENSATION RATE, AND CENTER LINE TEMPERATURES AS A FUNCTION OF HEIGHT

FIGURE 31. COMPARISON OF MODEL PREDICTIONS AND TEST DATA FOR THE METC FIXED-BED GASIFICATION HUMIDIFIER

transfer coefficients for the absorber and oxidizer were backed out of empirical HSDU data from past runs, the Stretford model is currently restricted to the METC process unit. Efforts are ongoing to better characterize the liquor chemistry and HSDU rate phenomena. This should result in a METC-specific computer model. This model is currently used as an ASPEN model, as well as a stand-alone model.

Systems Analysis - Gasifier and Full-Flow Cleanup. Integrated steady-state simulation of the overall process, including the gasifier and all elements of the cleanup system, was conducted using ASPEN. Figure 32 is an example of an ASPEN process simulation flowsheet (generated automatically on an ASPEN graphical flowsheet generator) used to perform an overall integrated simulation of the METC fixed-bed coal gasification system. Dynamic simulation of the process was planned for late FY83.

5.4.4 In-Service Valve Test Program

The overall valve testing program has tested over 20 different types of lockhopper valves in the valve testing facility at METC. These have been tested in both static and flowing conditions. The results of the tests are described in METC reports (July 1980, and October 15-17, 1980). For the in-service valve test program on the gasifier, Kamyr valves were chosen to be installed as lockhopper valves for the coal and ash hoppers on the METC fixed-bed gasifier. In 1976, when the State-of-the-Art (SOA) Lockhopper Valve Testing and Development Project was initiated, the maximum process condition for a lockhopper valve was a differential pressure of 500 psi at an operating temperature of 600°F. To maintain acceptable performance at this condition, the valve has to be rebuilt approximately every 500 cycles. Prior to installation gas leakrate for these valves was measured to be approximately 0.05 standard cubic feet per day (SCFD) at operating temperatures and pressures. In the METC stirred fixed-bed gasifier, feed lockhopper valves are now operating for 4,500 cycles at pressures of 165 psig with estimated temperatures of 450°F; cyclone dust removal lockhopper valves have been operated successfully for over 4,500 cycles with 500° to 700°F solids. SOA test valves have performed well in simulated lockhopper conditions for over 16,000 cycles at pressures to 1,000 psig and valve body temperatures to 600°F. This represents a significant improvement since the start of the project. It is believed that valves with a reliable service life of 15,000 cycles at 1,000 psig and 1000°F can be purchased.

Activities currently in progress include compiling valve inspection data related to the METC fixed-bed gasifier for evaluation and issuance as a separate report.

5.4.5 Corrosion/Erosion Test Program

The Ceramics Corrosion/Erosion study's main objective was to conduct a screening test for several ceramic materials to assess their probability of survival in turbine applications. The materials were exposed to combustion products from low heating value coal-derived gas and air at several high temperatures and gas flow velocities. The combustion product composition and temperatures simulated the actual environment found in stationary power-generating gas turbines except for the pressure levels. The results of approximately 1000 hours of testing are summarized. Detailed description of the test results can be found in Nakaishi's report (May 1982).

FIGURE 32. COMPUTERIZED ASPEN PROCESS FLOW SHEET INPUT FOR METC FIXED-BED COAL GASIFICATION SYSTEM

Two separate test units were used, one providing near-static, low-velocity combustion products, and the other providing dynamic, high-velocity combustion products. Both units were operated simultaneously using a common fuel gas source. The static unit operating conditions in its three different test cells were: (1) separate temperatures of 1850°, 2200°, and 2600°F; (2) exposure durations of 100, 300, and 1000 hours; and (3) combustion product velocities of less than 10 ft/sec. The test conditions for the dynamic unit were: (1) a single temperature of 2600°F; (2) a duration of 1000 hours; and (3) combustion product velocity of 1000 ft/sec. The test units are shown in Figure 14 in Section 4 of this report. The "dynamic" test should give an indication of the combined corrosive/erosive effects while the "static" test should indicate corrosive effects. A comparison of both tests should give a measure of each effect on the ceramic specimens, and should help eliminate materials that are not suited for use in a high-temperature, coal-derived combustion gas environment. An extensive characterization of the combustion environment was made during these tests, and the results are summarized in Table 41.

The static unit consisted of three separate test cells. Each cell had the capacity of exposing two racks of specimens simultaneously. Each rack had a duplication of four individual specimens of each of the 14 different material types (504 total specimens). At the start, each cell was loaded with the racks scheduled for 1000 and 100 hours of exposure. After the first phase, the 100-hour racks were replaced by racks scheduled for 300 hours of exposure. Finally, after Phase II (400 hours), the 300-hour racks were removed leaving only the three racks scheduled for the full 1000 hours of exposure. This totaled nine test racks. The durations of exposure times and the specimen arrangement on the nine racks are described in Nakaishi's report (May 1982). Table 42 is a listing of the materials tested in the corrosion/erosion facilities.

