FIXED-BED GASIFICATION RESEARCH USING U.S. COALS, VOLUME 1 PROGRAM AND FACILITY DESCRIPTION

By
**D. Thimsen
R.E. Maurer
A.R. Poole
D. Pui
B. Liu
D. Kittleson**

October 1, 1984

Work Performed Under Interagency Agreement No.: DE-AI21-7ET10205

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
P.O. Box 880
Morgantown, West Virginia 26505

By
Black, Sivalls & Bryson, Incorporated
BS&B Energy Systems
7324 Southwest Freeway
P.O. Box 27125
Houston, Texas 77227

This document is
PUBLICLY RELEASABLE
B. Amy Steels
Authorizing Official
Date: 2-23-07

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FOREWORD

This report was prepared by Black, Sivalls, and Bryson, Inc., Houston, Texas under USBM contract number H0222001. The contract was administered under the technical direction of the Twin Cities Research Center with Mr. Robert Zahl acting as Technical Project Officer. Mr. Frank Pavlich was the contract administrator for the Bureau of Mines. This report is a partial summary of the work recently completed as a part of this contract during the period June 1982 to May 1984. This report was submitted by the authors on October 1, 1984.

Funding for this contract was through USBM/USDOE Interagency Agreement DE-A121-7ET10205.

The University of Minnesota, Particle Technology Laboratory, Minneapolis, Minnesota, a subcontractor to Black, Sivalls, and Bryson, Inc., participated in preparation of this report.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
Introduction	1
1 Program History	
1.1 Industry Participation -- MIFGa	3
1.2 Program Objectives	3
1.3 Testing Supervised by USBM	5
1.4 BS&B Contractor Tests	8
2 Facility Description	
2.1 History and Overall Description	14
2.2 Coal Handling Equipment	14
2.2.1 Storage, Loader, Hopper, Belt	14
2.2.2 Coal Screen	18
2.2.3 Bucket Elevator	18
2.2.4 Weigh Bin	18
2.3 Gasifier	20
2.3.1 Lock Hopper	20
2.3.2 Retort and Water Jacket	22
2.3.3 Draft Arrestor and Agitator	24
2.3.4 Ash Removal Grate	24
2.3.5 Ash Cone and Weigh Bin	26
2.4 Support Equipment	26
2.4.1 Vent/Flare	26
2.4.2 Offtake Duct	28
2.4.3 Cyclone	28
2.4.4 Gas Duct	30
2.4.5 Burner/Combustor	30
2.4.6 Scrubber, Induced Draft Fan, Stack	33
2.5 Slip Stream Equipment	33
2.5.1 Taconite Pelletizing Kiln	33
2.5.2 Quench/ESP Tar Scrubber	33

TABLE OF CONTENTS

(Continued)

<u>Section</u>	<u>Page</u>
3 Operational Procedures	
3.1 Cold Start-Up	38
3.1.1 Traditional Start-Up Procedure	38
3.1.2 Modified Start-Up Procedure	40
3.2 Banking -- Warm Start-Up	40
3.3 Retort Monitoring	40
3.3.1 Fire Tests	42
3.3.2 Freeboard	42
3.3.3 Temperature Probings	42
3.3.4 Pressure Probings	43
3.4 Coal Addition	43
3.5 Ash Removal	43
3.6 Cyclone Dust Removal	43
3.7 Gasifier Dumping	45
3.8 Limits to Throughput Decision Making	45
3.9 Saturation Temperature Decision Making	46
4 Monitoring Systems Description	
4.1 Continuous Process Flows, Pressures, and Temperatures	47
4.2 Operator Logged Parameters	47
4.3 Gas Sampling and Conditioning System	47
4.3.1 Sampling Port	52
4.3.2 Liquid Condenser	52
4.3.3 Electrostatic Precipitator	54
4.3.4 Refrigeration Unit	57
4.3.5 Combined Filter-Dessicator	57
4.3.6 Flow Measuring and Transport System	57
4.3.7 Operation Summary	58
4.4 Gas Analysis Instruments	58
4.4.1 Continuous Gas Analyzers	58
4.4.2 Gas Chromatographs	60
4.5 Data Acquisition Systems	63
4.5.1 MACSYM 2 Computer	63
4.5.2 MACSYM 350 Computer	65
4.5.3 Software and Field Utilization	65
4.6 Product Gas Dust Sampling	66
4.7 Quench/ESP Exhaust Sampling	69

TABLE OF CONTENTS
(Continued)

<u>Section</u>	<u>Page</u>
5 Test Procedures	
5.1 Test Teams	71
5.1.1 Gasifier Operation and Overall Coordination	71
5.1.2 Gasifier Monitoring	71
5.1.3 Stack Gas Sampling	72
5.1.4 MIFGa Cooperators	72
5.2 Sampling and Data Acquisition Procedures	72
5.2.1 Continuous Data	72
5.2.2 Gas Analysis Data	72
5.2.3 Tar/Oil/Water Yield Data	75
5.2.4 Solids Data	76
5.2.5 Combustor Emissions Measurements	79
5.2.6 Combustor Flame Profile Sampling	80
5.2.7 Retort Pressure and Temperature Profiles	80
5.2.8 Product Gas Dust Sampling	81
5.2.9 Quench/ESP Efficiency Sampling	81
5.2.10 Freeboard/Fire Test Data	82
6 Calculation and Data Analysis Procedures	
6.1 Data Retrieval and Analysis	83
6.2 Material Balance and Thermal Efficiency Calculations	83
6.2.1 Input Data	84
6.2.2 Calculation Results	84
6.3 Tar/Oil Yield Correlations	85
6.4 Grate Performance Model	87
References	89
Appendix A Sample Data Sheets	92
Appendix B Sample Output From Data Acquisition System and Gas Chromatographs	100
Appendix C Material and Energy Balance Program	104

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
2-1	USBM/TCRC Gasifier Process Flow Schematic	15
2-2	USBM/TCRC Gasifier PID	16
2-3	Coal Handling System Schematic	17
2-4	Coal Weigh Bin	19
2-5	Overall Gasifier Layout	21
2-6	Retort Top	23
2-7	Top View of Grate	25
2-8	Ash Weigh Bin	27
2-9	Cyclone	29
2-10	Gas Burner	31
2-11	Combustion Chamber	32
2-12	Quench/Electrostatic Precipitator Process Flow Schematic	34
2-13	Quench/Electrostatic Precipitator PID	35
2-14	Modified Tar Handling System	37
3-1	Wick Boxes for Traditional Start-Up	39
3-2	Wick Boxes for Modified Start-Up	41
4-1	Gas Sampling and Conditioning System	51
4-2	Sample Electrostatic Precipitator	55
4-3	Product Gas Dust Particle Sampling Location	67
4-4	Product Gas Dust Particle Sampling System	68
4-5	Quench/ESP Exhaust Tar Particle Sampling System	70
6-1	Tar/Oil Yield Correlations	86
6-2	Grate Performance Model Schematic	88

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1-1	MIFGa Industrial Cooperators and Program Participants	4
1-2	Tests Conducted Under Supervision of the Bureau of Mines	6
1-3	Analyses of Fuels Gasified Under Supervision of the Bureau of Mines	7
1-4	Tests Conducted Under Supervision of Black, Sivalls, and Bryson, Inc., and the University of Minnesota, Particle Technology Laboratory	10
1-5	Analyses of Fuels Gasified Under Supervision of Black, Sivalls, and Bryson, Inc., and the University of Minnesota, Particle Technology Laboratory	11
1-6	Coal Test Objective Matrix	12
3-1	Ash Removal Procedure	44
4-1	Process Parameters Logged by the Data Acquisition System	48
4-2	Process Parameters Logged Manually by the Operating Team	50
4-3	Sample Electrostatic Precipitator Evaluation	56
4-4	Key Modifications Made on the Gas Sampling and Condition- ing System	59
4-5	Principal Features of the HP 5880A Gas Chromatograph	61
4-6	HP 5880A Gas Chromatograph Operating Conditions	62
4-7	Principal Features of the HP 5793A Gas Chromatograph/ HP 3390A Integrator Plotter	64
5-1	Analytical Tests Performed on Solid Materials	77

INTRODUCTION

The United States Department of Interior, Bureau of Mines, Twin Cities Research Center, Minneapolis, Minnesota is the site of a 6.5 foot diameter Wellman-Galusha gasifier, installed in 1977-78. This gasifier, combustor/incinerator, and flue gas scrubber system in the past had been operated jointly by Bureau of Mines personnel, personnel from member companies of the Mining and Industrial Fuel Gas Group (MIFGa), and United States Department of Energy (DOE) personnel-consultants. Numerous tests using a variety of coals have to date been performed.

In May of 1982, Black, Sivalls & Bryson, Incorporated (BS&B) was awarded the contract to plan, execute, and report gasification test performance data from this small industrial fixed-bed gasification test facility. BS&B is responsible for program administration, test planning, test execution, and all documentation of program activities and test reports. The University of Minnesota, Particle Technology Laboratory (UMPTL) is subcontractor to BS&B to monitor process parameters, and provide analysis for material inputs and outputs.

This report is the initial volume in a series of reports describing the fixed-bed gasification of U.S. coals at the Bureau of Mines, Twin Cities Research Center. A history of the program is given in Section 1 and a thorough description of the facility in Section 2. The operation of the facility is described in Section 3. Monitoring systems and procedures are described in Sections 4 and 5. Data reduction tools are outlined in Section 6. There is no executive summary or conclusions as this volume serves only to describe the research program. Subsequent volumes will detail each gasification test and other pertinent results of the gasification program.

SECTION 1

PROGRAM HISTORY

1.1 Industry Participation - MIFGa

In 1975 the Pellet Energy Group (PEG) was formed as a result of natural gas supply interruptions in the iron ore pelletizing industry. The PEG was a consortium of coal companies, railroads, gas companies, engineering and construction companies, and iron ore companies, along with the U. S. Department of Interior, Bureau of Mines (USBM).

Several studies were conducted during this period evaluating the feasibility of using low-Btu gas in iron ore pelletizing. (Farnam (1976), Ashworth et al (1977), Zahl and Nigro (1979)). Discussions and recommendations of the PEG resulted in the installation, for research and testing purposes, of a 6.5 foot ID Wellman-Galusha coal gasifier (rated at 30 million BTU/hr) at the USBM Twin Cities Research Center (USBM/TCRC) during 1977-78. This installation was supported by the United States Department of Energy (DOE), USBM, and industrial cooperators. The initial purpose was to evaluate the suitability of coal gasifiers of this type to supply fuel gas from western coals to iron ore pelletizing plants.

As operation of the gasifier expanded, the site became used as a test bed for evaluating the gasification characteristics of a wide variety of U. S. coals, and a location for the development of basic information on the physics and chemistry of coal gasification. The Mining and Industrial Fuel Gas Group (MIFGa) was formed out of the PEG to attract a wider participation from U.S. industry to advise on organization of a testing program, to participate in operation of the gasifier, and to share and discuss test results. Support for continuation of the testing program has come from DOE, USBM, U. S. Environmental Protection Agency, and MIFGa cooperators. The companies that have participated in MIFGa are listed in Table 1-1.

1.2 Program Objectives

The objectives of gasification tests at the USBM/TCRC are the following:

- 1) Identify the fundamental limitations of fixed-bed gasifier capacity and thermal efficiencies when converting coal to a low-Btu fuel gas.
- 2) Investigate the influence of coal type and fuel properties on fixed-bed gasifier operation.

Table 1-1

MIFGa Industrial Cooperators and Program Participants

MIFGa Industrial Cooperators

Allis-Chalmers
American Natural Resources
Amerigas
Bechtel, Incorporated
Black, Sivalls, and Bryson, Incorporated
Cleveland-Cliffs Iron
Davy McKee Corporation
Dravo Corporation
Electric Power Research Institute
Eveleth Expansion Company
Foster-Wheeler Synfuels
Hanna Mining
Heyward Robinson/Babcock Woodall-Duckham, Inc.
Inland Steel
Inter-City Gas Corporation
Mansfield Carbon Products
Meridian Land and Minerals (subsidiary of Burlington Northern)
Peoples Natural Gas/Division of Inter North
Pickands Mather & Company (Erie Mining)
Reserve Mining
Riley Stoker Corporation
Rocky Mountain Energy
Stone and Webster Engineering
U. S. Steel
Western Energy
Weyerhaeuser Company

MIFGa Program Participants

U. S. Bureau of Mines
U. S. Department of Energy
U. S. Environmental Protection Agency
Minnesota Department of Natural Resources
G. C. O. Minerals
Northern States Power Company

- 3) Characterize coal gas composition and quality for various gasifier operating conditions.
- 4) Prepare models to predict the physics and chemistry of fixed-bed gasification for various fuel types.
- 5) Identify design changes and operational procedures that can reduce gasifier downtime and operational requirements.
- 6) Provide a source of low-BTU gas for processing and utilization studies.
- 7) Provide an opportunity for "hands-on" gasifier operating experience for cooperators.
- 8) Evaluate environmental impacts of a Wellman-Galusha type, fixed-bed gasifier.

1.3 Testing Supervised by USBM

From 1978 through 1981 all gasification testing at the USBM/TCRC was supervised directly by the Bureau of Mines. Twelve tests were conducted during this period. These tests are listed in Table 1-2 along with the fuels gasified, dates and duration of the tests, and references to publications reporting test results (when available). Analyses of the fuels tested during this period are given in Table 1-3. Test reports are in preparation for those tests without references listed.

In addition to the gasifier investigations, hot, raw coal gas was used to fire a taconite pellet kiln during nine tests. Reports detailing the results of four of these pelleting tests are given by Zahl and Nigro (1979) and Nigro (1982a, 1982b).

During this period, operational personnel for the testing program were provided by the membership of MIFGa and the USBM. Contributions of coal, transportation, and engineering and analytical services were also provided by the membership of MIFGa.

A brief description of the tests conducted during this period follows:

Eastern Kentucky Bituminous Coal - This coal was used during the first test of the gasifier after installation and was primarily a training and shakedown test. This coal was selected for its high ash fusion temperatures which would minimize ash clinkering during the shakedown. No attempt was made to seek maximum throughput.

Colowyo and Absoloka Subbituminous Coals - These

Table 1-2

Tests Conducted under Supervision of the
Bureau of Mines

Test	Coal	Test Dates	Duration (Days)	References
GKP-26	Eastern Kentucky Bituminous	11/13/78 - 11/22/78	10	
GKP-27	Eastern Kentucky Bituminous	11/25/78 - 12/ 1/78	7	
GKP-28	Colowyo Subbituminous	12/ 4/78 - 12/ 8/78	5	
GKP-29	Indianhead Lignite	12/11/78 - 12/15/78	5	
GKP-30	Absoloka Subbituminous	9/17/79 - 9/24/79	8	
GKP-31	Indianhead Lignite	10/ 1/79 - 10/10/79	10	
GKP-32	Decker Subbituminous Briquettes	10/22/79 - 10/23/79	1	
GKP-34	Indianhead Lignite	10/23/80 - 11/21/80	30	Jones (1982, 1983a, 1983b)
GKP-35	Indianhead Lignite	6/16/81 - 6/25/81	10	
GKP-36	Texas Lignite	7/22/81 - 7/31/81	10	
GKP-37	Grassy Creek Subbituminous	8/12/81 - 8/21/81	10	Jones (1982, 1983a, 1983b)
GKP-38	Simplex Briquettes	10/20/81 - 10/29/81	10	Dynecology (1982),

Table 1-3

Analyses of Fuels Gasified under
Supervision of the Bureau of Mines

Coal	Kentucky Bituminous	Colowyo Subbitum	Indianhead Lignite	Absoloka Subbitum	Texas Lignite	Grassy Creek Subb	Simplex Briquettes
<hr/>							
<u>Proximate Analysis</u> wt %)							
Moisture	3.3	10.8	30.6	26.0	33.7	10.1	10.6
Volatile Matter	37.2	36.2	28.3	28.3	25.5	31.0	41.0
Fixed Carbon	54.1	46.2	33.4	37.0	24.0	47.3	34.2
Ash	5.4	6.8	7.7	8.7	16.8	11.7	14.1
<u>Ultimate Analysis</u> (wt %)							
Hydrogen	4.7	4.2	2.9	3.7	2.9	4.5	4.4
Carbon	79.0	63.8	44.7	50.1	35.7	61.3	55.2
Nitrogen	1.6	1.3	0.6	0.7	0.6	1.4	1.0
Oxygen	5.2	12.4	12.6	10.3	9.0	10.8	13.1
Sulfur	0.8	0.7	0.8	0.6	1.2	0.4	1.5
Moisture	3.3	10.8	30.6	26.0	33.7	10.1	10.6
Ash	5.4	6.8	7.7	8.7	16.8	11.7	14.1
<u>Heating Value</u> (Btu/lb)	13550	11030	7560	8450	6243	10700	9795
<u>Free Swelling Index</u>	4	0	0	0	-	-	1/2
<u>Ash Fusion Temperatures</u> (deg F) (Oxidizing Atmosphere)							
Initial Deformation	2630	2500	1920	1980	2290	2330	1920
Softening	2680	2550	1970	2030	2390	2420	2033
Fluid	2800	2680	2020	2100	2600	2580	2130

coals were gasified in two short tests to introduce subbituminous coals to the gasifier. Some problems were encountered controlling ash clinkering and gas distribution in the retort.

Indianhead Lignite - Four different tests gasifying this North Dakota lignite were undertaken. Fifty-five days of operation were logged. The lignite proved to gasify well, at very high throughputs. The lignite was friable and degraded some with handling. Gas produced during three of these tests was used in the taconite pellet kiln. Detailed environmental impact measurements were made by Kilpatrick et al (1980) during one of these tests.

Decker Subbituminous Briquettes - Pillow briquettes made from Decker Subbituminous coal with a petroleum asphalt binder were used for a short test. The briquettes gasified poorly as they did not maintain their structural integrity upon entering the retort.

Texas Lignite - This coal produced very high quality gas when gasified. High variability of ash content caused some problems controlling the ash removal from the gasifier. Only modest throughputs were possible. The lignite was friable and degraded with handling.

Grassy Creek Subbituminous Coal - This Colorado coal gasified well over a ten-day period. High throughputs were achieved with good gas quality. Maximum throughput was investigated but not reached due to lack of time.

Simplex Briquettes - These pillow briquettes were produced from 34% municipal solid waste (MSW), 64% high-swelling bituminous coal, and 2% ground lime. Some handling problems were encountered due to the MSW, but for the most part the briquettes held together well, and gasified well. Gas quality was high. Maximum throughput was not investigated. A USBM contract report on this test was prepared by Dynecology (1982).

1.4 BS&B Contractor Tests

In May of 1982 Black, Sivalls, and Bryson, Inc. (BS&B) was awarded a contract to plan, execute, and report on the gasification testing undertaken at the USBM/TCRC. All testing after this date was under the supervision of BS&B. The Particle Technology Laboratory of the University of Minnesota (UMPTL) is a subcontractor to BS&B to collect and process data during the tests. Coal, transportation, some engineering and analytical services, and some operating personnel continue to be provided by MIFGa membership

for tests conducted under the BS&B operating contract.

The tests conducted during this period along with the fuels gasified, dates, duration of the tests, and references detailing test results are shown in Table 1-4. The analyses of the fuels tested are given in Table 1-5. A coal test objective matrix, identifying coal properties of concern for fixed-bed gasification is shown in Table 1-6 along with entries for the tests conducted by BS&B to date. A broad overview of the testing program is given by Thimsen (1983).

This report describes only the gasification testing program during the period of the BS&B operating contract. Brief summaries of the tests undertaken through 1983 follow:

BOM/FGT-001/001A - Jetson Bituminous Coal - This medium-swelling bituminous coal is from the Illinois Basin. It served as the fuel for the first test under BS&B's operating contract. The test was relatively short, but high throughputs were achieved, and gas quality was good.

BOM/FGT-002 - Rosebud Subbituminous Coal - Gas quality was high, but only moderate throughputs were achieved gasifying this Montana coal. The coal is very friable and appeared to fall apart in the retort. A water spray tar scrubber was operated on a slipstream of the gasifier output. The detarred gas was sent to a pilot Stretford desulfurization plant. A description of the desulfurization test is given by PEDCo (1983).

BOM/FGT-003 - Leucite Hills Subbituminous Coal - This Wyoming coal gasified well with high throughput and high gas quality. The gasifier was operated for 20 days continuously with good performance.

