Evaluation of Coal Devolatilization Concept

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LECTRIC POWER RESEARCH INSTITUTE

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ABSTRACT

The objective of this test program was to evaluate the concept of increasing make gas heating value from an air-blown entrained gasifier by feeding some or all of the coal to a devolatilizer vessel downstream of the gasifier. It was further required that the increase in heating value should be accomplished without the production of tar or soot.

A pilot plant was constructed consisting of a one foot diameter gasifier and an eighteen inch I.D. by eight feet high devolatilizer. A total of 43 test runs were conducted using an Eastern bituminous coal as well as a Western sub-bituminous coal. Three modes of operation were employed; all coal fed to the gasifier, all coal fed to the devolatilizer, and a 50-50 split between the two.

Analysis of the pilot plant data yielded the following general results:

- The highest heating value gases were generated when all of the coal was fed to the gasifier.
- Unacceptably large tar quantities were generated when half or all of the coal was fed to the devolatilizer.
- Tar content of the make gas was negligibly small when all of the coal was fed to the gasifier.

Data analysis also showed that heat losses were considerably higher than those anticipated at the inception of this program. A detailed analysis of the pilot apparatus has shown that without modification there appears to be no way to operate so as to significantly lower heat losses.

It is recommended that the pilot gasifier be redesigned with the aid of the thermal model. This step, together with the addition of an externally fired air heater to the facility will reduce heat losses to those representative of a commercial installation.

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EXECUTIVE SUMMARY

TEST OBJECTIVE

The objective of this test program was to evaluate a concept for increasing the make-gas heating value leaving an air blown gasifier. Briefly, this concept involves feeding the coal to a devolatilizer vessel downstream of the gasifier rather than to the gasifier itself; the volatile matter in the coal will be driven off by the hot make gas coming from the gasifier leaving behind char which will be recycled to the gasifier. This could permit the gasifier to operate at a high local air-fuel ratio whereas the overall value is much lower. Thus, higher make-gas heating values might be achievable provided that the gasifier will operate on char. This increase in heating value must, however, be accomplished without the production of tars or soot.

SUMMARY OF WORK

A pilot plant was constructed consisting of a one-foot diameter gasifier followed by a devolatilizer (8 foot long by 1-1/2 foot inside diameter) and cyclone separator; a secondary combustion furnace was used to burn the make gas and also to supply preheated air to the pilot plant. The cost of the construction phase of this test program was assumed by The Babcock & Wilcox Company.

Initially the gasifier was designed for minimizing heat losses by surrounding the gasification zone by a natural gas fired furnace. However, after a short period of testing the refractory supporting the silicon carbide liner, which separates the gasification zone from the gas fired furnace, washed out allowing the liners to slip down, breaking the seals between the two areas. In addition the silicon carbide liners had cracked from either thermal or mechanical shock. This necessitated surrounding the gasifier with castable refractory and this resulted in excessive heat losses. A total of 43 tests were run. Of these 32 were selected for analysis since some of the others employed steam addition, or oxygen enrichment, or were obviously erroneous. The tests were carried out using two kinds of coal: an Eastern high volatile bituminous coal which was a caking coal and a Western sub-bituminous non-caking coal.

Three modes of operation were employed: all coal to the gasifier, all coal to the devolatilizer, and a 50-50 split between the two. Overall air-fuel ratios ranged from 30% to 60% of stoichiometric air.

Because high heat losses were incurred during this test program, a thermal analysis of the pilot apparatus was undertaken to determine:

- What heat losses might be achieved at steady-state, and how long might it take to achieve steady state?
- What changes to the apparatus might be necessary to shorten thermal equilibrating times or reduce heat losses?

In order to answer these questions a detailed thermal model of the pilot apparatus was developed and programmed for a high-speed computer.