The dynamic unit consisted of a single test section operating at a nominal temperature of 2600°F. The combustion products velocity across the specimens was designed to be 1000 ft/sec. Velocity at this temperature equals Mach 0.4. This unit could accommodate only 12 individual specimens simultaneously, and only 11 of the total 14 material types were tested in this unit. These dynamic test specimens were scheduled to be exposed for the entire 1000 hours. However, specimens were replaced during the test if they failed catastrophically, e.g., came out of their holders, broke off, or were excessively degraded (unless their distortion prevented removal). Most of the specimens, when removed at the end of the test period, showed signs of material removal from their upstream surfaces. An accurate measurement of material degradation is being made by the Illinois ITRI. A final report documenting the material characterization from both test units and their correlation is expected to be issued soon.

TABLE 41.

DESCRIPTION OF THE PRODUCTS OF COMBUSTION, CORROSION/EROSION TEST FACILITY

TEST UNIT	PHASE	NOMINAL TEMPERATURE	NOMINAL VELOCITY	A/F*	CHEMICAL COMPOSITION					
					PERCENTAGE				PPM	
					CO ₂	H ₂ O	N ₂	O ₂	SO ₂	NO _x
Static 1	I	1850°F	>10ft/sec	3.14	10.70	8.00	73.84	6.63	117	9
	II			3.93	7.26	6.79	75.55	10.35	70	3
	III			3.66	7.61	7.26	75.07	9.98	490	34
Static 2	I	2200°F	>10ft/sec	2.16	8.69	6.51	74.66	9.27	94	4
	II			2.70	9.80	8.48	74.48	7.15	90	7
	III			2.52	10.21	9.08	73.87	6.71	670	37
Static 3	I	2600°F	>10ft/sec	1.52	10.70	8.00	73.84	6.53	117	9
	II			1.82	13.05	10.62	73.12	3.05	120	19
	III			1.71	13.54	11.40	72.32	2.53	900	48
Dynamic	I	2600°F	1000ft/sec	2.12	10.67	7.98	73.85	6.57	117	14
	II			2.29	11.09	9.31	73.91	5.50	110	9
	III			2.20	12.56	9.85	71.53	5.84	750	32

NOTE: During Phases I and II Stretford system in service; during Phase III Kittanning coal used and Stretford system bypassed.

Ref.: DOE/METC-82-46

* Air to Fuel Ratio

TABLE 42.
TEST SPECIMEN MATERIAL AND VENDORS
CORROSION/EROSION TEST PROGRAM

VENDOR	DESCRIPTION
Carborundum	Sintered α -SiC
Norton/DCI Coating	CVD Si_3N_4 Coating on RS- Si_2N_4 (NC-350)
Ceradyne/Chemetal Coating . .	CNTD AlN Coating on HP-AlN
AiResearch Casting	HP- Al_2O_3 with ZrO_2 Particulates
Montana Energy R&D Institute.	50/50 Mole Percent Spinel
Greenleaf Corporation	HP-Sialon
Norton, Experimental	HP- Si_3N_4 + 4 Percent Y_2O_3
Norton.	HP-SiC (NC-203)
Norton/Chemetal Coating . . .	CNTD SiC Coating on HP-SiC (NC-203)
Ceradyne/Westinghouse, Experimental	Al_2O_3 + 60 Percent SiC Composite
Carborundum/Chemetal Coating.	CNTD SiC Coating on Sintered α -SiC
Norton.	RS- Si_3N_4 (NC-350)
GTE Sylvania	Sintered Si_3N_4
Westinghouse, Experimental. .	HP- Si_3N_4

Ref: DOE/METC-82-46

6.0 GLOSSARY OF ACRONYMS AND ABBREVIATIONS

ADA	Anthraquinone Disulphonic Acid
ADACS	Automatic Data Acquisition System
A/F	Air to Fuel Ratio
AFT	Ash Fusion Temperature
amu	Atomic Mass Units
ANL	Argonne National Laboratory
ASPEN	Advanced System for Process Engineering
BOD	Biological Oxygen Demand
Btu	British Thermal Units
Btu/lb	British Thermal Units per Pound
Btu/SCF	British Thermal Units per Standard Cubic Foot
CARS	Coherent Anti-Stokes Raman Spectroscopy
CH ₄	Methane
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COD	Chemical Oxygen Demand
COS	Carbonyl Sulfide
cp	Centipoise
CRT	Cathode Ray Tube
CS ₂	Carbon Disulfide
CTPV	Coal Tar Pitch Volatiles
cu ft	Cubic Feet
CWR	Cooling Water Return
CWS	Cooling Water Supply
DOE	Department of Energy
DUVAS	Derivative Ultraviolet Absorption Spectrometer
EG&G	EG&G, Washington Analytical Services Center, Inc.
EH&S	Environmental Health and Safety
EP	Toxicity Test Required by EPA
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ESP	Electrostatic Precipitator
°F	Temperature, Degrees Fahrenheit
FAI	Frummerman Associates, Inc.
FFCUS	Full-Flow Cleanup System
FQI	Flow Control Indicator
FSI	Free Swelling Index
ft/min	Feet per Minute
ft/sec	Feet per Second
GC	Gas Chromatograph
GE	General Electric
GFETC	Grand Forks Energy Technology Center
gm/m ³	Grams per Cubic Meter
gpm	Gallons per Minute
GRI	Gas Research Institute
g/scm	Grams per Standard Cubic Meter
H ₂	Hydrogen
H ₂ O	Water
H ₂ S	Hydrogen Sulfide
HC	Hydrocarbons
HCV	Hand Control Value