BOM/FGT-004, BOM/FGT-006 - Stahlman Stoker, and Piney Tipple Bituminous Coals - These highly swelling Western Pennsylvania Coals were gasified in short tests. The coals did not gasify well due to the agglomeration of the coals in the upper regions of the retort. These agglomerations were too severe to be effectively broken up by the agitator. Resulting gas quality was poor, and throughput limited.

BOM/FGT-005 - Delayed Petroleum Coke - The petroleum coke gasified very much like anthracite. The low rate of ash accumulation makes this a relatively problem-free fixed-bed gasifier fuel. Gas quality was lower than that observed during gasification of bituminous and subbituminous coals, and maximum throughput was also somewhat lower partially due to

Table 1-4
Tests Conducted under Supervision of
Black, Sivalls, and Bryson, Inc. and the
University of Minnesota, Particle Technology Laboratory

Test	Coal	Test Dates	Duration (Days)	References
BOM/FGT-001	Jetson Bituminous	8/18/82 - 8/25/82	8	BS&B (1983a)
BOM/FGT-001A	Jetson Bituminous	10/29/82 - 11/ 2/82	5	BS&B (1983a)
BOM/FGT-002	Rosebud Subbituminous	11/ 2/82 - 11/20/82	19	BS&B (1983b)
BOM/FGT-003	Leucite Hills Subbituminous	4/11/83 - 4/30/83	20	BS&B (1983c), Andrews and Gray (1984)
BOM/FGT-004	Stahlman Stoker Bituminous	4/30/83 - 5/ 4/83	4	BS&B (1983d)
BOM/FGT-005	Delayed Petroleum Coke	6/ 1/83 - 6/17/83	17	BS&B (1983e), Thimsen et al (1984)
BOM/FGT-006	Piney Tipple Bituminous	7/18/83 - 7/24/83	7	BS&B (1984a)
BOM/FGT-007	Illinois #6 Bituminous continued	7/28/83 - 8/10/83 8/15/83 - 8/19/83	19	BS&B (1984b)
BOM/FGT-008	Elkhorn Bituminous	9/13/83 - 10/13/83	31	BS&B (1984c)
BOM/FGT-009	Benton Lignite	11/ 1/83 - 11/ 8/83	8	BS&B (1984d)
BOM/FGT-010	Peat Pellets	11/ 9/83	1	BS&B (1984e)

Table 1-5

Analyses of Fuels Gasified under Supervision of
Black, Sivalls, and Bryson, Inc. and the
University of Minnesota, Particle Technology Laboratory

Coal	Jetson Bituminous	Rosebud Subbitum	Leucite Hills	Stahlman Stoker Bit.	Petroleum Coke	Piney Tipple Bit.	Illinois #6 Bit.	Elkhorn Bituminous	Benton Lignite	Peat Pellets
<hr/>										
Proximate Analysis (wt%)										
Moisture	7.1	23.0	16.8	3.2	2.7	1.9	10.3	4.4	32.8	34.4
Volatile Matter	38.8	29.1	29.6	31.7	9.1	37.7	35.3	37.2	34.9	42.2
Fixed Carbon	48.9	35.3	45.6	56.9	87.9	51.0	45.1	51.5	25.9	16.1
Ash	5.2	12.6	8.1	8.1	0.3	9.4	9.3	6.9	6.4	7.3
Ultimate Analysis (wt%)										
Hydrogen	4.2	3.3	3.8	5.0	3.5	5.2	4.6	5.1	3.7	3.5
Carbon	71.9	48.9	58.7	74.2	85.8	73.6	63.1	73.7	44.8	34.3
Nitrogen	1.6	0.7	1.4	1.5	1.4	1.3	1.1	1.5	.6	1.6
Oxygen	8.7	10.5	10.7	6.6	1.1	5.6	8.2	7.7	11.1	18.7
Sulfur	1.4	1.1	0.6	1.0	5.3	3.0	3.4	.8	.6	.2
Moisture	7.1	23.0	16.8	3.2	2.7	1.9	10.3	4.4	32.8	34.4
Ash	5.2	12.6	8.1	8.1	0.3	9.4	9.3	6.9	6.4	7.3
Heating Value (Btu/lb)	12845	8354	10209	13355	14699	13427	11389	13137	8081	6092
Free Swelling Index	2	0	0	8 1/2	0	6 1/2	3 1/2	3 1/2	1/2	0
Ash Fusion Temperatures (deg F) (Oxidizing Atmosphere)										
Initial Deformation	2520	2280	2700	2790	-	2545	2390	+2800	2320	2135
Softening	2570	2300	2800	+2800	-	2565	2450	+2800	2365	2155
Fluid	2715	2380	+2800	+2800	-	2615	2580	+2800	2465	2220

Table 1-6
Coal Test Objective Matrix

COAL TEST OBJECTIVE MATRIX									
PHYSICAL CHARACTERISTICS		COAL RANK							
TYPE	RANGE	BITUMINOUS	SUB-BITUMINOUS			LIGNITE	PEAT/BIO MASS	PETROLEUM COKE	BRIQUETTES
			A	B	C				
ASH CONTENT	H + 20%								
	M 10 - 20%			002					
	L - 10%	001, 004, 006, 007, 008	003			009	010	005	
ASH FUSION	H + 2700 F	004, 008	003						
	M 2300-2700 F	001, 006, 007						005	
	L - 2300 F			002		009	010		
FREE SWELLING INDEX	H 3 +	004, 006, 007, 008							
	M 1 - 3	001							
	L 0 - 1		003	002		009	010	005	
MOISTURE CONTENT	H + 15%		003	002		009	010		
	M 5 - 15%	001, 007							
	L - 5%	004, 006, 008						005	
FRIABILITY (GRINDABILITY)	H		003	002					
	M	001				009			
	L	001, 006, 007, 008					010	005	

the lack of volatile matter in the fuel.

BOM/FGT-007 - Illinois #6 Bituminous Coal - This medium-swelling, southern Illinois, high-sulfur coal gasified well with the highest throughput measured to date, and provided good gas quality.

BOM/FGT-008 - Elkhorn Bituminous Coal - This medium-swelling, eastern Kentucky coal gasified well. Again high throughputs with good gas quality were achieved.

BOM/FGT-009 - Benton Lignite - This Arkansas lignite gasified well. Very high throughputs were obtained, but were limited by the ability to deliver steam to the blast. The lignite was very hard when wet, but very friable when dry.

BOM/FGT-010 - Peat Pellets - In anticipation of an extended test in the Spring of 1984, a short screening test was undertaken to see if the peat pellets from northern Minnesota would maintain structural integrity in fixed-bed gasification. Very good results were achieved, and a longer test is planned for 1984.

Five additional tests were conducted in 1984. These include gasification of the following fuels: peat sods, Absoloka/Robinson subbituminous coal, peat pellets, Blind Canyon bituminous coal, and Kemmerer subbituminous coal. The results of these tests are included in references BS&B (1984e), BS&B (1984f), BS&B (1984g), and BS&B (1984h).

SECTION 2

FACILITY DESCRIPTION

2.1 History and Overall Description

Construction of the low-Btu gasification test facility at the Bureau of Mines, Twin Cities Research Center began during 1977 and commissioning occurred during the fall of 1978. The facility includes a coal storage and handling system to process, deliver, and meter coal to the gasifier, the gasifier and support equipment including fans and drives, a boiler to provide import steam when needed, a gas handling and combustion system, a flue gas clean-up system, and two slipstream systems.

The gasifier has remained essentially unchanged in the interim. A process flow schematic of the facility is given in Figure 2-1. A PID for the gasifier is given in Figure 2-2. (Table 4-1 gives identification for the individual signals.) Several modifications to the gas handling systems have occurred including replacement of the original gas burner, replacement of the induced draft fan, installation of a slip-stream hot-gas quench/electrostatic precipitator for gas clean-up, etc. The systems described below are those in use during the period of the BS&B operating contract (June 1982 - May 1984).

2.2 Coal Handling Equipment

The coal handling equipment in use at the facility includes concrete surface storage, front-end loader, hopper and conveyor belt, vibrating bottom-size screen, bucket elevator, and overhead weigh bin as shown in Figure 2-3. Adding coal to the gasifier system is normally done once or twice a shift. The coal handling system has a capacity of about 10 tons per hour and is limited by the conveyor-screen step.

2.2.1 Storage, Loader, Hopper, Belt

The active coal storage is a concrete pad with an area of about 3000 square feet. There is a 4-foot fence along two sides of the concrete storage area. The trucks that deliver the coal are able to unload to an average 5-foot height. The concrete surface has launders through the middle and along one edge to keep the surface essentially free of standing water. These launders were installed April 1983. Coal is recovered from the active storage with a diesel-powered front-end loader. The capacity of the bucket on the loader is approximately 1/2 ton of coal.

The coal is dropped into a hopper which feeds an inclined conveyor belt. During the spring of 1983 a 5-inch square mesh was installed in the hopper to intercept tramp mater-

Figure 2-1

USBM/TCRC Gasifier Process Flow Schematic

USBM/TCRC Gasifier PID

Figure 2-3

Coal Handling System Schematic

COAL HANDLING SYSTEM SCHEMATIC

ial which could choke flow in the gasifier feed system. The belt is powered by a 1 hp electric motor and moves at a speed of about 5 feet per second. The belt elevates the coal 8 feet over a run of 20 feet. Two and four-ply rubber belts have been used.

2.2.2 Coal Screen

A LECCO Model C222 vibrating screen is used to screen out the undersized coal in the deliveries. The screen is powered by a 10 hp electric motor. The screen is sloped at an angle of 4.5 degrees towards the screen exit. The active screen area is about 20 square feet.

The screen panels are interchangeable and several screen sizes are available for use. The screens are U.S. series, and the most commonly used mesh sizes are the 3/4, 1/2, and 1/4 inch. Bottom size of the coal is usually a test parameter.

It is possible to bypass the screen and feed from the belt directly into the bucket elevator. This has been done as part of specific test plans.

The undersize material that falls through the screen is removed by the front end loader to temporary storage prior to ultimate disposal. On occasion, the material passing through the 3/4-inch screen was recovered and fed to the 1/4-inch screen at the end of a test.

2.2.3 Bucket Elevator

The screen discharges into a Link Belt bucket elevator. The bucket elevator is powered by a 7.5 hp electric motor and lifts the coal 75 feet. The buckets are cast iron mounted on a rubber belt.

The belt discharges into a 20 x 17 inch rectangular chute that conveys the coal 9 horizontal feet with a drop of 13 feet. This chute has a metal plate at its end which splits the coal flow evenly into the two halves of the weigh bin.

2.2.4 Weigh Bin

The coal is metered into the gasifier by an overhead weigh bin. The weigh bin is mounted on four load cells as shown in Figure 2-4. The load cells are wired in parallel. The load cell output is processed and displayed in engineering units (tons) on the operator's console. Coal is discharged from the weigh bin through two electrically-powered slide gate valves.

Figure 2-4
Coal Weigh Bin

2.3 Gasifier

The gasifier is a Wellman-Galusha Gas Producer. It is equipped with coal lock hoppers, agitator, water jacket, an eccentric step-type grate, and an ash discharge system. A cyclone to remove dust from the product gas was also included with the gasifier. The gasifier and the weigh bin are enclosed in a metal sided building.

A schematic of the overall layout of the gasifier is shown in Figure 2-5. The coal from the weigh bin is added to the upper lock hopper, flows through the lower lock hopper and coal pipes into the retort. The coal falls away from the points of entry to fill the retort. The solid mass in the retort is supported by the grate. Ash generated in the retort is removed by the rotating grate.

Air is blown across the top of the water jacket where it becomes saturated with water vapor, then down the saturation pipe and into the ashpit. It then moves up through the grate openings and the coal bed where the gasification of the coal takes place. The product gas moves out at the top of the retort and into the cyclone.

The individual components of the gasifier are described below.

2.3.1 Lock Hopper

The lock hopper system is a circular bin 10.5 feet in diameter separated into two sections. The upper lock hopper has a capacity of about 1.5 tons of coal and is exposed to the atmosphere of the building interior. The upper section is sealed from the lower section by two rotating disk valves 32 inches in diameter with a 10-inch diameter opening. The metal disk seals against a stationary metal seat. The spacings between the metal surfaces are to be less than $5/1000$ inch. These valves are normally closed during operation, and must seal against the pressure of the gas being produced.

The lower lock hopper is 7 feet high with an active storage of about 2.5 tons of coal. At the bottom of the lower lock hopper there are a set of valves identical to those separating the lower and upper lock hoppers. These lower valves are normally open during operation allowing coal to flow from the lower lock hopper into the coal pipes. The product gas occupies the voids between the coal particles in the lower hopper at the pressure of the product gas.

The upper and lower coal valve disks are mounted on common drive shafts, and are oriented on the shafts such that it is impossible for both valves to be open at the same time. The valves are rotated periodically to add coal from the weigh bin and upper lock hopper to the lower lock hopper.

Figure 2-5
Overall Gasifier Layout

The coal enters the retort after traveling 10 feet through two 10-inch diameter coal pipes. The coal pipes are always full, and coal flows by gravity through the coal pipes and enters the retort only as coal in the retort is consumed.

2.3.2 Retort and Water Jacket

The retort has an inner diameter of 6.5 feet. The distance from the lower grate level to retort inner top is 9.25 feet. The inner walls of the retort are constructed of 1 inch thick mild steel. The outer surface of the retort wall is in contact with cooling water in the water jacket. The annulus occupied by water is 4 inches thick. The space at the top of the retort occupied by the water jacket is 9 inches thick. The water level in this space is approximately 4 inches high. The blast air passes over the water jacket through the remaining 5 inches.

As the air blast passes over the water jacket it is saturated with water vapor at a preselected temperature. This temperature is controlled by the rate at which cooling water is fed to the jacket. As more cooling water is fed to the jacket, the temperature at which the blast is saturated decreases. As less cooling water enters the jacket, the temperature at which the blast is saturated increases. In this manner, the steam/air ratio of the blast can be controlled (see Section 3.9).

Downstream of the water jacket steam nozzles have been installed to add imported steam to the blast for fine control of the blast saturation temperature and for those occasions when steam generated in the water jacket is inadequate to maintain the desired blast saturation temperature.

Access ports to the interior of the retort include two doors 180 degrees apart just above the grate level for ignition and dumping of the gasifier, two smaller ports at 90 degrees to those mentioned above, two doors just under the grate doors for access to the ashpit, and a manway in the top of the retort. These access ports are closed while making gas.

In addition to the ports described above, there are 7 small retort access ports (RAPs) on the top of the gasifier, as indicated in Figure 2-6. These RAPs are used for monitoring the firebed during operation (see Section 3.3). The RAPs have 7/8 inch diameter holes and are sealed against gas leaks by integral steam jet pumps. The RAPs also allow visual inspection of the top of the coal bed.

Figure 2-6

Retort top

AGITATOR SHAFT = $3\frac{1}{2}"$

2.3.3 Draft Arrestor and Agitator

The coal pipes enter the retort inside a sheet metal draft arrestor as shown in Figure 2-6. As this draft arrestor is not circular, an additional shroud was welded onto the draft arrestor that provides a circular line from which the coal falls (at its angle of repose) to the retort side walls. As the coal is gasified in the retort, fresh coal falls away from this shroud. In this manner, the addition of coal to the retort is controlled to maintain a constant level in the retort.

The gasifier is provided with a rotating, water-cooled agitator arm as indicated in Figure 2-6. The agitator serves two purposes. The first is to move coal from the draft arrestor to the side walls of the retort. In this fashion, the coal level can be brought up higher than would be possible if the coal were allowed to fall from the draft arrestor at its angle of repose. The second use of the agitator is to break up agglomerations that may occur in the top of the retort when gasifying swelling or caking coals.

The agitator is driven by a 2 hp, induction motor through gear reducers and can be rotated at speeds between 0 and 16 revolutions per hour (32 sweeps of an agitator arm per hour) with a variable frequency motor power supply. Prior to October 1982 a belt-driven variable speed transmission was used to drive the agitator.

In addition to rotational movement, the vertical agitator position can be continuously varied between preset limits.

2.3.4 Ash Removal Grate

Ash is removed from the gasifier through an eccentric, step-type grate as shown in Figure 2-7. There are three levels to the grate, and the distance between the three levels can be varied by insertion and removal of spacing shims. The eccentricity of the grate has not been varied during the testing to date.

The lower two grate levels are constructed of 1-inch thick mild steel plate. The edges of these plates are coated with a bead of stainless steel weld to protect against wear erosion. Similar weld beads are formed in a basket weave on the outer 6 inches of the tops of these plates. The top grate section is a mild steel cone with a 1 1/4 inch x 1 1/4 inch rib welded to the top in a gentle spiral from the point of the cone to the rim.

The grate is driven by a drive dog mounted on a crank engaging teeth on the outer rim of the lower grate. A check dog ensures forward motion of the grate. The grate drive is powered by a 2 hp induction motor through gear

Figure 2-7
Top View of Grate

reductions. At one stage of the reduction a crank arm engages a 64 tooth gear. The number of teeth actually engaged by the crank arm is adjustable from 1 to 9. One revolution of the 64 tooth gear advances the grate 1/116 of a grate revolution. The grate speed can be continuously varied between 0 and 50 grate revolutions per day with the crank arm engagement described above and a variable frequency motor power supply. Prior to April 1983, a belt driven variable-speed transmission was used to drive the grate.

2.3.5 Ash Cone and Weigh Bin

Ash falling from the grate is accumulated in a lock hopper weigh bin underneath the retort, as shown in Figure 2-8. The capacity of the weigh bin is 2500 lbs. The valves used to seal against leakage of blast during ash dumps are air-operated slide gate valves.

The lock hopper is supported by 4 load cells wired in parallel. The load cell signal is processed and displayed near the ash bin and on the operator's console.

The ash cone under the retort is equipped with a spray ring. During ash dumps water is metered through this spray ring to flush ash from the ash cone into the ash weigh bin.

On several occasions, a fine powdered ash accumulated on undergrate support members and ultimately inhibited ash removal by the grate, and operation of the grate drive and check dogs. Prior to the 1983 test season, water spray nozzles were installed to allow the option of flushing these areas during ash dumps.

2.4 Support Equipment

Support equipment for processing the produced gas includes a vent/flare for use during startup and banking, a refractory lined cyclone to remove dust in the product gas, a refractory lined gas duct to convey the hot, raw gas, a baffle burner attached to a cylindrical combustion chamber, and a flue gas scrubber/fan/stack system to remove sulfur dioxide and particulate from the products of combustion and to control pressures in the combustion chamber.

2.4.1 Vent/Flare

During startup there is a period during which the product gas is of insufficient quality to support combustion. The gases are vented through a 33-foot long, 10-inch diameter, uninsulated pipe to a flare on the roof. The vent pipe is located 4 pipe feet downstream of the retort, and 1.5 feet upstream of the cyclone. The flare is equipped with a

Figure 2-8
Ash Weigh Bin

natural gas pilot burner. This vent/flare is also used when the gasifier is banked. (see Section 3.2).

The vent/flare is isolated from the gas flow during normal operation by a 10-inch Chapman slide gate valve. The valve is actuated with a hydraulic cylinder. The position of the vent valve is fully controllable, and the vent is programmed to open immediately upon loss of the blast air fan or closure of the gas safety valve (see Section 2.4.5). In the event of a power failure, the hydraulic accumulator has enough capacity to open the vent. The vent valve is also provided with a hand wheel in the event that the hydraulic system is unable to open the valve.

2.4.2 Offtake Duct

The retort is connected to a refractory-lined cyclone by 5.5 feet of 20-inch ID mild steel pipe. The pipe is insulated with ceramic wool on the outside with sheet metal protecting the insulation. Three small access ports are located on the elbow leaving the retort. Two ports allow insertion of rods to clean the ductwork to the cyclone. One port is oriented to allow insertion of rods to clean the exit of the retort. A steam-sealed retort access port was installed over this last port in July 1983 to allow routine sampling of the product gas leaving the retort for particulate loadings and size distributions (see Section 5.2.8).

2.4.3 Cyclone

Dust is removed from the product gas in a refractory-lined cyclone. The dimensions of the cyclone are given in Figure 2-9. The dipleg of the cyclone extends into a water bath. Dust collected in the cyclone falls into the water seal. The dipleg can be sealed from the water bath by a 14-inch air-operated slide gate valve.