RESULTS AND CONCLUSIONS

Analysis of the data yielded the following results for comparison of operation with all coal fed to the gasifier to all or some coal fed to the devolatilizer, under conditions of the same air-to-fuel ratio:

- The highest heating values were observed when all of the coal was fed to the gasifier.
- Unacceptably large tar quantities were generated when half or all of the coal was fed to the devolatilizer.
- Tar content of the make-gas tended to be negligible or low when all the coal was fed to the gasifier.

However, the data analyses also showed that heat losses were generally high--much higher than had been anticipated at the inception of this program. This was due to a combination of transient heating of the mass of refractory that had been substituted for the unsuccessful annular-fired design of the gasifier, too much heat loss due to recycling cold char, and excessive uncompensated combustor heat loss.

Within the range of substoichiometric air-to-fuel ratios studied utilizing this particular test apparatus, heat losses were related to the air-to-fuel ratio; the higher air-to-fuel ratios tended to produce higher internal temperatures which resulted in higher heat losses. This made it difficult to separate the independent effects of air-to-fuel ratio and heat loss. Consequently, statistical projections to reasonable levels of heat loss assuming virtually 100% carbon utilization could give only a broad range, 100-150 Btu/dscf (dry standard cubic feet) for Western coal, all fed to the gasifier. However, the upper end of that range, if it would turn out to be actually attainable, would be quite encouraging.

A detailed thermal analysis of the pilot apparatus has shown that with the present design there appears to be no way to operate so as to significantly lower heat losses. However, by certain modifications and a change in operating procedure, a pilot apparatus of this scale can be made to produce heat losses fully comparable to the low losses expected in large commercial installations.

RECOMMENDATIONS

The next step should be a redesign, aided by the thermal model, of the pilot gasifier and the adding of an externally fired air heater to the facility in order to reduce heat losses to those representative of a commercial installation.

Upon completion of the necessary modifications, additional tests, using the gasification scheme only, should be conducted to achieve a definite answer to the question, "Can heat content be increased simply by reducing heat losses?"

The development of a mathematical model of suspension gasification based upon rate control by other than gas-phase diffusion (e.g., chemical kinetics) would make a significant contribution to continued development of this type gasification.

Section 1

INTRODUCTION

In an effort to achieve national energy independence and to find suitable substitutes for those fuels, notably natural gas and oil, whose supplies are rapidly diminishing, government, private institutions, and industry have been sponsoring research programs directed toward this goal. Fortunately the United States is blessed with abundant reserves of coal which, if properly processed, can provide the bulk of the nation's energy requirements for many years to come.

A number of approaches have been proposed and are currently being studied for the conversion of coal into a fuel which could be directly substituted for natural gas or oil without major equipment modifications. The approach that we will focus on in this report is coal gasification, in particular air blown suspension gasification. Briefly, the concept involves the combustion of coal with a deficiency of air to produce a make gas containing large amounts of carbon monoxide and hydrogen along with some hydrocarbon gases. The probable application of this type of gasifier would be in conjunction with a combined cycle.

One of the potential drawbacks to air blown suspension gasification is the relatively low heating value of the make gas, typically 80-100 Btu/dscf. Any proposed use for this type of gasification would benefit from an increase in make-gas heating value above and beyond that normally produced. Thus, the Electric Power Research Institute has sponsored this work to investigate a concept whereby the make-gas heating value produced by an air blown gasifier is increased through the use of a devolatilizer.

In the devolatilizer concept, some or all of the coal is injected into a vessel, the devolatilizer, following the gasifier. Here the coal is contacted with the hot make gases coming from the gasifier, releasing the volatile matter and leaving behind a solid residue, high in carbon content, called char. The char is separated from the gas by cyclone separators following the devolatilizer and recycled back to the gasifier. Thus, the gasifier is fired on recycled char instead of coal. By injecting the coal into a devolatilizer downstream of the gasifier, one can utilize "low level" heat in the make gas (which is, by then, too cold to accomplish gasification of char) to devolatilize the coal and preheat the char. This relieves part of the heat load on the gasifier and, at the same time, permits the gasifier to operate at a higher local air-to-fuel ratio — say, 50% — whereas the overall value is 42%. Thus, desirably high make-gas heating value may be achieved provided that the gasifier will operate on char and that the coal volatiles can still be reformed at the lower temperatures characteristic of the devolatilizer without leaving undesirable tars and soot in the make gas.