HHAS	Health Hazard Assessment
HSDU	Holmes Stretford Desulfurization Unit
HTA	High Temperature Ash
ITRI	Inhalation Toxicology Research Institute
LANL	Los Alamos National Laboratory
lb/hr	Pounds per Hour
lb/lb	Pounds per Pound
L.H.	Lockhopper
LIBS	Laser-Induced Breakdown Spectroscopy
MAF	Moisture and Ash Free
MATE	Minimum Acute Toxic Effluent
MBtu/hr	Thousands of British Thermal Units per Hour
METC	Morgantown Energy Technology Center
mg/l	Milligrams per Liter
mhos/cm	Conductivity Units as mhos per Centimeter
MIFGA	Mining and Industrial Fuel Gas Group
mil	Thousandths of an Inch
MIT	Massachusetts Institute of Technology
MMAD	Mass Medium Aerodynamic Diameter
MS	Mass Spectrometer
MSCFH	Thousands of Standard Cubic Feet per Hour
N ₂	Nitrogen
NG	Nitrogen Gas
NIOSH	National Institute for Occupational Safety and Health
ORNL	Oak Ridge National Laboratory
pH	Log of Hydrogen Ion Concentration
PNAs	Polynuclear Aromatics
ppb	Parts per Billion
ppm	Parts per Million
ppm vol	Parts per Million by Volume
ppm wt	Parts per Million by Weight
psi	Pounds per Square Inch
PSI	Physical Science, Inc.
psig	Pounds per Square Inch Gauge
R&D	Research and Development
RCRA	Resource Conservation and Recovery Act
ROE	Residue on Evaporation
SAI	Science Applications, Inc.
SCF	Standard Cubic Feet
SCFD	Standard Cubic Feet per Day
SCFH	Standard Cubic Feet per Hour
SCF/lb	Standard Cubic Feet per Pound
SDC	Scientific Design Company
SNG	Synthetic Natural Gas
SOA	State-of-the-Art
sq ft	Square Feet
TKN	Kjeldahl Nitrogen
Ton/hr	Tons per Hour
TRW	TRW, Inc.
UNDERC	University of North Dakota Energy Research Center
Vol%	Volume Percent
Wt%	Weight Percent
µm	Microns

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APPENDIX A

CHRONOLOGICAL LISTING OF GASIFICATION
SYSTEM TEST RUNS

Run No.	Date		Coal Type	Duration (hours)
	Start	End		
<u>Phase I. Gasifier Tests</u>				
1	10-22-67	10-24-67	Anthracite	21
2	10-30-67	11-04-67	Anthracite	100
3	11-06-67	11-10-67	Anthracite	73
4	11-27-67	12-01-67	Anthracite	90
5	12-04-67	12-09-67	Anthracite	78
6	12-11-67	12-16-67	Anthracite	76
7	03-11-68	03-12-68	Anthracite	28
8	03-18-68	03-22-68	Anthracite -- Ohio #8	59-40
9	04-08-68	04-10-68	Anthracite	51
10	04-15-68	04-19-68	Anthracite	88
11	04-22-68	04-24-68	Anthracite	46
12	04-29-68	05-03-68	Anthracite	86
13	05-13-68	05-17-68	Anthracite	97
14	05-20-68	05-24-68	Anthracite -- Lower Cedar Grove	43-50
15	06-10-68	06-14-68	Anthracite	100
16	06-17-68	06-21-68	Anthracite	87
17	06-24-68	06-28-68	Anthracite	99
18	07-29-68	08-02-68	Anthracite	65
19	09-09-68	09-12-68	Anthracite	90
20	09-20-68	No data	Run shut down, water leak in producer	
21	10-07-68	10-10-68	Lower Cedar Grove	109
22	11-04-68	11-08-68	Anthracite	112
23	04-07-69	04-09-69	Lower Cedar Grove	23
24	04-09-69	04-11-69	Lower Cedar Grove	24
25	06-02-69	06-06-69	Lower Cedar Grove	25
26	06-16-69	06-17-69	Lower Cedar Grove	50