The cyclone is periodically flushed by closing this valve and admitting 40-50 gallons of water to the cyclone and then rapidly opening the valve. During banked periods the gasifier is isolated from the downstream ductwork by a water seal internal to the cyclone. The dipleg valve is closed and water is admitted until the level is above the vortex finder outlet. Upon draining the cyclone to send gas downstream, instabilities in breaking the water seal are minimized by the bevel cut in the bottom of the vortex finder. (The vortex finder is a 42 inch diameter mild steel pipe.)

Figure 2-9

Cyclone

2.4.4 Gas Duct

The gas leaving the cyclone is conveyed through a 24-inch ID refractory-lined duct to the gas burner. Two wide radius 90 degree elbows are located 10 and 26 pipe feet from the cyclone outlet. These elbows turn the flow down and outside the building. Fifty-seven pipe feet from the cyclone is a 14.64-inch throat diameter venturi flow meter. Gas samples for analysis are withdrawn 59 pipe feet from the cyclone. A "Y" section removing gas for slip stream operations is located 64 pipe feet from the cyclone.

The gas is turned 90 degrees into a horizontal duct through a short radius elbow 71 pipe feet from the cyclone. A dropout trap is located under this elbow to remove dust and condensate accumulations. An air-operated gas safety butterfly valve is located 82 pipe feet from the cyclone, and a motor operated gas throttling butterfly valve is located 90 pipe feet from the cyclone. The burner is 103 pipe feet from the cyclone.

In the horizontal duct there are two sections of pipe that are not refractory-lined, including the section leading to the burner throat.

2.4.5 Burner/Combustor

The hot, raw gas is burned in a baffle burner shown in Figure 2-10. Up to 4500 cfm primary air and up to 11,000 cfm secondary air is supplied to the burner from separate fans. The primary air is admitted through 9 ports with 15 degree swirl number in each port.

The burner is supplied with a natural gas pilot. The flame supervision system will allow the gas safety valve to be open when the primary air fan is on, when the gasifier blast air fan is on, and when flame can be detected in either the pilot or main flames.

The gas burner is mounted on the end of a refractory-lined cylindrical combustion chamber shown in Figure 2-11. The combustion chamber is 7 feet ID and 22 feet long. Nine access doors (6 inches x 4 inches) are located along the centerline of the combustor for detailed monitoring of flame conditions.

The combustion chamber issues into a 64-inch ID refractory lined duct which carries the exhaust gases to the scrubber. An access port for combustor emissions monitoring is located 12.5 pipe feet downstream of the combustor outlet. A pipe with cocurrent flow water sprays is located 14 pipe feet from the combustor outlet. These sprays are turned on when the exhaust gas temperature exceeds a preset level (typically 1400 F).

Figure 2-10

Gas Burner

Figure 2-11
Combustion Chamber

2.4.6 Scrubber, Induced Draft Fan, Stack

The partially-cooled combustor exhaust is cooled to its adiabatic saturation temperature in a impingement type single tray scrubber. The pH of the recycle water is maintained at 5-7 with caustic soda to facilitate capture of sulfur oxides. The scrubber exhaust is demisted and conveyed to the induced draft fan. Suction created by the fan is controlled to maintain a preset pressure in the combustion chamber. The induced draft fan blows the scrubbed products of combustion out through a 76-foot tall, 36 inch diameter stack.

2.5 Slip Stream Equipment

Gas for use in slip stream operations is taken from a "Y" section 7 pipe feet downstream of the gas sampling port in the 24-inch gas downcomer duct. The withdrawal port is an 8-inch ID refractory-lined pipe. The gas has been used to fire a taconite pellet kiln, and evaluate a tar scrubber.

2.5.1 Taconite Pelletizing Kiln

Operation of a pilot plant taconite pelletizing kiln has been described by Nigro (1982a, 1982b). Hot, raw gas was delivered to the kiln through an 8-inch diameter refractory-lined duct. Gas consumption of the kiln varied from 2 - 4 million BTU/hr or 6% - 13% of the rated gasifier output.

2.5.2 Quench/ESP Tar Scrubber

The tar scrubber slip stream contains components for gas delivery, quench, tar fog precipitation, compression, and return to the gas duct. A process flow schematic of this system is shown in Figure 2-12 and a process PID as built is shown in Figure 2-13.

Hot, raw gas is taken from the main gas duct 64 pipe feet from the cyclone outlet. It moves through an 8-inch steel duct insulated on the outside 16 feet to the entrance of the quench tank. Isolation of the slip stream from the gas duct is accomplished by a spectacle valve, a hand-operated butterfly valve, and an air-operated butterfly valve.

The quench tank is a light gauge, stainless steel vessel 36 inches in diameter by 9 feet high with a flat top and slightly conical bottom, that quenches the gas stream by means of seven spray nozzles. Four of these nozzles spray fresh water and the remainder spray recycle liquor drawn near the bottom of the tank. One fresh water nozzle is located in the center of the vessel inlet and sprays directly into the gas stream which enters the tank tangen-

Figure 2-12

Quench/Electrostatic Precipitator Process Flow Schematic

Figure 2-13

Quench/Electrostatic Precipitator PID

tially. The remaining six nozzles are spaced evenly and alternately positioned around the vessel at the level of the inlet. The collected liquor is periodically drained from the bottom of the tank. The quench tank gas outlet is 8 inches in diameter, points downward, and has a centerline 60 inches from the top of the vessel. Various nozzles for sampling and recycle draw are located up the side of the tank.

The quenched gas enters the bottom of the rectangular parallel plate wet electrostatic precipitator (ESP). The ESP is positively grounded and has 7 steel parallel plates (including the outside walls) 60 inches by 36 inches. The precipitated matter is drained by gravity back into the quench tank. The detarred gas leaves the ESP through an 8-inch pipe from the top of the vessel.

The gas is moved about 40 pipe feet to a compressor skid comprised of a knockout vessel, an inlet silencer, a lobed blower, and an outlet silencer. The clean compressed gas is returned to the gas duct by an 8-inch pipe approximately 100 feet long. Gas flow is measured 65 pipe feet from the outlet silencer. Isolation of the slip stream at the gas return is accomplished with a 4-inch hand gate valve. Just ahead of the gate valve is a 2-inch ball valve that allows purging to atmosphere during start-up and shut-down of the slip stream.

The liquor level in the quench tank is monitored by the operator and drawn down as required. This is accomplished by opening a manual 3-inch stainless steel ball valve which allows liquor to drain to a steam heated rectangular sump tank of approximately 120 gallons volume. The liquor is heated to and maintained at 180 F in this tank. A cast iron gear pump constantly recycles the heated liquor to prevent agglomeration or separation. The level of this tank is monitored by the operator and, as required, liquor is transferred to a 500-gallon tar storage tank through a steam traced 1-inch pipe using the same gear pump.

The tar tank is a vessel 6 feet high and 48 inches in diameter with a flat top and conical bottom that contains a circular 3/4-inch copper heating coil about 100 feet long. Heating media is steam and tank temperature is maintained at 180 F.

Liquor is drawn from the bottom of the tar tank by 2 orbital gear pumps piped in parallel, with all interconnecting lines being steam traced. These pumps deliver the liquor to the combustion chamber and are relieved back to the tar tank. From the tar pumps, the liquor moves through a steam-traced 1-inch pipe 35 feet long to two electric heaters piped in series that maintain the liquor at 180 F. The liquor is sprayed into the low-Btu gas flame by a retractable steam atomizing heavy oil nozzle.

This liquid tar handling system was installed during the summer of 1983 and is shown in schematic in Figure 2-14.

Figure 2-14
Modified Tar Handling System

SECTION 3

OPERATIONAL PROCEDURES

3.1 Cold Start-up

Two start-up procedures were used. For BOM/FGT-001 through BOM/FGT-004 the traditional start-up procedure described below was used. The petroleum coke gasified during BOM/FGT-005 had less than 0.5 % ash. A fabricated ash layer of broken firebrick was installed to protect the grate. The traditional start-up procedure had to be modified to ensure complete coverage of the grate with the firebrick from the very beginning of the test. For this reason the modified start-up procedure was developed. The modified start-up procedure resulted in the following improvements: 1.) no fire during start-up in the ashpit or undergrate section 2.) greater ignition area in contact with the charcoal layer 3.) no voids between the fire zone and grate 4.) less fuel oil required 5.) less time elapsed between light-off and production of gas with stable burning properties. For these reasons the modified start-up procedure was adopted for routine use for all further tests.

3.1.1 Traditional Start-up Procedure

For the traditional procedure six square "wick boxes" are constructed. The boxes are constructed of 1 x 6 inch pine nailed into a square box 18 inches long. The boxes are open on the ends, and the bottom has an opening of about 4 inches on one side for the wick. Four of the boxes are placed upright on the lowest grate level at positions 90 degrees apart as shown in Figure 3-1. The remaining two boxes are placed upright on the second grate level near the third level cone.

Burlap wicks 3 inches wide and 10 feet long are threaded through the boxes. Approximately 3 feet of wick extends out the top of the boxes, and 5 feet of wick out the bottom. The wick ends coming out the bottom of the boxes are led through the grate to the ashpit where they are all tied together.

Coal ash from previous tests is placed on the grate around the wick boxes to their top. Six inches of lump charcoal are placed on top of the ash and in the wick boxes. Pipes are placed through the retort access ports on the gasifier top to each wick box. The wicks coming out of the top of the wick boxes are laid across the top of the charcoal.

Fuel oil is poured down the pipes leading to the wick boxes to saturate the wicks. Additional fuel oil (15 gallons) is sprayed onto the charcoal from the manway. The pipes are removed and the top of the gasifier is

Figure 3-1

Wick Boxes for Traditional Start-up

sealed. The gasifier is then filled with coke.

The wicks are lit through an ashpit access door which is closed when it is observed that the wicks are burning well. Upon closing the ashpit door, the blast fan is immediately turned on to a preset airflow of approximately 100 cfm.

The gases produced during start-up are vented. The flare is ignited when gas produced at a test port on a coal pipe can be burned with a stable flame (approximately 30 minutes). The airflow is increased and gas sent to the combustion chamber after about 1 hour.

3.1.2 Modified Start-up Procedure

Four wick boxes similar to the ones described above, but 36 inches long, are constructed. These wick boxes are laid on their sides on top of the ash layer as shown in Figure 3-2. The burlap wicks are led out the side retort access doors. The wick boxes are surrounded with lump charcoal. The wicks and charcoal are saturated with fuel oil as before, and the retort filled with coke.

The wicks are lit simultaneously on both sides of the retort. When it is observed that the wicks are burning well the doors are closed and the blast fan turned on immediately to a preset air flow of about 100 cfm. The remainder of the start-up proceeds the same as the traditional start-up.

3.2 Banking - Warm Start-up

When the gasifier is shut down, whether at the end of a test or due to power loss or deliberately in the middle of a test, the following procedure is used:

1. Blast fan shut off
2. Vent valve positive open
3. Flood cyclone to isolate downstream systems
4. Set small draft through the coal bed

On restart from a bank, the blast air flow is maintained at 200cfm for about 15 minutes while the product gas is vented. After this period the gas is sent to the combustor and the airflow increased to desired level. The warm start-up is usually completed in 1/2 to 1 hour.

3.3 Retort Monitoring

As the retort is operated near atmospheric pressure it is relatively easy to obtain information about the coal bed directly. Access to the coal bed is through seven retort

Figure 3-2

Wick Boxes for Modified Start-up

access ports (RAPs) located on the top of the retort as shown in Figure 2-7. These RAPs have a steam jet pump to seal the retort against gas leaks during monitoring operations. The RAPs are foot-operated and mechanically interlocked so that they cannot be opened if the steam valve feeding the jet pump is not open. The actual access hole is 7/8 inch diameter.

3.3.1 Firetests

The thickness of the ash layer and condition and uniformity of the combustion zone is monitored by the firetest on a routine basis every 2 hours. (Common industrial practice is to monitor the fire zone 1 - 2 times during an eight hour shift.) Steel bars 3/4 inch diameter are pushed through the RAPs and coal bed to the grate. They are left in the retort for 2 - 5 minutes depending on the temperature of the combustion zone. When the bars are retracted, an incandescent zone on the bar can usually be seen. Below the incandescent zone the bar is in contact with the relatively cool ash.

The distance from the tip of the bar to the incandescent zone is a measure of the ash layer thickness. With some lower rank coals an incandescent zone does not appear after 5 minutes. In these cases the bars are retracted and the hot zone is detected by rubbing the bar with rubber or leather. The average ash thickness over the seven bars is used to adjust the grate speed (ash removal rate).

Multiple fire zones, very cold fire zones relative to the rest of the retort, regions of low or high ash, clinkers, and coal agglomerations can be detected during the firetests. These anomalies are usually indicative of upset conditions in the retort.

3.3.2 Freeboard

The freeboard measurement is made to monitor the top of the coal bed. A steel ruler is inserted through the RAPs until it reaches the top of the coal bed. This distance is recorded. Freeboard measurements are routinely made at two opposing RAPs every hour. During some tests they were made every half hour. Different opposing RAPs are used each measurement. The freeboard measurement is used to adjust the agitator speed when the agitator is used.

3.3.3 Temperature Probing

Measurements of detailed temperature profiles of the coal bed are made using a rod with thermocouples mounted on it. The procedure is described in Section 5.2.7. The information gathered by this method is not used for operational purposes.

3.3.4 Pressure Probings

Measurements of the pressure profile in the coal bed are made using the procedure described in Section 5.2.7. This information is not normally used for operational purposes, but on several occasions pressure profiles were taken to discover the location of excessive pressure drops inside the retort when they were noted. This proved to be very useful in understanding the behavior of the fuel inside the retort, and, in some cases, to apply corrective measures.

3.4 Coal Addition

Coal is transferred from the weigh bin to the lock hoppers routinely every hour. When coal consumptions exceed 2.5 tons per hour, coal is transferred every half hour. The net weight transferred is recorded.

The lower lock hopper is normally opened to the coal pipes leading to the retort while the upper coal valve seals against the retort pressure. During coal addition the lower coal valves are closed and the upper coal valves are opened. The slide gates on the bottom of the weigh bin are opened until the lower and upper lock hoppers are full of coal. The slide gate valves on the weigh bin are then closed and the lock hopper coal valves returned to their normal operating position.

3.5 Ash Removal

In an effort to obtain relatively reliable ash removal data, a fairly elaborate ash removal procedure was instituted. The main problem is to get accurate dry ash removal data. The ash as collected in the ash bin and ashpit is moist with water condensed from the saturated blast. In addition, water is used to flush surfaces in the ash-pit. The procedure outlined in Table 3-1 is used to quantify the water content of the all of ash discharged from weight measurements made at ash removal, and from sample water content measurements made in the lab.

3.6 Cyclone Dust Removal

Dust collected by the cyclone is removed through a water seal pot at the bottom of the cyclone dipleg. The valve at the bottom of the cyclone is normally open. Dust collected falls into the water seal. The bottom of the cyclone is routinely cleared of dust by closing the valve, admitting about 50 gallons of water above the valve and opening the valve quickly. The dust that falls and is

Table 3-1
Ash Removal Procedure

1. Close ash weigh bin top valve
2. Take weigh bin weight (initial "dry")
3. Open ash weigh bin bottom valve, dump ash
4. Take weigh bin weight (final "dry")
5. Collect ash sample for moisture determination and physical/chemical analysis
6. Close bottom valve
7. Open top valve
8. Flush with metered water
9. Close top valve
10. Take weigh bin weight (initial "wet")
11. Open bottom valve, dump wet ash
12. Take ash bin weight (final "wet")
13. Close bottom valve
14. Open top valve

flushed through the seal pot is raked into an accumulation bin. All attempts to quantify the dust removal were unsuccessful.

3.7 Gasifier Dumping

The gasifier is ordinarily dumped at the end of each test. Dumping begins with banking the gasifier as described in Section 3.2. A retort access port is opened and a water hose inserted. Water is run through several RAPs in succession into the bed for 12 - 15 hours to cool the fire. The grate is then turned on at high speed to remove the solids. Not all of the solids can be removed by the grate. Final cleaning of the retort is by raking the solids out of the retort through the grate access doors.

3.8 Limits to Throughput Decision Making

Identification of the fundamental limits to coal throughput is a major objective of the current research program. The maximum throughput is determined in a somewhat subjective way. The determination is made by the facility manager. One of the following factors may be the prime consideration in the decision:

1. Excessive Gas Channeling - At very high throughputs gas flow may not be uniform throughout the cross section of the retort. Some nonuniformities are probably always present even at low loads. If the gas flow in one area is such that the top of the coal bed at that location is glowing brightly due to hot gases channeling through that region, and this condition persists after efforts to correct by poking and raking coal to the spot, or speeding of the agitator, the load is reduced somewhat until the conditions stabilize, and this is identified as the maximum throughput. This is the most common limit to throughput.

2. Excessive Ash Clinkering - If the ash clinkering does not respond to changes in blast saturation temperature, and clinker is being continually generated in some part of the fire zone, then the load is reduced until the problems are manageable, and this is identified as the maximum throughput. This problem is closely related to the gas channeling problem as the clinker usually forms under the gas channels.

3. Undercapacity of Auxiliary and Support Systems - On several occasions throughput was limited by capacity of the blast fan. On one occasion throughput was limited by the grate's ability to remove ash fast enough. On still another occasion throughput was limited by imported saturation steam delivery capacity. Imported steam could not

be delivered in volumes large enough to maintain the steam/air ratio necessary to avoid clinkering at high air flow rates. None of these limitations are fundamental to the physics and chemistry of gasification.

3.9 Saturation Temperature Decision Making

Initial blast saturation temperature (steam/air ratio) is based on the ash fusion temperatures of the coal ash. If the reported ash fusion temperatures are high (+2700 F) an initial blast saturation temperature near 60 F is selected. If the reported ash fusion temperatures are lower, a higher initial blast saturation temperature is selected.

Once the test is underway the conditions of the ash layer dictate the blast saturation temperature. If excessive fusing of the ash, or ash clinkering are observed the saturation temperature is increased to cool the combustion zone (by dilution of the blast with steam). The blast saturation temperature is normally maintained at the lowest possible level that avoids ash clinkering.

Oversaturation of the blast is indicated by excessive torque on the grate drive when no clinkering is present and reduced ash discharge per unit grate revolution. This excessive torque is probably the result of liquid water wetting the ash near the grate and hydration reactions increasing the effective viscosity of the ash. The ash also tends to stick to the grate layers when it is wet. A decrease in blast saturation temperature is instituted under these conditions.

Tests of fuels with high ash fusion temperatures will often include arbitrary blast saturation temperature changes to investigate the effect of blast steam/air ratio on product gas quality.

SECTION 4

MONITORING SYSTEMS DESCRIPTION

4.1 Continuous Process Flows, Pressures, and Temperatures

Some 50 continuous output transducer signals are acquired by the MACSYM computer data acquisition system (Section 4.5). These signals include measurements of temperature, pressure, weight, flow rate and gas analysis. Table 4-1 gives a list of the computer recognized names for various sensors, their descriptions, and transducer types. The transducer output is in the form of a voltage, 1 to 10 volts, which is recorded by the MACSYM. The recorded voltage, a measurement of the magnitude of the measured quantity, can be converted to the respective engineering quantity through a set of conversion equations. The computer recognized names for the sensors correspond to the process PID in Figure 2-2.

4.2 Operator Logged Parameters

The operating parameters logged manually by the operations team (and not logged by the data acquisition system) are listed in Table 4-2. These parameters are recorded every hour. Sample data sheets are in the Appendix.

4.3 Gas Sampling and Conditioning System

The gas sampling and conditioning system underwent several modifications during the initial tests as a result of operating experiences. The description below pertains to the final configuration as used during BOM/FGT-010. (Some of the key modifications made on the system are summarized in Table 4-4.)

Figure 4-1 is a schematic diagram of the gas sampling and conditioning system in its final configuration. It consists of six major components, namely, a sample port, a liquid condenser, an electrostatic precipitator, a refrigeration unit, a combined filter-dessicator, and a flow measuring and transport system. The sampling port is thermally insulated to prevent tar condensation. The hot producer gas is quenched rapidly upon entering the condenser which is cooled by cold water or cold, compressed air. The rapid quenching causes tar, water and oil to condense on the inner surface of the condenser tube. Both condensed oil and water serve as lubricants to help the condensed tar to flow freely down the tube wall. During the gas cooling process, large quantities of fine tar particles are formed which are not removed in the condensing tube. They are removed by an electrostatic precipitator located downstream of the condenser. The producer gas is then

Table 4-1

Process Parameters Logged by the Data Acquisition System

NAME	DESCRIPTION	TYPE
T-701	Inlet air temperature	Thermocouple type T
T-702	Blower Outlet temperature	Thermocouple type T
T-703	Saturation temperature	Thermocouple type T
T-703A	Jacket air exhaust temperature	Thermocouple type T
TT1-703	Sat temp trans (RTD)	4-20 mA (15 ohm)
TT2-703	Sat temp trans (RTD)	4-20 mA (15 ohm)
T-705	Offtake temperature	Thermocouple type K
T-706	Cyclone temperature	Thermocouple type K
T-707	Gas temperature (at flow element)	Thermocouple type K
T-710	Jacket water inlet temperature	Thermocouple type T
T-711	Jacket water outlet temperature	Thermocouple type T
T-712	Agitator water inlet temperature	Thermocouple type T
T-713	Agitator water outlet temperature	Thermocouple type T
T-715	Injection steam temperature	Thermocouple type K
T-806	Gas temperature (at burner)	Thermocouple type K
T-811	Combustion chamber temperature	Thermocouple type S
T-812	Combustion chamber temperature	Thermocouple type K
T-813	Combustion chamber temperature	Thermocouple type K
T-814	Combustion chamber temperature	Thermocouple type K
T-815	Combustion chamber temperature	Thermocouple type K
T-816	Combustion chamber temperature	Thermocouple type K
T-817	Combustion chamber temperature	Thermocouple type K
T-818	Combustion chamber temperature	Thermocouple type K
T-819	Combustion chamber temperature	Thermocouple type K
T-820	Combustion discharge temperature	Thermocouple type K
T-821	Scrubber inlet temperature	Thermocouple type K
T-822	Scrubber sieve temperature	Thermocouple type K
T-823	Scrubber discharge temperature	Thermocouple type K
REF Temp	Isothermal box temperature	Thermocouple type T
F-701	Saturation air flow (Annubar)	4-20 mA (15 ohm)
F-707	Coal gas flow (Venturi flowmeter)	0-40 mA (15 ohm)
F-802	Primary combustion air flow	4-20 mA (15 ohm)
F-803	Secondary combustion air flow	4-20 mA (15 ohm)
P-703	Ash pit pressure	4-20 mA (15 ohm)
P-704	Fire loss pressure	calculated in software
P-705	Gas Offtake pressure	4-20 mA (15 ohm)
P-706	Cyclone outlet pressure	4-20 mA (15 ohm)
P-707	Main gas pressure control	4-20 mA (15 ohm)
P-810	Chamber pressure control	4-20 mA (15 ohm)
WT-720	Coal storage bin weight	1-10 Volts
AG VEL	Agitator speed	0-5 Volts
GIR VEL	Grate speed	0-5 Volts

Table 4-1 (cont)

CO	CO IR continuous dry gas analysis	0-5 Volts
CO2	CO2 IR continuous dry gas analysis	0-5 Volts
O2	O2 continuous dry gas analysis	0-5 Volts
SIGMA	Sigma gas calorimeter	0-2 Volts
GCH2	H2 (molar %)	-- HP5880 GC
GCCO	CO (molar %)	-- HP5880 GC
GCCH4	CH4 (molar %)	-- HP5880 GC
GCC2H4	C2H4 (molar %)	-- HP5880 GC
GCCO2	CO2 (molar %)	-- HP5880 GC
GCN2	N2 (molar %)	-- HP5880 GC
GCO2	O2 (molar %)	-- HP5880 GC
GCC2H6	C2H6 (molar %)	-- HP5880 GC
GCC3H6	C3H6 (molar %)	-- HP5880 GC
GCC3H8	C3H8 (molar %)	-- HP5880 GC
CO(1)	CO (ppm): cyclone dust dump area	0-5 Volts
CO(2)	CO (ppm): poking area	0-5 Volts
CO(3)	CO (ppm): coal feed area	0-5 Volts
CO(4)	CO (ppm): instrument room	0-5 Volts

Table 4-2

Process Parameters Logged Manually by the Operating Team

NAME	INSTRUMENT
Agitator water flow rate	Rotameter
Jacket water flow rate	Rotameter
Jacket water flow total	Water clock
Saturation steam flow rate	Venturi steam meter
Saturation steam valve position	
Saturation steam meter inlet pressure	Bourdon tube gauge
Saturation steam valve inlet pressure	Bourdon tube gauge
Saturation steam valve outlet pressure	Bourdon tube gauge
Agitator sweeps	counter
Agitator rate	VFPS indicator
Grate gear revolutions	counter
Grate drive rate	VFPS indicator
Grate gear teeth engaged	

Figure 4-1
Gas Sampling and Conditioning System

passed through the refrigeration unit and the dessicator which are used to remove the remaining water vapor from the gas stream. This dry, detarred gas is metered and transported to the instrument room through the flow measuring and transport system. The nominal flow rate through the system is about 10 l/m. The description of the individual components, their performance, and the routine operating procedures are described below.

4.3.1 Sampling Port

The gas sampling port is located immediately above the venturi flow meter 59 pipe feet from the cyclone outlet. The port is elevated so that the sample gas stream can flow downward in the condenser concurrently with the condensed liquid. The down-flow feature allows tar to drain by gravity into a reservoir.

The inlet is a 1" diameter pipe with a 45 degree angle cut at the end. The pipe is rotated so that the tapered side is facing away from the oncoming gas stream. This orientation is used to minimize the entry of large dust particles into the sampling system and thus avoids plugging of the inlet pipe by these particles.

A shut-off valve is installed immediately outside of the sampling port flange. It is a high temperature ball valve with metal seat capable of operating at temperatures above 1000 F. The valve is used to isolate the gas sampling and conditioning system during maintenance.

A 1" cross is placed immediately behind the ball valve. It connects the ball valve to the vertical condensing tube. A cross is used so that the remaining two ports can serve as access ports for steam injection and for pushing a cleaning rod through the sampling port or the condensing tube should they become plugged with tar. The entire sampling port from the flange to the condenser inlet is thermally insulated to prevent tar condensation.

Field inspection during all tests indicated that very little tar had accumulated inside the 1" pipe connecting the ball valve and the liquid condenser. The only minor clogging was found upstream of the ball valve during BOM/FGT-001 due to dust accumulation during the beginning of the test. The dust accumulation was easily removed by steam injection.

4.3.2 Liquid Condenser

The liquid condenser is two concentric cylinders of 1" and 2" in diameter. The sampled gas passes through the inner cylinder while water or compressed air flows in the annular space between the cylinders. The rapid quenching of the gas from up to 1000 F to about 100 F causes tar, oil,

and water to condense on the inner surface of the inner tube. Both condensed oil and water serve as lubricants to help the condensed tar to flow freely down the tube.

The condensed materials flow into a 2 liter reservoir. A ball valve is installed at the bottom of the reservoir so that the liquid can be drained periodically to a jar placed below the valve.

Several minor clogging problems were encountered during BOM/FGT-001 and at the beginning of BOM/FGT-002. Tar accumulations were found near the top section of the condenser during BOM/FGT-001, which was caused by the existence of a "hot zone". In the hot zone, only viscous tar condensed but not the lubricating water and oil. The hot zone was developed as a result of insufficient cooling near the top section of the condenser. During BOM/FGT-002, tar accumulation was found near the bottom of the condenser where the cold water first entered the condenser in the counter current flow configuration. The condenser surface was apparently maintained at below the pour point temperature of the tar (approx. 70 F) at this section, causing the tar accumulation problem.

These problems were remedied by converting the condenser from a counter current flow configuration to a parallel flow configuration and by providing two ports spaced 180 degrees apart for the coolant to enter the top section of the condenser, as indicated in Figure 4-1. The parallel flow configuration allows the producer gas to be quenched more quickly near the top section. In addition, the bottom section of the condenser is kept at a higher temperature, enabling the tar to flow more easily. The installation of the dual ports allows more uniform cooling of the top section of the condenser and thereby minimized the hot zone problem.

Several thermocouples are installed in the condenser to monitor its performance. T1 monitors the effectiveness of the condenser in cooling the gas, which is kept at about 100 F by adjusting the coolant flow rate. T6 and T7 measure the coolant temperature at the inlet and the outlet of the condenser. When the condensor is water cooled, the coolant temperature typically increases by about 3-5 F at about 1.0 l/m water flow rate. When the condensor is air cooled, the coolant temperature typically increases by about 30-50 F at about 50 l/m air flow rate. A pressure gage P1 is used to monitor the condition of the sampling line. If the line becomes clogged with tar, the sampling pump draws a vacuum in the system, causing a negative deflection for P1.

During BOM/FGT-001A, a significant amount of tar accumulation was found in the transport line between the condenser and the ESP. The accumulation resulted from tar condensa-

tion was found in the transport line between the condenser and the ESP. The accumulation resulted from tar condensation on the cold line due to low ambient temperatures. To prevent tar condensation and to provide better temperature control for both the condenser and the ESP, the outer surfaces of the condenser, the transport line and the ESP are thermally insulated. In addition, a heating element is used to increase the surface temperature of the condenser reservoir, the transport line and the ESP during periods of low ambient temperature.

4.3.3 Electrostatic Precipitator

Figure 4-2 is a detailed schematic diagram of the electrostatic precipitator. The precipitator is designed to operate at near ambient temperature. To prevent condensation on the insulator and the subsequent electrical breakdown of the insulation, a 100 watt heater is installed close to the electrode insulator. The current flow of the high-voltage power supply is closely monitored during the test. A steady corona discharge current of about 100 uA indicates the cleanliness of the insulator. The precipitator is also equipped with a stainless steel sleeve on the inside surface of the collecting electrode. This sleeve may be removed periodically for cleaning if tar should accumulate on the collecting surface.

The collection efficiency of the precipitator was evaluated in the lab. Monodisperse Dioctyl Phthalate (DOP) particles of 0.3 micron diameter were suspended in ambient air. Studies in the UMPTL laboratory have shown that the minimum precipitator efficiency generally occurs in the vicinity of 0.3 um particle diameter. Therefore, an evaluation of the precipitator performance using 0.3 um particles provides a good indication of the minimum performance of the precipitator. Table 4-3 gives the collection efficiency as a function of the applied voltage on the discharge electrode. It is seen that as soon as the corona current has been observed to flow, the collection efficiency immediately attains the relatively high value of 95%.

An applied voltage of 12 KV to 15 KV is used during the tests which gives a minimum collection efficiency of 99.8 to 99.9% for the precipitator. Inspections after operation have shown that only 1/2 of the total precipitating length had evidence of tar particle deposition. The top half of the collecting electrode and the heated top flange with the electrode insulator were all free of condensed material and particles.

The precipitator performed extremely well and operated virtually maintenance-free. During BOM/FGT-002, heat tracing elements and thermal insulation were wrapped around the precipitator housing. The collecting electrode

Figure 4-2
Sample Electrostatic Precipitator

Table 4-3

Sample Electrostatic Precipitator Evaluation

Aerosol: 0.3 um Monodisperse Dioctyl-Phthalate (DOP)

Electrical Aerosol Detector Output

Voltage	Corona Current	Upstream Concentration	Downstream Concentration	Collection Efficiency
kV	uA	pA	pA	%
0	0	5.730	5.730	0
4	0	5.730	5.35	6.6
6	0	5.730	5.25	8.4
8	1	5.730	0.20	96.5
9	4	5.730	0.07	98.8
10	7	5.730	0.02	99.7
12	16	5.730	0.01	99.8
15	33	5.730	0.007	99.9
17	53	5.730	0.030	99.5
20	100	5.730	0.016	99.7

reservoir. A ball valve is installed between the precipitator and the liquid condenser. It is used to isolate the system downstream of the condenser during steam cleaning of the condenser.

4.3.4 Refrigeration Unit

The refrigeration unit and the dessicator are used to further remove water vapor from the gas stream. The refrigeration unit has a drain reservoir similar to that of the condenser and the electrostatic precipitator. A thermocouple T2 is installed downstream of the refrigeration unit to monitor its performance. T2 varied from about 30 F to 60 F depending on the ambient temperature. The liquid collected was mostly water with a minute amount of oil.

4.3.5 Combined Filter-Dessicator

A Wilkerson dryer equipped with a quick-disconnect clamp is used as a combined filter-drying unit. The container is packed with a glass wool filter and a dessicant to remove the remaining particles and water vapor in the gas stream. The dessicant (commercial calcium sulfate) is changed every shift. During BOM/FGT-001 changing dessicant required shut-down of the sampling system. A parallel filter-dessicant unit was installed for BOM/FGT-002 which enabled truly non-stop operation of the sampling system. To further insure that the transport line is completely free of tar particles, an absolute filter is installed at the outlet of the filter-dessicant unit. Post-test inspections indicated no evidence of tar particle collection on the filter. The electrostatic precipitator upstream of the unit had effectively removed all the tar particles.

4.3.6 Flow Measuring and Transport System

The flow measuring and transport system consists of a dry gas meter, a diaphragm pump, a rotometer and about 150 feet of 1/4" Teflon tubing which connects the outlet of the sampling system to the sampling manifold located inside the instrument room. The diaphragm pump provides a stable sampling flow rate at about 7-10 l/m to the sampling manifold. Pressure P2 and temperature T3 readings together with the dry gas meter indication are used to calculate the total sampling flow through the conditioning system.

A needle valve is placed between the sampling manifold and the exhaust manifold. It is used to provide a back pressure of about 20 in wg required for the gas instruments. The excess gas and the exhaust gases from the gas instruments are vented through an exhaust stack on the roof of the building.

4.3.7 Operation Summary

Table 4-4 provides a list of key changes made on the system as a result of operating experiences. Most of the modifications were implemented during BOM/FGT-002. With these modifications, the system has been performing extremely well with a cumulative operating time of over 97% of gasifier operating time during subsequent tests.

4.4 Gas Analysis Instruments

This section describes the gas analysis system used in this project. Dry, tar-free gas is supplied to a manifold at 20 in wg by the gas sampling and conditioning system. All gas analysis instruments draw gas from this manifold. Syringe samples of gas for sulfur analysis are taken from a septum connected to this manifold.

4.4.1 Continuous Gas Analyzers

Carbon monoxide and carbon dioxide concentrations are measured continuously with individual Beckman 864 non-dispersive infrared (NDIR) gas analyzers. Oxygen concentrations are measured continuously with a Beckman 755 paramagnetic oxygen analyzer. Heating Value of the gas is measured continuously with a SIGMA continuous flow calorimeter. These signals are all recorded by the automatic data acquisition system.

As some problems were encountered with operation of the SIGMA calorimeter its operation will be described in more detail. The Sigma Calorimeter is a continuous flow gas calorimeter. It measures the volumetric lower heating value of gases in the 120-180 Btu/scf range. It automatically compensates for changes in ambient conditions and gas specific gravity.

The gas sample flows into the calorimeter through two flow control elements which maintain a constant, standard conditions volumetric flow to the burner. This burner is mounted at the base of a tube which is heated by the products of combustion. The resulting thermal expansion of the tube is amplified by a mechanical linkage which drives a recorder pen. The pen drive is also connected to an electronic transducer which provides a signal for the data acquisition system. As there is no condensation of the water of combustion the SIGMA actually measures the lower heating value of the sample gas.

This instrument was somewhat more difficult to work with than the other gas analyzers. Its response was slow. It required more than half an hour to stabilize on the calibration gas. At least another half hour was required for

Table 4-4

Key Modifications Made on the Gas Sampling and Conditioning System

<u>DATE</u>	<u>PROBLEM</u>	<u>SOLUTION</u>
6/82	Inlet pipe clogged	Push rod through cross connector. Install steam clean port
10/82	Condenser clogged near upper tube portion due to non-uniform cooling of hot gas	Add a second water coolant tube 180 degree to the original tube in the condenser
10/82	Sampling system shut-down due to dessicant change	Add parallel dessicant unit thus permitting non-stop sampling
10/82	Tar accumulation in transport line between the condenser and the ESP: Slow tar drains from reservoirs due to low ambient temperature	Thermal insulating reservoirs, the condenser and the transport tubings; Wrap heating element around reservoirs, transport lines and the ESP
11/82	Condenser clogged due to low coolant temperature	Change condenser from counter-current to parallel flow with coolant; add 3-way valve to coolant inlet so that condenser can be air-cooled or water-cooled
5/83	ESP insulator breakdown due to insulator overheating	Add voltage regulator to insulator heater to prevent accidental overheating
5/83	Operation inconvenience	Install more thermocouples to monitor system temperatures

it to stabilize after it reconnected to sample gas. The instrument showed considerable drift, typically 2-3% in three days. Therefore, a new calibration curve was established every three days.

4.4.2 Gas Chromatographs

4.4.2.1 HP 5880A Chromatograph

The gasifier offgas bulk composition was determined every 18-33 minutes using a Hewlett Packard model 5880A gas chromatograph. The features of the chromatograph and its current configuration are listed in Table 4-5. Table 4-6 lists modifications made for specific tests.

Chromatograph operation is supervised by an integrator/controller. The main function of the integrator/controller is to perform the following tasks: control carrier and reference gas flows, control switching of the six and ten port valves, and to process and integrate the peaks of interest. Processed data from the detectors are stored on the Cartridge Tape Unit (CTU) in raw, not integrated, form. Integrated data can be sent to the data acquisition system through the RS-232 interface.

Data are stored in three forms: hard copy in the form of plots of the detector output against time and report tables listing the measured concentrations of the species of interest which are produced by the printer/plotter on the integrator/controller, tape cassettes produced by the CTU, and floppy disk produced by the data acquisition system. This redundancy is necessary to minimize the chances of losing data. The CTU stores data in a form which can be reintegrated at any time using adjusted integration procedures or new calibration constants.

The integrator/controller also has considerable computing power. It has been programmed to calculate the lower heating value and specific gravity for each sample analyzed. It has also been programmed to determine average properties of a selected set of samples. These properties include mass and molar compositions, higher and lower heating value, and molecular weight.

The instrument automatically switches back and forth between detectors during the cycle. Thus, the thermal conductivity detector (TCD) is used for hydrogen, carbon dioxide, oxygen, nitrogen, and carbon monoxide, while the flame ionization detector (FID) is used for hydrocarbons.

The integrator/recorder prints out the results of the analysis, stores the data on cassette tape, and also sends them to the data acquisition system via the RS-232 interface. The entire analysis, printout, and data recording process currently requires 18 minutes. At the end

Table 4-5

Principal Features of the
HP 5880A Gas Chromatograph

- Integrator/controller with alphanumeric keyboard and computing capabilities
- Cartridge tape unit
- Electronic flow control
- RS-232 interface
- Dual detectors-flame ionization detector in series with thermal conductivity detector
- Four columns
 - 1- 10 ft. x 1/8 in. SS Porapak Q
 - 1 - 10 ft. x 1/8 in. SS Molecular Sieve 5A
 - 2 - 18 in. x 1/8 in. SS 2% OV-101 on WHP
- Ten port valve and six port valve for automatic sample injection and column switching

Operating Configuration and Conditions:

- Set-up for analysis of the following species:
CH₄, CO₂, C₂H₄, C₂H₆, C₃H₆, C₃H₈, H₂, O₂, N₂, and CO
- Argon carrier gas
- Carrier flowrate = 28 ml/min.
- Temperature programmed from 100 C to 165 C
- Sample size = 1.0 ml
- Analysis time = 18.00 min

Table 4-6
 HP-5880
 Gas Chromatograph Operating Conditions

Species Analyzed	Temperature Program	Analysis Time	Test
H2, CO2, C2H4, C2H6 O2, N2, CH4, CO	70 C Isothermal	33 minutes	001, 002
CH4, CO2, C2H4, C2H6, C3H6, C3H8, H2, O2 N2, CO	75 C to 165 C 165 C to 135 C	18 minutes	003,004,005 006,007,008 009,010

of this period, valve 1 is opened and another cycle begins.

4.4.2.2 HP-5793A Gas Chromatograph

After August 1983 sulfur species in the sample gas were analyzed using a HP-5793A gas chromatograph and HP-3390A integrator. The principal features of this system are listed in Table 4-7.

The HP-5793A gas chromatograph is equipped with a flame photometric detector. This detector is capable of detecting sulfur or phosphorous compounds only. All flows to this detector are manually set to give the best performance. A gas-tight syringe was used to obtain samples from a manifold in the instrument room. The output of the detector is sent to an HP-3390A integrator/plotter. The output of the integrator is a chromatogram of sulfur species. The peaks are integrated yielding an area % report. The peak areas are compared to the peak areas of the calibration gas.