Run No.	Date		Coal Type	Duration (hours)
	Start	End		
27	08-05-69	08-08-69	Anthracite -- Lignite Mix	90
28	08-11-69	08-12-69	Anthracite -- Lignite Mix	34
29	08-21-69	08-22-69	Arkwright	23
30	10-06-69	10-14-69	Lower Cedar Grove	105
31	10-15-69	10-16-69	Ohio No. 8	40
32	10-27-69	10-28-69	Ohio No. 3	44
33	11-17-69	11-19-69	Arkwright	52
34	06-15-70	06-19-70	Anthracite	38
35	06-22-70	06-22-70	N. D. Lignite	19
36	06-29-70	07-01-70	N. D. Lignite	/
37	07-14-70	07-17-70	N. D. Lignite	14
38	07-22-70	07-24-70	Arkwright	24
39	09-14-70	09-17-70	Illinois No. 6	73
40	09-28-70	10-02-70	Arkwright	90
41	N O T E S T			
42	08-30-71	09-02-71	Arkwright	92
43	09-13-71	09-16-71	Arkwright	78
44	09-20-71	09-24-71	Middle Kittanning	51
45	10-04-71	10-07-71	Middle Kittanning	57
46	10-18-71	10-22-71	Middle Kittanning Upper Freeport	39-29
47	11-08-71	11-10-71	Upper Freeport	43
48	11-15-71	11-17-71	Anthracite	57
49	11-29-71	12-03-71	Upper Freeport	37
50	N O T E S T			
51	05-24-72	05-26-72	Loveridge	39
52	06-12-72	06-14-72	Loveridge	51
53	06-26-72	06-29-72	Upper Freeport	55
54	N O T E S T			

Run No.	Date		Coal Type	Duration (hours)
	Start	End		
55	09-18-72	09-20-72	Western Kentucky #9	34
56	10-02-72	10-06-72	Western Kentucky #9	86
57	07-04-73	07-09-73	Arkwright	88
58	07-09-73	07-10-73	Arkwright	38
59	07-31-73	08-05-73	Arkwright	52
60	B A D S T A R T - U P ; N O T E S T			
61	09-06-73	09-11-73	Upper Freeport	111
62	09-24-73	09-25-73	New Mexico	16
63	10-10-73	10-12-73	New Mexico	45
64	10-23-73	10-26-73	Western Kentucky #9	52
65	10-29-73	10-30-73	Western Kentucky #9	29
66	11-14-73	11-15-73	Arkwright	25
67	06-18-74	06-27-74	Arkwright	142
68	07-10-74	07-10-74	Arkwright	12
69	08-02-74	08-06-74	Arkwright	84
70	08-28-74	09-05-74	Arkwright	130
71	09-10-74	09-19-74	Arkwright	171
72	08-02-75	08-05-75	Arkwright	68
73	08-19-75	08-26-75	Arkwright	117
74	10-10-75	10-10-75	Arkwright	9
75	11-20-75	11-21-75	Arkwright	44
76	12-08-75	12-12-75	Arkwright	58
77	01-14-76	01-16-76	Arkwright	39
78	03-17-76	03-25-76	Arkwright	20
79	N O T E S T			
80	04-09-76	04-16-76	Arkwright	37
81	05-13-76	05-14-76	Arkwright	18

Run No.	Date		Coal Type	Duration (hours)
	Start	End		

Phase II. Side-Stream Cleanup Tests

First Side-Stream Cleanup Test Series

82	06-04-76	06-04-76	Illinois #6	7
83	06-23-76	06-29-76	Illinois #6	68
84	07-23-76	07-25-76	Rosebud-Anthracite Mix	48

Second Side-Stream Cleanup Test Series

85	12-07-76	12-16-76	Arkwright	79
86	03-29-77	04-02-77	Arkwright	96
87	06-17-77	06-18-77	Arkwright	54
88	08-22-77	08-31-77	Arkwright	170

Third Side-Stream Cleanup Test Series

89	10-25-77	10-29-77	Arkwright	75
90	12-04-77	12-15-77	Arkwright	154

Phase III. Initial Full-Flow Cleanup Tests

91 & 92	08-15-78	8-18-78	Arkwright	91
93	06-05-79		Arkwright	304
94	11-28-79	12-09-79	Arkwright	260

Phase IV. Full-Flow/Sulfur Removal Cleanup Tests

95	09-03-80	10-03-80	Arkwright	608
96	11-11-80	11-22-80	Arkwright	270
97	05-27-81	06-16-81	Arkwright	383
98	07-16-81	08-19-81	Kittanning	733
99	03-14-82	03-31-82	Arkwright	286
100	06-14-82	06-18-82	Arkwright	96