After the report has been generated, it is sent to a Quad RAM/Microfazer buffer via RS-232 interface where it is held until the data acquisition system can receive it.

4.5 Data Acquisition Systems

The signals from the continuous output transducers and the gas chromatographs are recorded by an Analog Devices MACSYM measurement and control computer on-site. The data are processed and printed out on a line printer every 1/2 hour. They are also stored on either a 9-track tape or a floppy disk from which the data are transferred at regular intervals to a Digital Equipment VAX computer at the University of Minnesota, Mechanical Engineering Department. The final processing and graphical display of the summary data are performed on the VAX computer.

Two Analog Devices MACSYM computers were used for data acquisition. Through June 17, 1983 (BOM/FGT-005) a MACSYM 2 system was used. It was replaced by a more advanced MACSYM 350 system July, 1983. The principal features of the two systems and the data acquisition and processing softwares are described below.

4.5.1 MACSYM 2 Computer

The MACSYM 2 is a 16 bit, BASIC programmable processor configured with 64 kilo-bytes of memory for data storage and processing. As presently configured, MACSYM 2 can monitor 64 separate voltage inputs, 4 base temperature thermocouples, and react to 8 software-defined external events such as switch closures. MACSYM 2 may also insti-

Table 4-7

Principal Features of HP-5793A Gas Chromatograph/
HP-3390A Integrator Plotter

- Integrator with plotting capabilities
- RS-232 interface
- Single flame photometric detector
- Column, 18" x 1/8" Teflon Supelpak-S
- One ten-port gas sampling valve for sample injection and stripper column backflush
- Set-up for analysis of the following species:
 H₂S, COS, CH₃SH, CH₃CH₂SH
- Nitrogen carrier gas
- Carrier flowrate = 30 ml/min
- Temperature program from 30 C to 170 C
- Analysis time: 12 min

gate up to 16 external events by means of switch closures. The peripherals used with MACSYM 2 include: 1.) A Kennedy 9-track tape drive for data recording, storage and transport to the University for further data reduction and 2.) A Data Royal 5000 or TTY-43 character printer utilized for field available data reports.

4.5.2 MACSYM 350 Computer

The data monitoring and recording system was replaced just prior to BOM/FGT-006 due to other commitments for the MACSYM 2. The replacement system is an Analog Devices MACSYM 350 measurement and control computer. The MACSYM 350 is a 16 bit, BASIC programmable computer and uses a subset of the MP/M 86 operating system (from Digital Laboratories, Inc.). The computer is presently configured with 256 kilo-bytes of RAM memory and two 5 1/4 inch and 320 kilo-byte floppy disk drives. Hardcopy is provided by a Tele-Terminals TTY-43 printer/terminal.

At present the MACSYM 350 is configured to monitor up to 64 separate voltage inputs and directly interpret 4 thermocouple types plus react to 8 software-defined external events (such as switch closures).

4.5.3 Software and Field Utilization

The MACSYM systems have the capability of time-sharing the processor among several user-defined tasks. Currently 6 tasks are specified. The individual tasks may each "continuously" execute, task execution may be externally triggered (such as by switch closures, etc.), or a task may be executed periodically. The system normally divides resources evenly among the active tasks, but tasks may be assigned priorities to gain sole access to system resources when necessary.

The software currently has 6 primary tasks:

1.) Data Collection: This periodic task scans the transducer signals and stores the acquired signal values. This task normally executes once per minute scanning each channel 10 times. During selected periods of gasifier operation when transients are being investigated, the execution period is shortened to 10 seconds. This task then executes the scan 9 times before storing the averaged data.

2.) Raw Voltage Write to Disk and Engineering Unit Conversions: This periodic task normally activates every 10 minutes. The task computes the average of the stored data collected by task 1 and writes that average to the floppy disk along with the date and time describing the interval. A second section of this task converts the signal averages to usable engineering unit numbers to be averaged for output to the line printer. During investigation of tran-

sients this task writes 90 second averages to storage.

3.) Line Printer Output: This task presently executes every 30 minutes and prints the average of the three 10 minute averages in that 30 minutes. The output includes both voltages and rough conversions to engineering units. This listing uses only preliminary calibrations and is produced only for immediate on-site use and as a hard copy back-up for the floppy disk data storage.

4.) Gas Chromatograph Data: This task is activated by the Hewlett Packard 5880-A gas chromatograph at the end of each chromatogram to enable the transfer of data from the chromatograph to the MACSYM storage.

5.) Four Point CO Monitor: This task monitors the Inter-scan Four Point Carbon Monoxide Monitor installed in the plant. The task senses the location being monitored and after waiting for the monitor to stabilize, reads a voltage convertible to CO concentration. The voltage is averaged and recorded as with the other signals.

6.) Data Transfer over the Telephone: This task allows the MACSYM 350 to emulate a normal computer terminal and to send the data accumulated on floppy disk over the phone lines to the VAX computer. This task operates without affecting the other tasks.

4.6 Product Gas Dust Sampling

In the fixed-bed gasifier, the air flow passing through the coal bed entrains coal and ash particles as it flows vertically upward. In addition, coal dust is generated near the top of the retort as coal is fed into the retort and distributed by an agitator. Preliminary estimates suggested that coal and ash particles would be in the 20 to 500 micron diameter range. A sampling system was therefore designed to collect representative samples of the particles for size distribution and chemical composition analyses.

The sampling location is shown in Figure 4-3. The particle sampling system consists of a sampling probe, a cooling coil for reducing the gas temperature, two bubblers to remove condensed tar droplets, a final filter, and a sampling pump with a valve and flowmeter. Figure 4-4 is a schematic diagram of the particle sampling probe nozzle. The probe may be inserted into the retort through the retort access ports on the top of the gasifier, through an access port on the top of the offtake elbow leaving the retort, or through a port downstream of the cyclone.

Figure 4-3

Product Gas Dust Particle Sampling Location

Figure 4-4
Product Gas Dust Particle Sampling System

4.7 Quench/ESP Exhaust Sampling

Figure 4-5 shows a schematic diagram of the quench/ESP exhaust tar particle sampling system. It is installed immediately downstream of the quench/ESP in the horizontal 8 inch discharge pipe, which is accessible via the permanent scaffolding. The system consists of an isokinetic sampling probe, a high efficiency filter, a condenser trap and a flow measuring-transport system.

The sampling probe is in the form of a 0.25-inch tube connected to a 0.5-inch elbow. The expanded tube diameter through the bend minimizes the particle loss in the elbow. A ball valve is connected to the sampling tube outlet for positive shut off of the sample gas during filter change. A similar arrangement is set up for the return gas port. By returning sample gas back to the main gas stream, the closed loop system prevents oxygen from entering the 8-inch discharge duct during a malfunction. In addition, should the first sampling tube become plugged, the sampling system could be moved down to the return port, which is kept clean by the flow of the clean sample gas and by facing away from the gas flow. The return tube is easily rotated 180-degrees so that it can quickly be converted into a new sampling inlet.

The tar particles are collected by a high efficiency glass fiber filter (MSA Ultra Filter). Since the gas exiting the Quench/ESP is saturated with water vapor, heater tapes are used to wrap around the sampling tube and the filter holder to prevent condensation from occurring upstream of the filter. A liquid condenser is installed downstream of the filter holder to capture the water and the light oil in the sampled gas stream. The condenser is water-cooled and serves two functions. First, by removing water from the gas stream condensation is prevented in the flow orifice and the vacuum pump. Second, the condensate collected enables the water and oil content in the gas stream to be calculated. The sampling flow rate is determined by measuring the pressure difference across an orifice. A rotameter with a needle valve provides an approximate flow rate and flow control. The sample gas is returned back to the main gas flow with a diaphragm pump.

Figure 4-5
Quench/ESP Exhaust Tar Particle Sampling System

SECTION 5

TEST PROCEDURES

5.1 Test Teams

Overall administration of the facility is performed by the Program Manager and directed from the Black, Sivalis & Bryson, Incorporated (BS&B) main headquarters in Houston, Texas. On site facility operations are directed by the facility manager. These include local staffing, training, facility maintenance, subcontract coordination, test planning and the conduct of testing. Administration of the monitoring systems is provided by faculty from the Mechanical Engineering Department of the University of Minnesota.

5.1.1 Gasifier Operation and Overall Coordination

The gasifier operations team is organized by BS&B and consists of the facility manager, facility engineers, three employees as shift lead operators, and additional helpers employed through a local temporary employment agency. The gasifier is staffed with a lead operator and two helpers for three eight hour shifts each day from start-up to termination of each test.

The gasifier operations team is responsible for overall operation of the gasifier and associated process equipment, and coordination of the test teams. This includes: gasifier start up, coal gas handling and incineration, flue gas cleanup, coal addition and sample collection, fire bed monitoring, process equipment maintenance and repair, operation of the boiler, changes in process conditions, sampling of waste water streams, and measurement of retort temperature and pressure profiles.

5.1.2 Gasifier Monitoring

The gas sampling and data retrieval/monitoring team is organized by the University of Minnesota, Particle Technology Laboratory, and consists of persons with individual responsibility for:

- 1) sample gas cleanup
- 2) gas chromatograph
- 3) continuous gas analysis and SIGMA continuous calorimeter
- 4) data acquisition system
- 5) safety evaluation

and such equipment operators as are necessary. One or two people per shift staff the monitoring systems, and are trained in the operation of all equipment. The monitoring

systems are staffed 24 hours per day.

The monitoring team is responsible for recording continuous process signals, operation of the gas chromatograph and continuous gas analysis equipment, operation of the gas sampling and conditioning system, collection and analysis of tar and oil samples, analysis of coal and cyclone dust samples, product gas dust measurements, and quench/ESP efficiency determinations.

5.1.3 Stack Gas Sampling

Interpoll, Incorporated, Circle Pines, Minnesota, a subcontractor to the University of Minnesota, provides a two man team for sampling the combustor emissions. This is done once during each test.

5.1.4 MIFGa Cooperators

From time to time MIFGa members send personnel to the test site to collect information of particular interest to the companies. This has included collection of tar/oil samples, combustion chamber flame profiles, coal, ash, and dust samples for additional analyses, etc. The results from these efforts are reported along with the information collected by the operating, monitoring, and stack sampling teams.

5.2 Sampling and Data Acquisition Procedures

5.2.1 Continuous Data

The computer data acquisition system has been described in detail in Section 4.5. In summary, the continuous transducer signals are normally read by the MACSYM computer once per minute scanning each channel 10 times. Every 10 minutes, the computer computes the average of the 10-minute data and stores the data on the 9-track tape or the floppy disk. Every 30 minutes, the computer prints the average of the three 10-minute averages and their conversion to engineering units on the line printer. The data stored on the tapes or disks are transmitted to the VAX computer via phone line daily. The final processing, data quality assurance, and graphical outputs are performed on the VAX computer. During periods when gasifier transients are being investigated, the continuous signals are sampled every 10 seconds and 90 second averages of the signals are recorded.

5.2.2 Gas Analysis Data

The continuous gas analyzers are operated during the entire test period and calibrated daily according to the manufacturers' recommendations. Analyzer readings are

logged by the data acquisition system along with the continuous data.

The HP 5880A gas chromatograph measuring major gas species is operated on-line. The HP 5793A gas chromatograph measuring sulfur species is operated on samples obtained from a manifold in the instrument room and injected by hand. These samples were obtained downstream of the entire gas sampling and conditioning system. This may produce some loss of sulfur species, but preliminary experiments suggest these losses are negligible.

5.2.2.1 Calibration of the NDIR CO and CO₂ Analyzers

The Beckman 864 CO and CO₂ infrared analyzers are tuned, linearized, and calibrated according to the manufacturer's recommendations. They are set to operate on the 0-5V output scale.

Calibrations are performed at ambient pressure with the sample flows through the instruments set to about 750 ml min. Ultra-pure N₂ is used as a zero gas. Both high and low span gases are used to calibrate the instruments. The high span is used to set the sensitivity and the low span is used to check the linearity once the sensitivity is set. High span gases near the normal gasifier offgas concentrations are used for tests subsequent to BOM/FGT-004. This is done to minimize the effect of a slight lack of linearity detected during the first three tests. Both the CO and CO₂ analyzers show a departure from linearity. The effect is much less severe with the CO₂ analyzer. The CO₂ analyzer suffers from a slight CO interference. Effective span gas concentrations are determined taking this into account.

5.2.2.2 Calibration of Oxygen Analyzer

This analyzer was set-up and calibrated according to the manufacturer's instructions. Two ranges were used: 0-1% and 0-10% O₂. Three calibration gases were used: ultra pure nitrogen zero gas, 0.91% oxygen in nitrogen low span gas, and 9.07% oxygen in nitrogen high span gas. Most gases are slightly diamagnetic and give a small negative interference with this type of instrument. Oxygen equivalent of the zero, low span, and high span gases were calculated to be -0.358%, 0.555%, and 8.75%, respectively.

The instrument normally is operated and calibrated on the 0-10% range using a sample flowrate of 250 ml/min. The first step of the calibration process consists of connecting zero gas to the instrument and adjusting the zero control to give a reading of -0.358%. Next the high span gas is connected and the span control was adjusted to give a reading of 8.75%. This process is repeated until no

further change in either the zero or span is required. The low span gas is occasionally used to check the linearity of the instrument. The difference between the observed and expected reading is always less than 0.1%.

5.2.2.3 Calibration of the SIGMA Calorimeter

Calibration of the SIGMA calorimeter is performed using three gases covering the range of bulk compositions and heating values expected for the gasifier offgas. The lower heating values of the gases range from 126 to 175 Btu/scf. Initial calibration consists of connecting the middle heating value gas to the calorimeter, lighting it, allowing it to stabilize, and then adjusting the linkage to give the correct reading on the pen recorder. The voltage output at this condition is recorded. Then voltage outputs for the other two span gases are measured and a calibration curve established. No adjustments are made to the instrument during subsequent calibrations, instead, a new calibration curve is determined.

5.2.2.4 Gas Chromatograph Calibration

The HP-5880A chromatograph is calibrated using multi-component gas mixtures. The standard calibration gas is a mixture of oxygen, carbon monoxide, carbon dioxide, hydrogen, methane, ethane, ethylene, propylene, propane, and nitrogen at concentrations representative of gasifier offgas. Another calibration mixture with the concentrations of all of the species except nitrogen increased by about 50%, and the nitrogen correspondingly reduced, is used to check the linearity of the detectors.

The integrator/controller can be used in conjunction with four different calibration methods: the area % method, the normalized % method, the internal standard method, and the external standard method. Standard procedure for these tests is to use the external standard method. This method does not normalize the sum of the mole or mass fractions to 1.0. Thus each species is treated independently and errors in one do not influence any other composition report.

The instrument has the capability of doing non-linear multi-level calibrations. However, comparisons between calibrations made with the standard and high concentration gas mixtures do not reveal any significant departures from linearity for either of the detectors. Consequently, routine calibrations are single-level using the standard concentration gas mixture.

Whenever possible, calibrations for the HP 5880A are performed daily during the gasifier tests. Several recalibration options are available. Normally, a new set of calibration factors is determined at each calibration. Alter-

natively, either cumulative or sliding average calibration factors may be established.

The HP 5793A sulfur chromatograph is calibrated with hydrogen sulfide span gas. The calibration gases are 535, 1000, 1505, and 2000 ppm H₂S in N₂. The detector response is found to be nonlinear following essentially a square law response. (Peak area is proportional to the square of concentration.) The sensitivity to sulfur atoms in other species is assumed to be the same as for H₂S. Calibrations are performed at the beginning and end of each test.

5.2.3 Tar/Oil/Water Yield Data

The condensed material from the gas sampling and conditioning system is drained at regular intervals during each test. During BOM/FGT-001 to -003, the condensed liquid was drained every shift. The drain frequency was reduced to twice daily for BOM/FGT-004 and then reduced to once a day during the remaining tests. The condensed material is drained from three different reservoirs: the liquid condenser, the ESP, and the refrigeration unit. Typically, the liquid condenser material contains mostly water with about 15% tar. The ESP material contains mostly tar and light oil with varying amounts (10-30%) of water which is dependent on the condenser operating temperature. The refrigeration material contains mostly water with a minute amount of light oil. The total volumetric gas flow through the system for each drain period is recorded by the dry gas meter located downstream of the dessicator. This then allows the condensed material yields per unit dry gas volume to be calculated.

The total "tar" and "water" yields are determined on-site by the monitoring team. The following procedures are used:

1. Water (clear liquid) from the liquid condenser and the ESP is decanted and combined with the liquid in the refrigeration unit.
2. The remaining "tar" from the liquid condenser drain is combined with the ESP tar.
3. The "combined tar" is analyzed for its moisture content using ASTM method D 95-70 to determine the net dry tar yield on a daily basis.
4. Three samples each of the "water" and "tar" for each test are sent for analysis. The "water" sample is analyzed for total organics. The "tar" analyses include heating value, ultimate analysis, specific gravity, flash point, pour point, viscosity and water by distillation. Analyses are performed by Interpoll, Inc., Circle Pines, Minnesota.

5.2.4 Solids Data

This section describes the procedures to be followed for the collection, preparation and analysis of the coal, ash, and cyclone and duct dust samples. The analytical tests used to characterize the physical and chemical properties of each material are then presented. A list of the analytical tests are given by the type of material in Table 5-1.

The basic test objective for sample collection is to collect several bulk material samples each shift so that in addition to accurate composite averages of the material properties, subtle changes in coal and ash properties can be detected. These changes can then be correlated with the gasifier operating conditions and producer gas characteristics. Another consequence of frequent material analyses is that sufficient data can be obtained to determine the degree of variability in the coal and ash properties.

A second objective involves characterizing the coal size distribution at various places in the feed system. One area of interest is the source of the fine particles in the coal as fed to the retort.

Chemical analyses of coal and dust are performed by Interpoll, Inc., Circle Pines, Minnesota. Chemical analyses of ash are performed by the Bureau of Mines, Twin Cities Research Center.

5.2.4.1 Coal

Representative samples of the feed coal are obtained by the operating team. One composite sample for each shift is obtained by collecting a sample of coal four times per shift. The coal samples are accumulated in 3-gallon plastic pails during each shift. The containers are sealed. Consequently, three 3-gallon samples are collected every 24 hours. The quantity of coal collected for each shift sample ranges from 8000 to 9000 gm.

The particle size distribution of the entire quantity of material collected in each sample is determined using a dry sieving process. The coal is size classified into six size fractions using a Gilson testing screen and U.S. series square meshes. The mesh sizes of the wire cloth sieves used in the Gilson screen are 1/4, 1/2, 3/4, 1 and 1 1/2 inch. The vibration time used for particle classification is 15 sec. The total mass of each bulk sample is also measured before and after the test to determine the magnitude of particle loss associated with the analysis procedure. After analysis, a representative coal sample

Table 5-1

Analytical Tests Performed on Solid Materials

Material	Type of Analysis
Coal	Particle size distribution Proximate analysis Ultimate analysis Heating value Ash fusion temperature Free swelling index
Ash	Particle size distribution Bulk density Moisture content Carbon content Sulfur content Chemical analysis
Cyclone dust	Proximate analysis Ultimate analysis

is obtained by using a splitter for the division of the sample. Each sample is individually stored in a sealed plastic bag to prevent the loss of moisture.

Detailed chemical analysis of the coal is performed on samples which are composites of coal from several shift samples. The samples are composited on either a 24-hour (3 shift) basis or over time periods when coal with similar particle size distributions were fed to the retort. At the completion of the gasifier test, a 250 gm sample is obtained from each shift sample and composited. The composite samples are resealed in plastic bags and submitted for detailed chemical analysis.

In addition to the coal samples collected on a per-shift basis from the coal weigh bin, coal samples are collected at the feed to and the discharge from the screen. These samples are collected for only a select number of tests when there appeared to be a significant fraction of fine particles in the coal as fed to the retort. These samples are collected periodically at each point. The quantity of coal collected and the procedure used to obtain the particle size distribution are equivalent to that described for the coal weigh bin samples. These samples, together with those collected in the weigh bin, are used to trace the size distribution for the coal through the coal handling system. In particular, the fraction of fine particles in the coal as fed to the gasifier resulting from carryover from the screen versus that which results from coal breakage during transport to the weigh bin are determined.

5.2.4.2 Ash

A "dry" ash sample is collected by the operating team in 1-gallon plastic pails each time the ash is dumped from the ash bin. This sample is collected before the bin is flushed with water. (See Section 3.5) The quantity of material collected ranges from 1200 to 2000 gm.

For each ash sample, the bulk density, particle size distributions, and carbon, sulfur and moisture contents of the ash are determined. The moisture content is determined by comparing the sample weight obtained after drying the sample in an oven for four hours at a temperature of 215 F to the weight of the sample obtained immediately after the ash dump. The bulk density of the dried ash sample is obtained by determining the mass of ash which can be placed in a cylindrical container of known volume. The particle size distribution is obtained using the same procedure used for the coal analysis. The mesh sizes of the wire cloth sieves are 1/4, 1/2, 3/4, 1 and 2 inch. A vibration time of 5 sec is used to classify the particles on the Gilson screen.

The carbon and sulfur content of each ash sample is determined using specially prepared samples. A representative ash sample is obtained using a splitter for the division of the sample. This representative sample is then crushed, milled and sieved through a 100 mesh screen. A 50 gm sample of sieved material is submitted for carbon and sulfur analysis.

Detailed chemical analysis of the ash is obtained by compositing the samples over the same time periods that the coal samples are composited. The composited ash samples are obtained by combining 4 gm of the sieved ash from each bulk ash sample which has been prepared in the same manner as used to obtain the samples used for carbon and sulfur analysis.

5.2.4.3 Cyclone and Duct Dust

Samples of the dust collected by the cyclone are collected on a daily basis by the operating team. Water content of these samples is artificial as they are wetted by the process. Hence these samples are dried and composited to obtain one composite sample of each material for the entire test period. A portion of each composite sample is submitted for proximate and ultimate analyses.

5.2.5 Combustor Emissions Measurements

The stack emission measurement is performed by Interpoll, Inc., under a subcontract from the University of Minnesota. Most of the testing in this work was performed at the combustion chamber outlet, however, flow determinations were performed at the forced draft fan outlet to allow assessment of the combustion air usage and in the stack to ascertain the total volumetric flow rate of the combustion products.

Particulate and sulfur dioxide determinations are performed in accordance with EPA Methods 1-6, CRF Title 40, Part 60, Appendix A (Revised July 1, 1982). A preliminary determination of the gas velocity profile is made before the first particulate run to allow selection of the appropriate nozzle diameter required for isokinetic sample withdrawal. An Interpoll sampling train which meets or exceeds specifications in the above-cited reference is used to collect particulate samples by means of a heated stainless steel-lined probe. A single diameter traverse is used in this work due to the high cost of installing a second test port at 90 degrees to the existing port.

The back half of the EPA Method 5 particulate sampling train is used to collect sulfur dioxide samples. This is the large impinger version specified in EPA Method 6 and

provides for a complete stack traverse during sample collection. Collected sulfur dioxide samples are returned to the laboratory for sulfate analysis by the standard barium/Thorin I titration technique.

Nitrogen oxides are measured by means of a Monitor Labs chemiluminescent nitric oxide analyzer. Nitric oxide concentrations are read at each traverse point in the particulate determination. The nitric oxide concentrations are determined on a dry basis using the exhaust gas stream from the EPA Method 5 sampling train. (Nitrogen oxide concentrations are for comparison only as the samples are withdrawn through a hot stainless steel tube which may result in partial decomposition of the nitrogen oxides.)

An integrated flue gas sample is extracted simultaneously with each particulate and sulfur dioxide sample using a specially designed gas sampling system. Integrated flue gas samples are collected in 44-liter Tedlar bags. After sampling is complete, the bags are sealed and returned to the laboratory for Orsat analysis. The integrity of the sample bags is insured by reading the oxygen concentration of the bag in the field immediately after sampling and again in the laboratory immediately prior to Orsat analysis using a Teledyne Model 320P oxygen analyzer.

Testing at the combustion chamber outlet test site is conducted from one test port on the combustion chamber outlet duct. Each traverse point is sampled five minutes to give a total sampling time of 60 minutes per run.

5.2.6 Combustor Flame Profile Sampling

The composition profiles of the coal gas flame in the combustion chamber were measured during BOM/FGT-001 and BOM/FGT-003. Gas samples are withdrawn from the combustion chamber through the side ports and a small port in the elbow at the end of the combustion chamber. Gas samples from various locations in the combustion chamber are removed through a 1/4 inch stainless steel tube (un-cooled) and filtered before being sent to the analyzer. Combustibles and oxygen are measured by a combustion analyzer. Carbon monoxide, nitrogen oxides, hydrogen sulfide, and sulfur dioxide values reported are measured by drawing fixed volume samples through "Dreger" tubes and observing the extent of color changes.

5.2.7 Retort Pressure and Temperature Profiles

Vertical temperature and pressure profiles in the retort are collected at selected times by the operating team. The pressure profiles are measured from a 1/2 inch schedule 40 steel pipe with a 1/8 inch hole drilled into the closed bottom. The pipe is inserted into the retort

through a retort access port on the top of the gasifier all the way to the grate. The pipe is connected to a differential pressure gauge. As the pipe is retracted from the grate up the retort the pressure differential between the gas in the retort and the ashpit is recorded at 6-inch intervals. Approximately 5 - 10 minutes is required to record one full temperature profile.

A similar scheme is used to measure the temperature profile. The temperature probe is constructed of 1/2 inch schedule 40 304 SS pipe. Six sheathed, type K thermocouples are mounted inside the pipe at six-inch intervals beginning at the bottom. The junction temperatures read out on a mechanical multipoint recorder. In order to obtain temperatures at various levels in the retort, the temperature probe is inserted to at least two different depths. The probe is retracted from the retort if any junction reads 2400 F (the temperature limit of the materials of the probe). This does not allow detailed measurements in the combustion zone of most fuels. Approximately 30 minutes is required to read temperatures at 3 probe positions in the retort.

5.2.8 Product Gas Dust Sampling

Particle concentrations and size distributions in the product gas are measured at selected times and gasifier operating conditions beginning June 1983. The sampling probe is allowed to equilibrate thermally with the offgas before sampling begins. The sampling flowrate is adjusted to near isokinetic conditions to minimize sampling errors. The particles entering the inlet are collected by impaction, by the glass wool, or by the final filter. Sampling times range from 1 to 2 minutes.

After collection the particles are sized by optical microscopy and wet sieving and analyzed chemically by x-ray spectrometry.

5.2.9 Quench/ESP Efficiency Sampling

Isokinetic sampling conditions at the sample nozzle are established and a sample of the quench/ESP exhaust is withdrawn for a specific period of time. The flow of gas and its temperature are used to calculate the total gas sampled. The filter is weighed before and after the run to determine the weight gain over a certain time period. The tar loading upstream of the ESP can be calculated from the tar yield data obtained at the gas sampling and conditioning system. The loading at the upstream and the downstream of the ESP then enable the ESP efficiency to be calculated.

5.2.10 Freeboard/Firetest Data

Data on the physical condition of the coal bed in the retort are taken periodically by the operating team. Two parameters are measured: the freeboard and the firetest. Both measurements are taken through the seven retort access ports on the top of the retort. These measurements are used to calculate the thickness of the ash layer, and the thickness of the coal layer.

The freeboard measurement is taken hourly at two retort access ports 180 degrees apart. The specific ports are rotated from hour to hour. If conditions dictate, it is taken more often. The freeboard measurement is made by inserting a steel ruler into the retort and measuring the distance from the top of the coal bed to the top of the retort access ports. If the agitator is being used, the measurement is made when the agitator is crossways to the port being used.

The firetest measurement is taken at all retort access ports every two hours, and occasionally more often if conditions dictate. The measurement is taken by inserting 3/4 inch solid steel rods into the retort all the way to the grate. The rods are left in the coal bed from 2 to 5 minutes depending on the temperature in the combustion zone. The bars are then retracted. An incandescent zone normally appears on the bars. This zone is heated by the combustion zone in the retort. Below the incandescent zone the bar is in contact with the relatively cool ash and is not incandescent. The distance from the tip of the bar to the beginning of the incandescent zone is a measure of the thickness of the ash zone.

With the low rank coals excessive time is required to heat the bars to incandescence. The bars are retracted before this can occur, and the beginning of the hot zone is detected with a piece of rubber or leather.

SECTION 6

CALCULATION AND DATA ANALYSIS PROCEDURES

6.1 Data Retrieval and Analysis

Data logged by the MACSYM 350 is transferred over the phone to the VAX computer. Data logged by the MACSYM 2 is written on 9 track tape which is hand carried to the VAX computer. The data is assembled and reformatted after each test to allow final processing. Four major software groups have been developed for this processing.

1. Software for processing the continuous output transducer data: The continuous data are recorded as transducer voltages. These voltages are converted to their respective engineering quantities using the latest calibration information. The converted values are proofread, averages are taken, and various forms of output are made.

2. Software for processing the gas chromatograph data: The chromatograph data are retrieved as molar percents. Processing the data consists primarily of proofreading each chromatograph run and editing where necessary. Various forms of output are made.

3. Software for material balance and thermal efficiency calculation: The material balance and thermal efficiency program uses transducer and chromatograph data as well as some data from the operator's log to evaluate the performance of the gasifier. The program is described more fully in Section 6.2.

4. Graphics: The continuous output transducer data and the chromatograph data are plotted in various formats using a graphics package developed specifically for this data. This graphics package is Plot-10 based and implemented on the VAX computer.

6.2 Material Balance and Thermal Efficiency Calculations

Material balance and thermal efficiency calculations are performed over several selected periods during each test. The details of the computer program for performing the calculations are described in Appendix C. The input data consist of computer acquired data for the continuous output transducers and the gas chromatograph averaged over the selected periods, several manual entry data for the solid materials flow and their physical and chemical properties, and a few other quantities not recorded continuously by the computer. The calculation results include a

detailed material balance and energy balance around the gasifier and several key performance data. An example of the balance calculation is included in Appendix C. The calculation procedures are summarized below.

6.2.1 Input Data

In general the input data include the gasifier process data, coal ash, tar and dust composition data, gas composition, and tar and water yields. All but the cyclone dust yield is the actual data averaged over the period. The cyclone dust weight cannot be measured accurately using the existing collection technique. Estimates are made on the basis of product gas particle sampling when these results are available.

The input parameters describing the gasifier operation are the coal feed rate, blast air flow, blast saturation temperature, import steam temperature and flow, cooling water temperature and flow, ash yield, and the product gas temperature. The coal feed, import steam data, ash yield, and the cooling water flows are obtained from the operating team's manual logs. The remaining data are taken from the computer-logged data files.

The coal, ash, tar and dust composition data included in the balance calculations are the carbon, sulfur, ash, and nitrogen fractions, the moisture content and the heating value (as received).

Dry gas composition obtained by the gas chromatograph is listed. Also shown is the calculated argon concentration and the hydrogen sulfide concentration expected if all the sulfur in the gas was hydrogen sulfide. Both calculated concentrations are achieved by elemental balance. The calculated values for the molecular weight and HHV are also listed. It should be noted that several minor species, such as the higher order hydrocarbon gases were not measured. However, they do not contribute significant errors as the total molar percent reported here is generally around 99%.

Tar and water yield data are available on a daily basis. Condensed material from the gas sampling and conditioning system are separated into tar and water fractions as described in section 5.2.3. Moisture free values are given for both the tar yield and HHV.

6.2.2 Calculation Results

The calculation results include detailed material balance, detailed energy and performance data. Calculations are performed assuming nitrogen and carbon elemental conservation around the gasifier. Since coal bin weight is calibrated to a greater accuracy than the flowmeter calibration

tion, the measured coal rate averaged over the time period of interest is assumed to be correct. Mass flow of dry coal gas is calculated by assuming all carbon in the coal goes to the ash, the dust carry over, tar, and the dry gas. The saturation air flow is then calculated assuming all nitrogen in the coal gas comes from the coal and the saturation air. (Calculations correspond closely to blast air flow measurements when recent air flow calibrations are used.) The total water input into the retort is calculated assuming the blast air is saturated with steam at the blast saturation temperature. Calculation of the steam energy input includes only steam imported from the boiler. Steam contributed by the water jacket is accounted for internally.

Four thermal efficiencies are given in the last section, namely, cold gas efficiency, cold gas with tar efficiency, hot gas without tar efficiency, and hot gas with tar efficiency. The efficiencies are obtained by taking the ratio of the heat content of the desired output quantity to the heat content of the total input stream. The input stream consists of heat contribution from coal, air and steam. Therefore, the four efficiencies can be calculated using the following equations:

$$\text{Efficiency (cold dry gas)} = H_g / (H_c + H_a + H_s + H_w)$$

$$\text{Efficiency (cold gas with tar)} = (H_g + H_t) / (H_c + H_a + H_s + H_w)$$

$$\text{Efficiency (hot gas w/o tar)} = (H_g + S) / (H_c + H_a + H_s + H_w)$$

$$\text{Efficiency (hot gas with tar)} = (H_g + H_t + S) / (H_c + H_a + H_s + H_w)$$

H_c = heat content of coal

H_g = heat content of cold dry gas

H_t = heat content of oil and tar

S = sensible heat of producer gas

H_a = heat content of air

H_s = heat content of steam

H_w = heat content of cooling water

6.3 Tar/Oil Yield Correlations

The gas sampling and conditioning system described in section 4.3 provides quantitative measurements of the tar/oil content of the raw product gas in lb/1000 dry scf gas. The average tar/oil contents of the product gas over an entire test are used to calculate the yield of tar/oil in lb/100 lb coal input. These tar/oil yields are then compared to correlations based on the Fischer-Schrader Carbonization Assay (USBM (1967), Selvig and Ode (1957)). The tar/oil yields are compared against correlations offered by Ode and Selvig (1944) and Gomez et al (1958). Graphs showing the assay correlations are presented in Figure 6-1.

Figure 6-1
Tar/Oil Yield Correlations

Reference: Ode and Selvig (1944)

Reference: Gomez et al (1958)

6.4 Grate Performance Model

A simple grate performance model has been developed to calculate the ash removal rate from the gasifier. The model is based entirely on the gasifier geometrical considerations. It has been shown to predict the general pattern of ash removal rate as a function of the grate speed. This model can be used as a basis for developing a more sophisticated model in which the coal and ash properties and the gasifier operating conditions will also be considered.

Figure 6-2 shows a schematic diagram of the gas producer and the basic dimensions of the rotating eccentric grate. Ash is formed below the combustion zone. It is swept down to the ash cone by a set of parallel rotating eccentric grates with adjustable vertical spacings. The ash removal rate can be varied by either adjusting the grate rotating speed or by adjusting the vertical grate spacings.

An expression for the ash removal rate can be obtained by simple geometrical considerations as follows. As shown in Figure 6-2, r_1 and r_2 denote the minimum and the maximum distances from the producer axis to the outer edge of the top eccentric grate and r_3 and r_4 are those distances for the eccentric middle grate, respectively. h_1 and h_2 are the grate spacings between the parallel top and middle grate and the middle and the bottom grate. The volume of ash removed per revolution, V_o , is therefore:

$$V_o = \pi(r_2^2 - r_1^2)h_1 + \pi(r_4^2 - r_3^2)h_2$$

The maximum and the minimum gap distances between the producer inside surface and the eccentric grate outer edges have been measured as shown in Figure 6-2. The grate spacings are adjusted to various spacing heights depending on coal ash content and expected maximum throughput. The ash weight and density exiting the producer are measured. As described in Table 3-1, dry ash is first dumped and its weight, W_d , and bulk density, d and moisture content, C_w , are measured. The remainder of the ash is flushed with a measured weight of water, W_f and the total wet weight, W_w measured. The total dry ash volume removed during the period is then

$$V_o = (W_d + W_w - W_f) * (1 - C_w) / d$$

The grate rotation speed is logged by the operating team.

The above calculations allow the actual ash removal rate from the producer as a function of grate speed to be compared with the theoretical prediction.

Figure 6-2
Grate Performance Model Schematic

REFERENCES

- Ashworth, R. A., Vyas, K. C., Bonamer, D. G.; "Study of Low and Intermediate Btu Gas from Coal for Iron Ore Pelletizing" (Contract J0255021); USBM Open File Report 36-77, March 1977; NTIS PB 264-702 AS
- Andrews, R. D., Gray, D. A.; "Performance of Leucite Hills Coal in Fixed Bed Gasifiers"; AIChE Winter Meeting, Atlanta, Georgia, March 11-14, 1983
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 2 - Gasification of Jetson Bituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, June 1983a
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 3 - Gasification of Rosebud Subbituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, March 1983b
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 4 - Gasification of Leucite Hills Subbituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, June 1983c
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 5 - Gasification of Stahlman Stoker Bituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, September 1983d
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 6 - Gasification of Delayed Petroleum Coke"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, September 1983e
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 7 - Gasification of Piney Tipple Bituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, 1984a
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 8 - Gasification of Illinois #6 Bituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, 1984b
- BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 9 - Gasification of Elkhorn Bituminous Coal"; Draft

test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, 1984c

BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 10 - Gasification of Benton Lignite"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, 1984d

BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 11 - Gasification of Minnesota Peat"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, (in preparation) 1984e

BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 12 - Gasification of Absoloka/Robinson Subbituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, (in preparation) 1984f

BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 13 - Gasification of Blind Canyon Bituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, (in preparation) 1984g

BS&B; "Fixed Bed Gasification Research Using U.S. Coals - Volume 14 - Gasification of Kemmerer Subbituminous Coal"; Draft test report submitted to U.S. Bureau of Mines, Twin Cities Research Center by Black, Sivalls, and Bryson, Inc., Contract HO222001, (in preparation) 1984h

Dynecology; "Simplex Gasification in the Wellman-Galusha Gasifier" (Contract J0205070); USBM Final Contract Report, Dynacology, Inc.; June 30, 1982

Farnam, H. E., Jr.; "Energy Alternatives for the Taconite Industry"; Proceedings 49th Annual Meeting of Minnesota Section, AIME, and 37th Annual Mining Symposium; University of Minnesota, Duluth; 1976

Gomez, M., Goodman, J. B., Parry, V. F.; "General Properties of Low-Temperature Tar"; USBM Bulletin 569; 1958

Jones, F. L., Rick, N.; "Gasification of Western Coals - Fuels for Thought"; Institute of Gas Technology Symp, Advances in Coal Utilization Technology, Denver, Colorado; April 1981

Jones, F. L.; "Low-Btu Coal Gasification: Bringing Back an Old Workhorse"; Joint Power Generation Conference (ASME-IEEE); Denver, CO; October 17-21, 1982

Jones, F. L.; "Low Btu Coal Gasification: Yesterday's Industrial Fuel for Tomorrow"; 1983 Energy Sources Technology Conference and Exhibition, Houston, Texas; January 30 - February 3, 1983a

Jones, F. L.; "Low-Btu Gas - A Fuel for Industry"; 10th Energy Technology Conference and Exhibition, Washington, D.C.; February 28 - March 2, 1983b

Kilpatrick, M. P., Mage, R. A., Emel, T. E.; "Environmental Assessment: Source Test and Evaluation Report, Wellman-Galusha (Fort Snelling) Low-Btu Gasification"; Radian Corporation Final Report, USEPA Contract No. 68-02-2147, Exhibit A; DCN 80-218-143-116; 1980

Nigro, J. C.; "Firing an Iron Ore Pelletizing Furnace with Low-Btu Gas from Lignite"; USBM R.I. 8670; 1982a

Nigro, J. C.; "Use of Low-Btu Gas in Iron Ore Pelletizing"; Mining Congress Journal; August 1982b

Ode, W. H., Selvig, W. A.; "Low-Temperature Distillation Yields of Primary Tar and Light Oil from Coals of Various Ranks and Types"; USBM R.I. 3748; March 1944

PEDCO; "Testing and Evaluation of Stretford Technology for Coal Gasification Gas Stream Cleanup", Final Report; Pedco Environmental, Inc.; USEPA Contract No. 68-02-3173; May 1983

Selvig, W. A., Ode, W. H.; "Low Temperature Carbonization Assays of North American Coals"; USBM Bulletin 571; 1957

Thimsen, D., Pooler, A. R., Pui, D., Kittelson, D., Liu, B. Y. H.; "Synthetic Fuel Gas from Petroleum Coke - Performance in an Industrial Gasifier"; Energy Sources Technology Conference and Exhibition, New Orleans, Louisiana; February 12-16, 1984

Thimsen, D.; "Performance of U. S. Coals in an Industrial Air-Blown Gasifier"; Coal Technology '83 Proceedings. Volume IV, Industrial Applications, Houston, Texas; November 1983

USBM; "Methods of Analyzing and Testing Coal and Coke"; USBM Bulletin 638; 1967

Zahl, R. K., Nigro, J. C.; "The Use of Low-Btu Gas for Iron Oxide Pellet Induration: An Interim Report"; Symposium Proceedings: Environmental Aspects of Fuel Conversion Technology, IV, Hollywood, Florida; April 1979; EPA-600/7-79-217; September, 1979

APPENDIX A
SAMPLE DATA SHEETS

The following Sample Data Sheets are included:

1. Hand Logged Continuous Data (also logged by computer)
2. Hand Logged Continuous Data (not logged by computer)
3. Coal Addition Log
4. Ash Removal Log
5. Firetest Log
6. Freeboard Log
7. Retort Temperature and Pressure Profile Log

OPERATOR DATA LOG # 2

Shift 1 _____ Shift 2 _____ Date _____
Shift 3 _____

	BLAST AIR INLET		SATURATION AIR INLET		JACKET AIR EXHAUST		ASHPIT AIR INLET		JACKET WATER		AGITATOR WATER		COAL LEGS		SATURATION STEAM		OFFTAKE TEMPERATURE		CYCLONE GAS OUTLET		VENTURI GAS DISCHARGE		BURNER INLET		COMBUSTOR TERMINUS		COMBUSTOR DISCHARGE		SCRUBBER INLET		SCRUBBER SIEVE DISCHARGE		SCRUBBER DISCHARGE		SATURATION TEMPERATURE		BLAST AIR FLOW		RETORT PRESSURE			GAS SUPPLY PRESSURE		FURNACE PRESSURE		FLAME HOLDER AIR FLOW		GAS LINE BACK PRESSURE																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
	T-700		T-702		T-703		T-704		T-710		T-711		T-712		T-713		T-714		T-715		T-716		T-717		T-718		T-719		T-720		T-721		T-722		T-723		T-724		CFM		InWC		InWC		InWC		InWC		T-725		T-726		T-727		T-728		CFM		CFM		PIC702																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		
	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	Deg.C	CFM	InWC	InWC	InWC	InWC		CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM	CFM

Hand Logged Continuous Data (also logged by computer)

Hand Logged Continuous Data (not logged by computer)

OPERATOR DATA LOG No. 1

PAGE 1 OF 2

TEST 308/167_____

35197 (1) _____
(2) _____
(3) _____

DATE _____ COAL TYPE _____

[illegible]

OPERATOR DATA LOG No. 1

PAGE 2 OF 3

TEST 302/167

58177 (1) _____
(2) _____
(3) _____

DATE _____ COAL TYPE _____

[illegible]

COAL TYPE ELKHORN (ANR)

[illegible]

COMMENTS _____

Ash Removal Log

COAL GASIFICATION SYSTEMS
TWIN CITIES OPERATIONS
GASIFIER ASH

Test No. BOM/FGT-008

Page _____ of _____

[illegible]

Firetest Log

FIRE TEST

TEST NO. _____

COAL TYPE _____

DATE _____

[illegible]

COMMENTS: _____

Freeboard Log

FREEBOARD HEIGHT

DATE _____

TEST BOM/FGT 008

COAL TYPE ELKHORN (ANR)

[illegible]

COMMENTS: _____

Pressure and Temperature Probe Log

Temperature and Pressure Probing Data Sheet

TEST: BOM/FGT- _____

OPERATORS: _____

DATE: _____

Bar Indication	Height above Grate (inches)	P - Pash (inwg)	Temperature (deg F)
120	0	_____	_____
114	6	_____	_____
108	12	_____	_____
102	18	_____	_____
96	24	_____	_____
90	30	_____	_____
84	36	_____	_____
78	42	_____	_____
72	48	_____	_____
66	54	_____	_____
60	60	_____	_____
54	66	_____	_____
48	72	_____	_____
42	78	_____	_____
36	84	_____	_____
30	90	_____	_____

TIME: _____

SAF: _____

ASHPIT _____

Temp: _____

Press: _____

OFFTAKE _____

Temp: _____

Press: _____

FIRETEST: _____

FREEBOARD: _____

APPENDIX B

SAMPLE OUTPUT FROM DATA ACQUISITION SYSTEM AND GAS CHROMATOGRAPHS

Included are:

1. Hard copy computer output available during the test.
2. Sample chromatogram from HP 5880A chromatograph.
3. Sample Chromatogram from HP 5793 chromatograph.

Hard Copy Computer Output

AVERAGE READINGS FOR THE PERIOD 9 /16 10 :43 TO 9 /16 11 :20

SIGNAL ID	AVERAGE READING	UNITS	PERIOD LOW	PERIOD HIGH	STANDARD DEVIATION	AVG VOLTAGE
T-701	12.40E+00	DEG C	99.95E-01	15.04E+00	25.33E-01	-26.87E-05
T-702	23.97E+00	DEG C	22.57E+00	26.52E+00	22.14E-01	17.74E-05
T-703	61.03E+00	DEG C	58.88E+00	63.99E+00	26.52E-01	17.80E-04
T-710	23.50E+00	DEG C	17.66E+00	27.39E+00	36.62E-01	17.88E-05
T-711	72.17E+00	DEG C	70.29E+00	73.70E+00	17.33E-01	22.50E-04
T-712	21.47E+00	DEG C	20.75E+00	22.52E+00	92.46E-02	98.03E-06
T-713	31.02E+00	DEG C	30.23E+00	31.61E+00	71.46E-02	48.66E-05
T-705	45.54E+01	DEG C	45.16E+01	46.23E+01	59.70E-01	17.98E-03
T-706	41.31E+01	DEG C	40.93E+01	41.76E+01	41.92E-01	16.18E-03
T-707	38.92E+01	DEG C	38.56E+01	39.27E+01	35.76E-01	15.17E-03
T-812	11.10E+02	DEG C	10.84E+02	11.32E+02	24.37E+00	44.75E-03
T-813	10.50E+02	DEG C	10.25E+02	10.71E+02	23.28E+00	42.46E-03
T-814	-99.99E+02	DEG C	-9999.	-9999.	00.00E+00	-9999.
T-815	11.85E+02	DEG C	10.66E+02	13.78E+02	16.85E+01	47.41E-03
T-816	-99.99E+02	DEG C	-9999.	-9999.	00.00E+00	-9999.
T-817	90.27E+01	DEG C	88.55E+01	91.98E+01	17.14E+00	36.67E-03
T-818	-99.99E+02	DEG C	-9999.	-9999.	00.00E+00	-9999.
T-819	87.02E+01	DEG C	85.41E+01	88.63E+01	16.09E+00	35.36E-03
T-820	73.86E+01	DEG C	73.03E+01	74.75E+01	65.88E-01	29.96E-03
T-823	68.11E+00	DEG C	67.68E+00	68.44E+00	39.43E-02	20.25E-04
T-822	69.65E+00	DEG C	69.24E+00	69.93E+00	36.40E-02	20.88E-04
T-806	31.77E+01	DEG C	31.06E+01	32.73E+01	86.36E-01	12.17E-03
T-811	10.59E+02	DEG C	10.41E+02	10.76E+02	17.88E+00	10.15E-03
F-701	11.90E+02	SCFM	11.11E+02	11.14E+02	20.69E-01	15.68E-02
TI1-703	58.84E+00	DEG C	58.77E+00	58.96E+00	10.21E-02	98.98E-03
P-703	76.42E-01	IN WC	75.90E-01	76.83E-01	47.46E-03	12.17E-02
P-704	63.58E-01	IN WC	---	---	---	---
P-705	12.03E-01	IN WC	12.77E-01	12.91E-01	74.97E-04	70.24E-03
P-706	97.71E-02	IN WC	97.28E-02	98.53E-02	71.25E-04	67.76E-03
F-707	11.08E+02	SLFN	00.00E+00	00.00E+00	00.00E+00	66.37E-03
MI-720	58.56E-01	TONS	58.54E-01	58.58E-01	13.72E-04	58.56E-01
P-707	93.71E-02	IN WC	79.43E-02	11.90E-01	22.02E-02	87.25E-03
P-810	-45.42E-02	IN WC	-45.63E-02	-45.13E-02	25.94E-04	17.63E-02
F-802	59.59E+02	CFM	58.98E+02	60.60E+02	87.79E+00	40.11E-02
F-803	11.03E+03	CFM	10.61E+03	11.62E+03	52.44E+01	19.01E-02
TI2-703	58.71E+00	DEG C	58.62E+00	58.78E+00	10.13E-02	97.80E-03
C0	27.16E+00	Z	27.49E+00	27.49E+00	27.54E-02	13.58E-01
C02	53.94E-01	Z	53.53E-01	53.53E-01	63.63E-03	13.48E-01
U2	-68.16E-03	Z	-68.73E-03	-68.73E-03	37.68E-04	-34.08E-03
SIGMA	16.49E+01	BTU	16.50E+01	16.50E+01	12.27E-02	24.97E-01
T-715	15.45E+01	DEG C	15.39E+01	15.39E+01	27.67E-01	55.42E-04
T-821	54.18E+01	DEG C	54.55E+01	54.55E+01	86.57E-01	21.67E-03
T-703A	38.80E+00	DEG C	37.71E+00	37.71E+00	20.95E-01	81.30E-05
PM	-17.57E-04	PM	-24.41E-04	-24.41E-04	60.72E-05	-67.89E-05
AG VEL	73.42E-01	SPM	71.63E-01	71.63E-01	16.28E-02	73.42E-03
GR VEL	29.09E-01	RPM/T	29.08E-01	29.08E-01	19.83E-03	29.09E-02
P-702	---	IN WC	---	---	00.00E+00	19.91E-02
C0(1)	14.28E-01	PPM	33.22E-02	25.47E-01	84.56E-02	24.60E-05
C0(2)	15.94E-01	PPM	44.29E-02	26.57E-01	82.45E-02	27.46E-05
C0(3)	16.61E-01	PPM	11.62E-01	21.07E-01	46.54E-02	28.61E-05
C0(4)	18.49E-01	PPM	77.52E-02	25.47E-01	93.12E-02	31.85E-05

AVERAGE BASE TEMPERATURE 19.0394 DEG C

.000747106 VOLTS

COAL GAS KUN 8 6 SEPTEMBER 1983

HP 5880A Chromatogram

UNIVER. OF MINN. 6348-V.S. SOIL GASIFICATION PROJECT
CARRIER GAS--ARGON; FLOW RATE=23ML/MIN
INJECTION METHOD--GAS SAMPLING VALVE
DETECTORS--TCD-FID
REPORT # = 66

108

END 5880A VALVE # 1 INJECTION # 02125 SEP 26, 1963
COAL GAS ANALYSIS BY RINDI SMITH-AGENT
ESTD

RT	AREA	TYPE	CAL	AMOUNT	NAME	
2.69	134041.00	A	PV	1	METHANE	
3.49	32816.10	SV	2	5.793	CARBON DIOX	
4.69	19364.10	SV	3	0.424	ETHYLENE	
5.37	31937.00	SV	4	0.204	ETHANE	
8.65	17116.30	SV	5	5.407E-02	PROPYLENE	
9.28	14253.20	SV	6	5.349E-02	PROPANE	
10.79	1047800.00	SV	7	18.736	HYDROGEN	
11.64	240001.00	SV	9	43.012	NITROGEN	
12.32	130042.00	A	VB	10	20.013	CARBON MON

MULTIPLIER = 1

END 5880A VALVE # 1 INJECTION # 02125 SEP 26, 1963
AREA %

AT	AREA	TYPE	AREA %
2.69	134041.00	A PV	7.653
3.46	32816.10	SV	0.132
4.69	19364.10	SV	1.723
5.37	31937.00	SV	1.140
8.65	17116.30	SV	1.071
9.28	14253.20	SV	0.835
9.55	89.33	SV	0.005
10.79	22300.00	A SV	1.319
10.79	1047800.00	SV	61.391
11.64	240001.00	SV	14.432
12.32	130042.00	A SV	7.978

TOTAL AREA = 1700090.00
MULTIPLIER = 1

COAL GAS LOWER HEATING VALUE (IN BTU/FT3) = 161.116
COAL GAS HIGHER HEATING VALUE (IN BTU/FT3) = 172.883
COAL GAS MOLECULAR WEIGHT = 33.9677
AMOUNT OF HYDROGEN SULFIDE IN GAS (PPM) = 0
COAL GAS SPECIFIC GRAVITY (AIR=1.0) = 0.81421
MOLAR HYDROCARBONS = 2.1004
TOTAL MOLAR = 94.9013
PROCESS SELECTIVITY = 4.93421
REPORT RECORDED ON TAPE
G.C. REPORT SENT TO NACS:m
REPORT COMPLETED

HP 5793 Chromatogram

RUN # 575

SEP/25/03 21:11:07

AREA%

RT	AREA	TYPE	AP/HT	AREA%
1.51	6.8879E+07	SBB	0.209	98.856
2.58	331540	TBP	0.419	0.476
6.22	465320	PB	0.293	0.668
7.72	0	PB	0.000	0.000

TOTAL AREA= 6.9674E+07
MUL FACTOR= 1.0000E+00

APPENDIX C

MATERIAL AND ENERGY BALANCE PROGRAM

1. Sample Calculation Output
2. Computer Program Description
3. Physical Constants Used by the
Material and Energy Balance Program
4. Program Flow Chart

SAMPLE CALCULATION OUTPUT

Input Data

Time period: Design Point (24.0 hours)

Gasifier Operation:

Coal feed, Ton/hour = 1.67
 Blast air flow, Scfm = 1416.
 Saturated air temperature, F = 149.
 Steam/Air Ratio (lb./lb.) = 0.20
 Ambient air temperature, F = 47.
 Off-take temperature, F = 545.

Coal Data:

Type = Leucite Hills
 Mass Percent carbon = 57.5
 Mass Percent fixed carbon = 44.86
 Mass Percent moisture = 17.36
 Mass Percent nitrogen = 1.37
 Heating value, Btu/lb = 10016.
 Mass Percent sulfur = 0.45

Tar and Water Yield (dry basis):

Tar yield, lb/1000 SCF = 1.52
 Carbon in Tar (percent) = 75.2
 Sulfur in Tar (percent) = 0.31
 Tar HHV, thou. Btu/lb = 15.43
 Water yield, lb./1000 SCF = 6.96

Ash and Dust Data:(dry basis)

Ash discharge, lb/hour = 351.
 Ash carbon, percent = 16.2
 Ash sulfur, percent = 0.17
 Ash moisture (wet), percent = 21.2
 Cyclone dust, lb/hour(est.) = 67.

Gas Composition (Dry):

Molar Percent H2 = 19.2
 Molar Percent CO = 28.6
 Molar Percent CH4 = 1.64
 Molar Percent N2 = 43.5
 Molar Percent C3H6 = 0.037
 MOL WT, lb/lb-mol = 23.80
 Sulfur as H2S (est) = 0.110
 Molar Percent Ar(est) = 0.515

Molar Percent CO2 = 5.88
 Molar Percent C2H4 = 0.054
 Molar Percent C2H6 = 0.015
 Molar Percent O2 = 0.252
 Molar Percent C3H8 = 0.036
 HHV, Btu/SCF = 175.
 LHV, Btu/SCF = 163.

Calculation Results (based on nitrogen and carbon balance)

Material Balance (Percent unaccounted for: -0.18)

Input,	lb/hr	% Total	Output,	lb/hr	% Total
Coal	= 3341.	31.4	Dry gas	= 9050.	84.8
Steam	= 1238.	11.6	Water in gas	= 1004.	9.4
Air (calc)	= 6076.	57.0	Oil and tar	= 219.	2.0
			Ash (calc)	= 335.	3.1
			Dust	= 67.	0.6
Total	= 10655.		Total	= 10674.	

Energy Balance (Percent unaccounted for: 2.69)

Input,	MM BTU/hr	Output,	MM Btu/hr	% Total
Coal	= 33.5	Dry coal gas	= 25.2	76.4
Air	= -0.020	Oil and tar	= 3.37	10.2
Steam(import)	= 0.541	Sens.& latent	= 2.71	8.2
Cooling water	= -0.073	Ash	= 0.774	2.3
		Dust	= 0.595	1.8
		Cooling water	= 0.327	1.0
Total	= 33.9	Total	= 33.0	

Performance Data

Cold gas efficiency, percent = 74.4
 Cold gas with tar efficiency, percent = 84.3
 Hot gas without tar efficiency, percent = 82.1
 Hot gas with tar efficiency, percent = 92.3
 Air/Coal (lb./lb.) = 1.819
 Steam/Coal (lb./lb.) = 0.371
 Air/Fixed Carbon (lb./lb.) = 4.054
 Coal/Gasifier Area (lb./hr./sqft) = 100.7
 Fixed Carbon/Area (lb./hr./sqft) = 45.2
 Producer Gas/Coal (SCF/lb.) = 49.6
 Producer Gas/Fixed Carbon (SCF/lb.) = 110.6
 Tar Yield (lb./lb. coal) = 0.065

MATERIAL AND ENERGY BALANCE PROGRAM

The purpose of the Mass-Energy Balance program is to calculate the material and energy balances for the Wellman-Galusha coal gasifier located at the U. S. Bureau of Mines, Twin Cities Research Center. This appendix is an explanation of the method of the program and also contains a flow chart for the program, a list of the input variables, and an explanation of the output items.

MATERIAL BALANCE

A control volume drawn around the gasifier indicates the following inputs: air, steam, coal, water to the water jacket, and cooling water to the agitator. The outputs indicated are: dry, tar-free gas, tar, water vapor in the gas, ash, dust, water from the water jacket, and water from the agitator. The mass-energy program is based upon this control volume and upon these mass and energy flows.

Of the mass flows entering the retort, the coal weights and the cooling water in are the only flows taken to be known with certainty. The dust mass leaving the retort is estimated from particle sampling at the retort outlet. The dust mass is characterized as a fraction of the coal entering the retort. Dust samples are taken and analyzed for composition. It is the true dust composition which is used in the calculations.

The sources of the water entering the retort are the jacket cooling water and imported steam, when used. Both the import steam and cooling water flows into the retort are measured, but since evaporation of water from the cooling jacket is impractical to measure and the overflow of the jacket cooling water is unmeasured, the assumption is made that the air which enters the retort is in a saturated state and is characterized by the blast saturation temperature.

The saturated air temperature is used with in the Magnus equation (optimized for the range of 55 C to 65 C):

$$P_{\text{sat}} = A * \exp(B * T / (T + C)) ; \text{atmospheres} \quad (1)$$

$$A = 0.005990924$$

$$B = 17.08162$$

$$C = 233.5957$$

$$T = \text{Blast Saturation Temperature (deg C)}$$

to obtain the saturated vapor pressure and thus the steam-air ratio of the moist air entering the retort. This steam partial pressure, when combined with the blast air

flow (measured or calculated), yields the total mass of water entering the retort, allowing the water entering the cooling jacket can be apportioned between evaporation and overflow.

$$\text{Jacket water in} = \text{Overflow} + \text{Evaporated} \quad (2)$$

The blast air flow measurement has been fairly accurate since the installation of a new annubar prior to test BOM/FGT-003. Before that test, the poor quality of air flow measurement necessitated calculating an air mass flow for the mass/energy balance calculations. The air flow may be described by a nitrogen balance as follows :

$$\text{Nitrogen In} = \text{Nitrogen Out}$$

$$\text{N}_2(\text{Coal} + \text{Air}) = \text{N}_2(\text{Gas} + \text{Tar} + \text{Ash} + \text{Dust}) \quad (3a)$$

$$\text{N}_2(\text{Air}) = \text{N}_2(\text{Gas} + \text{Tar} + \text{Ash} + \text{Dust} - \text{Coal}) \quad (3b)$$

The mass fractions of nitrogen in the gas, tar, ash, dust, and coal come from analysis, a standard composition for dry air is assumed. A calculated air flow remains the value used in computation. The remaining mass flows are ash and producer gas.

The ash leaving the retort is weighed, but there are uncertainties in assigning a number for use by the program. The first uncertainty is that the ash that is dumped is characterized by the 2 - 7 pound sample taken out of a 1000 pound ash dump. The mass fraction of water in this sample is probably not representative of the mass fraction of water of the actual ash dump. This probable error in the water content seriously compromises the mass fraction of carbon and mineral ash the program will "see" in the reported ash mass.

Second, the ash inventory in the retort does not remain constant. This introduces some uncertainty over shorter time periods as to what mass of ash should be assigned as having been produced in that period. This capacitance also makes it difficult to estimate the appropriate composition to assign the ash.

Because of these uncertainties, the ash mass used and reported by the Mass/Energy program is calculated using the assumption that the measured composition of the ash is representative for the period and then requiring a mass balance on the flows of mineral ash. This is a steady state, zero accumulation assumption and results in a control volume which excludes the accumulated ash below the fire zone of the retort. The mineral ash enters the retort in the coal and leaves in the ash, in the dust, and in the tar. The following equation is used to calculate ash production:

$$\text{Ash Mass} = (\text{Ash}(\text{coal}) - \text{Ash}(\text{dust}) - \text{Ash}(\text{tar})) / \text{Ash}(\text{ash}) \quad (4)$$

Operational ash dumps contain significant quantities of water. This water is not considered to have originated in or to have affected the mass/energy control volume and thus does not appear in the mass/energy balance calculations.

The dust mass leaving the retort is estimated by the operators from observations of the cyclone discharge when measurements of dust loadings in the gas are not available. Where dust loading data has been taken, and is valid, the loading data is modeled with the following power law:

$$\text{Dust (lb/lb coal)} = A * (G^{**}B) + C \quad (5)$$

where A, B, and C are constants from least squares fit of the data collected for that test, and G is the actual wet, tar-free, dust-free volumetric gas flow.

The last undescribed mass flow is that of the producer gas. Producer gas is composed of water vapor, tar and dry, tar free gas. The gas sampling and conditioning system used for these tests produces water and tar yields as a fraction of the flow of dry, tar-free gas, thus leaving the dry, tar free gas as the last mass flow to be determined. The venturi flow meter is unreliable due to plugging, therefore the flow of dry, tar free gas is determined by requiring a carbon balance on the control volume. Working with the carbon mass of each stream:

$$C(\text{Coal} + \text{Air}(\text{minor})) = C(\text{Gas} + \text{Tar} + \text{Ash} + \text{Dust}) \quad (6a)$$

$$C(\text{Gas}) = C(\text{Coal} + \text{Air} - \text{Tar} - \text{Ash} - \text{Dust}) \quad (6b)$$

Only one mass flow measurement, the coal, is used to determine the gas flow, the equation elements being composition data and the saturation temperature.

The mole fractions of the major species which make up the dry, tar-free gas are obtained from a gas chromatograph. Because the gas chromatograph presently used (a Hewlett Packard model 5880A) uses argon as the carrier gas, the argon content of the dry, tar-free gas must be calculated by elemental balance:

$$\text{Argon (mol \%)} = (\text{Ar}(\text{Air}) \text{ rate} / \text{MO}(\text{Ar})) / (\text{Gas rate} / \text{MO}(\text{Gas})) \quad (7)$$

where MO(gas) is the molecular weight of the dry, tar-free gas.

In August 1983 a HP 5793 gas chromatograph was put into service to measure the sulfur species in the gas. The

data collected from this instrument was useful only for measuring relative sulfur gas species. An elemental mass balance is performed to calculate the absolute concentrations of these species from the normalized concentrations measured by the gas chromatograph. For tests where this data is not available the gas sulfur is also calculated by elemental balance and is reported as hydrogen sulfide only. The sulfur balance is:

$$S(\text{Gas}) = S(\text{Coal} - \text{Ash} - \text{Dust} - \text{Tar}) \quad (8)$$

The gas composition data reported from the HP 5880A chromatograph plus the addition of calculated argon and sulfur species often does not add to 100%. After examination and testing of the system, the following have been identified as possible causes for the discrepancies: changes in sample gas pressure or barometric pressure change the mass of gas entering the chromatograph, or some moisture may penetrate the gas sampling and conditioning system.

All of these errors affect only the quantity of dry gas entering the chromatograph, not the relative gas concentrations. Therefore all gas chromatograph data is taken as relative. A value of 99.9 mol % is taken as the detection limit and the chromatograph data is normalized to that amount minus the calculated sulfur and argon in the gas:

$$\text{Moles (5880A)} = \text{Sum of species detected by 5880A} \quad (9)$$

$$\text{Moles (sulfur gases)} = \text{Mass sulfur in gas} / \text{MO sulfur} \quad (10)$$

$$99.9 = \text{Moles (5880A)} + \text{Ar} + \text{Moles (sulfur gases)} \quad (11)$$

The higher and lower heating values and the molecular weight of the dry, tar-free gas are calculated from this combination of measured and calculated mole fractions.

To describe the retort mass flows, five elemental balances, two gas analysis normalizations, and the calculation of the dry gas molecular weight have been necessary. The gas analysis normalizations are equations 9 and 10. The five elemental balances are equations 3,4,6,7, and 8. The gas molecular weight is calculated from the final gas composition. An iterative technique is therefore employed to solve these equations simultaneously.

Additional elemental balances for hydrogen and oxygen are calculated, but these elemental balances are calculated only as diagnostics.

Once all the relevant masses are available the total input mass (saturated blast air and coal) and the total outflow mass (ash, cyclone dust, producer gas) may be compared to determine the amount which is not recovered:

Unaccounted = ((In - Out)/In) * 100 percent

In summary, the mass/energy balance program determines mass balance for the retort by forcing elemental balance for nitrogen, carbon, argon, sulfur, and ash, by assuming that the coal feed rate is the one fixed, immutable mass flow into the retort, and by assuming that the blast air is saturated with water vapor at the blast saturation temperature.

ENERGY BALANCE

The energy flows of the gasifier parallel the mass flows. There is the sensible energy, the latent energy, if any, and the chemical energy, if any, of each mass component. A reference state of 60 degrees Fahrenheit and 1 atmosphere is used.

The sensible energies of the various mass flows are calculated using specific heats calculated as temperature-dependent polynomials whenever possible. Since the molar composition of the dry, tar-free gas is known, a specific heat for this mixture of gases is easily calculated from the specific heat polynomials of the components. The specific heats of the coal and ash are taken to be constants and the specific heat of the dust is taken to be that of the coal. These specific heat polynomials are integrated each over the appropriate temperature range and used with the respective mass flow to give the sensible energy. The sensible energy entering the retort is the sum of the sensible energy of the air, the coal, the import steam, the water entering the water jacket, and the cooling water entering the agitator during a given test period.

The coal's specific enthalpy of combustion and the mass of coal entering the retort during a test period is the only chemical energy entering the gasifier. The latent energy of the import steam constitutes the sole latent energy entering the retort, the water evaporated off the cooling jacket entered the control volume as a liquid.

The total energy entering the gasifier is thus the sum of the chemical energy of the coal, all the sensible energies, and latent energy of the import steam.

The total sensible energy leaving the retort is the sum of the sensible energy of the dry, tar-free gas, the tar and water in the gas, the dust, the ash, the cooling water leaving the agitator, and the water exiting the water jacket.

The total chemical energy leaving the retort is the chemical energy in the dry, tar-free gas, in the tar, in the cyclone dust, and in the ash. The enthalpy of combustion for the ash is assumed to be that of the carbon in the ash. The enthalpy of combustion of the tar comes from analysis.

The total energy leaving the gasifier is thus the sum all of the sensible energies, the chemical energies and the latent energy.

An energy balance is executed comparing the total energy entering the gasifier with the total energy leaving the gasifier and expressing the difference as a percent unaccounted for, exactly as with the mass flows.

THERMAL EFFICIENCY

In calculating the thermal efficiency of the gasifier, the following conventional definition of efficiency is used:

$EFF = \text{Energy in desired product} / \text{Total energy into process.}$

The total energy into the process is always taken to be the sum of all the energies entering the control volume during a given test period.

Energy(Coal + Air + Cooling Water + Import Steam)

The above definition of efficiency allows various definitions of the "desired product". If a cold, tar-free gas is the "desired product" of the process, then the efficiency is given by dividing the total chemical energy of the dry, tar-free producer gas by the total energy into the process. Similarly, the hot, tar-free efficiency is found by allowing the total sensible energy and the latent energy of water in the gas to contribute to the "energy in desired product" term. The cold, with-tar efficiency is calculated by letting the energy in the desired product equal the total chemical energy of the dry, tar-free producer gas plus the total chemical energy of the tar. The hot, with-tar efficiency is found by setting the "energy in desired product" term equal to the total sensible, the total latent and the total chemical energies of the producer gas.

PROGRAM INPUT

The following is a complete list of the inputs to the Mass/Energy Balance program. The inputs fall into several categories: the composition data for the coal, ash, tar,

and dust, the gas composition data, the temperature and flow data, and the labels for the output. In total some 65 input items are needed for a complete Mass/Energy program run.

COAL COMPOSITION DATA

Mass fraction ash in coal
Mass fraction carbon in coal
Mass fraction hydrogen in coal
Mass fraction nitrogen in coal
Mass fraction oxygen in coal
Mass fraction sulfur in coal
Mass fraction water in ash
Higher heating value of coal (Btu/lb)
Mass fraction fixed carbon in coal

ASH COMPOSITION DATA

Mass fraction ash in ash
Mass fraction carbon in ash
Mass fraction hydrogen in ash
Mass fraction nitrogen in ash
Mass fraction oxygen in ash
Mass fraction sulfur in ash
Mass fraction water in ash

TAR COMPOSITION DATA

Mass fraction ash in tar
Mass fraction carbon in tar
Mass fraction hydrogen in tar
Mass fraction nitrogen in tar
Mass fraction oxygen in tar
Mass fraction sulfur in tar
Higher heating value of tar (Btu/lb)

DUST COMPOSITION DATA

Mass fraction ash in dust
Mass fraction carbon in dust
Mass fraction hydrogen in dust
Mass fraction nitrogen in dust
Mass fraction oxygen in dust
Mass fraction sulfur in dust
Higher heating value of dust
Mass fraction dust from coal

LABELS

Test number
Period descriptor

Coal descriptor

MASS FLOW DATA

Period length (decimal hours)
Coal Weight (tons/period)
Mass of manifold tar (lb./1000 cu. ft. dry gas)
Mass of water collected in sampling system
(lb./1000 cu. ft. dry gas)
Temperature of sample gas at gas meter (T3) (deg F)
Ash weight (lb./period)

GAS COMPOSTION DATA

Mole fraction H2
Mole fraction CO2
Mole fraction C2H4
Mole fraction C2H6
Mole fraction C3H6
Mole fraction C3H8
Mole fraction O2
Mole fraction N2
Mole fraction CH4
Mole fraction CO

TEMPERATURE AND FLOW DATA

Barometric pressure (inch HG)
Flow rate of inlet air (SCFM)
Temperature of saturated air (deg C)
Temperature of inlet air (deg C)
Flow rate of producer gas (SCFM)
Offtake temperature (deg C)
Steam inlet temperature (deg C)
Jacket inlet temperature (deg C)
Jacket outlet temperature (deg C)
Agitator inlet temperature (deg C)
Agitator outlet temperature (deg C)
Import steam pressure at flow meter (PSIG)
Import steam flow rate (100 lb./hr)
Flow through agitator (gal/min)
Flow through jacket (gal/min)

OUTPUT ITEM DESCRIPTION

Below is a brief description of each item in the Mass/Energy report. Where the items are self explanatory, the comments may refer to the origin of the number or its method of calculation.

Time period: A brief description of the time interval of

the balance

Gasifier Operation:

Coal feed, Ton/hour = Actual coal feed from operator's log
Blast air flow , Scfm = Measured and logged by computer
Saturated air temperature, F= Measured and logged by computer
Steam/Air Ratio (lb./lb.) = Calculated from Saturated blast temperature
Ambient air temperature, F = Measured and logged by computer
Off-take temperature, F = Measured and logged by computer

Coal Data:

Type = Descriptive title of coal
Mass Percent carbon = From ultimate analysis of composited samples
Percent fixed carbon = From proximate analysis of composited samples
Mass Percent moisture = From ultimate analysis of composited samples
Mass Percent nitrogen = From ultimate analysis of composited samples
Heating value, Btu/lb = From proximate analysis of composited samples
Mass Percent sulfur = From ultimate analysis of composited samples

Tar and Water Yield (dry basis):

Tar yield, lb/1000 SCF = Measured by gas sampling system
Carbon in Tar (percent) = From ultimate analysis of composited samples
sulfur in Tar (percent) = From ultimate analysis of composited samples
Tar HHV, thou. Btu/lb = From ultimate analysis of composited samples
Water yield, lb./1000 SCF = Measured by gas sampling system

Ash and Dust Data:(dry basis)

Ash discharge ,lb/hour = Actual from operator's log
Ash carbon ,percent = From analysis of samples
Ash sulfur ,percent = From analysis of samples
Ash moisture (wet),percent = From analysis of samples
Dust ,lb/hour(est.) = Estimated from particle sampling

Gas Composition (Dry):

Mol Percent H₂ = Measured by Gas Chromatograph
Mol Percent CO₂ = Measured by Gas Chromatograph
Mol Percent CO = Measured by Gas Chromatograph
Mol Percent C₂H₄ = Measured by Gas Chromatograph
Mol Percent CH₄ = Measured by Gas Chromatograph
Mol Percent C₂H₆ = Measured by Gas Chromatograph
Mol Percent N₂ = Measured by Gas Chromatograph
Mol Percent O₂ = Measured by Gas Chromatograph
Mol Percent C₃H₆ = Measured by Gas Chromatograph
Mol Percent C₃H₈ = Measured by Gas Chromatograph
Sulfur as H₂S (est)= Calculated by sulfur balance, with the
requirement that all gaseous sulfur be H₂S

Mol Percent Ar(est)= Calculated by elemental balance on argon

MOL WT, lb/lb-mol = Calculated using measured and calculated gas composition data

HHV, Btu/SCF = Calculated using measured and calculated gas composition data

LHV, Btu/SCF = Calculated using measured and calculated gas composition data

Material Balance:

Percent unaccounted for: $(\text{Inflow} - \text{Outflow})/\text{Inflow}$

Input, All input data reported as both mass flows and as a percent of the total inflow stream

Coal = Measured coal flow, from operator's log

Steam = Estimated from Steam/Air ratio

Air (calc) = Calculated from nitrogen balance

Total = Sum of Coal + Steam + Air

Output, All output data reported as both mass flows and as a percent of the total outflow stream

Dry gas = Calculated from a carbon balance

Water in gas = Calculated from measured water yield and calculated dry gas data

Oil and tar = Calculated from measured water yield and calculated dry gas data

Ash (calc) = Calculated from a mineral ash balance

Dust = Calculated from estimated mass fraction of coal flow

Total = Sum of dry gas + water + oil and tar + ash + dust

Energy Balance:

Percent unaccounted for: $(\text{Inflow} - \text{Outflow})/\text{Inflow}$

Input, Energy flows into retort

Coal = Chemical and sensible energy

Air = Sensible energy

Steam(import) = Sensible and latent energy of imported steam

Cooling water = Sensible energy

Total = Sum of Coal + Air + Import Steam + Cooling Water

Output,

All output data reported as both energy flows and as a percent of the total outflow energy stream

Dry coal gas = Chemical energy
 Oil and tar = Chemical energy
 Sens. latent = Sensible and latent energy of producer
 gas products
 Ash = Chemical energy plus sensible energy
 Dust = Chemical energy plus sensible energy
 Cooling water = Sensible energy
 Total = Sum of Dry Gas + Oil and Tar + Sensible and Latent +
 Ash + Dust + Cooling Water

Performance Data:

Cold gas efficiency, percent = Based on cold, tar free dry gas
 Cold gas with tar efficiency, percent = Based on cold dry gas
 Hot gas without tar efficiency percent = Based on hot tar free gas
 Hot gas with tar efficiency, percent = Based on hot raw gas
 Air/Coal (lb./lb.) = Calculated air, measured coal
 Steam/Coal (lb./lb.) = Ratio of measured quantities
 Air/Fixed Carbon (lb./lb.) = Calculated air
 Coal/Gasifier Area (lb./hr./sqft) = Measured coal
 Fixed Carbon/Area (lb./hr./sqft) = Measured coal
 Producer Gas/Coal (SCF/lb.) = Producer gas flow* is calculated
 from elemental balances
 Producer Gas/Fixed Carbon (SCF/lb.) = Producer gas flow* is calculated
 from elemental balances
 Tar Yield (lb./lb. coal) = Tar yield partly measured and
 partly due to balances

* dry, tar-free gas

Physical Constants Used by the
Material and Energy Balance Program

		CP/RU = A + B*T + C*T**2 + D*T**3 (T in degree Kelvin)				f MOL. WEIGHT	LHV g (BTU/LB.MOLE)	HHV
SPECIES		A	B	C	D			
a	H2	3.23510	7.1229e-04	-4.8796e-07	1.9330e-10	2.016	274.49	324.40
a	CO	3.43800	5.1659e-06	8.5508e-07	-3.2980e-10	28.011	321.19	321.19
a	CH4	2.55270	6.0856e-03	7.9581e-07	-8.8200e-10	16.043	910.14	1010.00
a	C2H4	1.16230	1.6268e-02	-7.2875e-06	1.2165e-09	28.054	1500.70	1600.40
b	C2H6	1.38600	1.8705e-02	-5.4069e-06	6.1224e-11	30.070	1619.60	1768.40
e	C3H6	1.21720	2.5557e-02	-1.0166e-05	1.6755e-09	42.080	2185.20	2334.90
b	C3H8	0.66326	3.2148e-02	-1.3903e-05	2.1085e-09	44.097	2318.70	2518.20
c	CH3SH	2.58740	1.3091e-02	-4.5532e-06	2.1341e-10	48.110	1314.20	1414.00
c	C2H5SH	1.20150	3.1104e-02	-1.9898e-05	5.2934e-09	62.130	2006.50	2156.20
a	H2S	3.66790	1.3038e-03	9.8297e-07	-4.7841e-10	34.082	588.37	638.27
a	COS	2.94370	8.2466e-03	-5.6580e-06	1.3667e-09	60.077	628.69	627.69
a	CO2	2.60470	7.4850e-03	-4.5338e-06	9.9802e-10	44.011		
a	O2	3.19890	1.3094e-03	-3.3424e-07	1.3416e-12	32.000		
a	N2	3.48800	-2.2922e-04	1.0135e-06	-3.5977e-10	28.016		
d	ARG	2.52320	-6.6495e-05	5.9465e-08	-1.6671e-11	39.948		
d	AIR	3.61060	-9.0583e-04	2.1008e-06	-8.1590e-10	28.970		
a	H2O(gas)	3.92230	3.7452e-05	1.4622e-06	-4.7504e-10	18.016		
	TAR	0.2016	8.549e-4	0	0	260.		

Standard Conditions: 60 degrees F, 1 Atmos.
RU (Universal Gas Constant) =0.73 ATM*CUFT/(RANKINE)

Other Constants

Specific Heats		Heat of Vaporization	
H2O(liq)	1.0 BTU/lb.	1059.6	BTU/lb.
Tar	0.2016 BTU/lb.	g	85.0 BTU/lb.
Ash	0.3 BTU/lb.		
Coal	0.315 BTU/lb.		

Notes:

- Data derived from D.R.Stull & H. Prophet(Editors),"JANAF Thermochemical Tables" and Addendums, 1st Edition(1965),(PB-168-370),National Bureau of Standards
- Data derived from J. Chao,R.C. Wilhoit,B.J. Zwolinski,"Ideal Gas Thermodynamic Properties of Ethane and Propane",J. of Physical and Chemical Reference Data,vol. 2,(1973)
- Data derived from G.M. Barrow,K.S. Pitzer,Industrial and Engineering Chemistry,vol. 41,(1949), "Thermodynamic Properties of Some Sulfur Compounds"
- Data derived from TABLES OF THERMAL PROPERTIES OF GASES (NBS 1955)
- Data dreived from J. Chao,B.J. Zwolinski,"Ideal Gas Thermodynamic Properties of Ethylene and Propylene",J. of Physical and Chemical Reference Data,vol. 4,(1975)
- Molecular Weights derived where available from the JANAF (1965) tables, otherwise derived from THE HANDBOOK OF PHYSICS AND CHEMISTRY
- Heating values calculated from heat of formation data with a standard condition of 298.15 K and then converted to 60 degree F standard state

Program Flow Chart