The object of this contract was to evaluate experimentally the devolatilizer concept on a small-scale pilot plant. This report documents all of the results obtained during the test program. A transient thermal analysis of the gasifier-devolatilizer was also done, and its results are also discussed.

Section 2

PILOT PLANT

The major components of the test facility are shown schematically in Figure 2.1. They consist of the following:

1. Pulverized coal storage tank
2. Coal feed tank
3. Coal screening tank
4. Gasifier
5. Devolatilizer
6. Char collection and recycle system
7. Secondary combustion furnace.

A detailed description of the above components and ancillary facilities will be covered in this section.

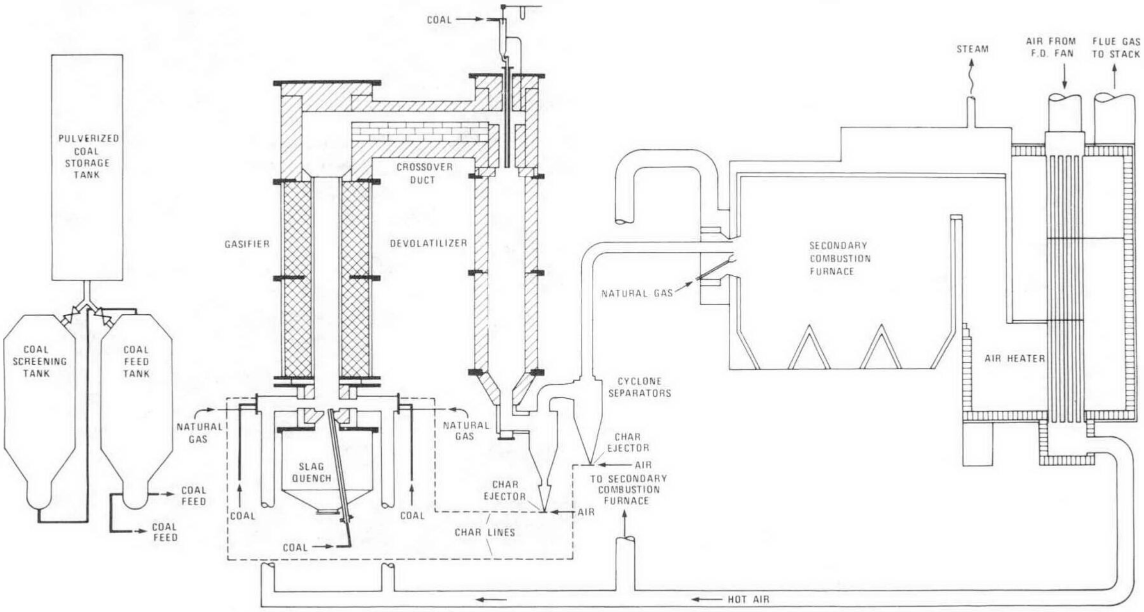


FIGURE 2.1 PILOT PLANT

2.1 COAL PREPARATION FACILITIES

The raw coal purchased for these tests arrived by truck and was stored in our coal storage yard under cover. Size of the raw coal was approximately 1" x 0" and was pulverized to the required fineness by a small (one ton/hour) hammer mill pulverizer located in the boiler room. It was then pneumatically transported about 300 feet to the coal storage tank at the gasifier-devolatilizer test facility. This tank had a capacity of about 3,000 pounds. From here it was fed to the coal screening tank below by gravity.

2.2 COAL FEED SYSTEM

2.2.1 Coal Screening Tank

Early in the test program our intention was to utilize two coal feed tanks which would permit continuous feeding of coal to the system. However, during the initial shakedown phase maintaining a steady coal feed was a major problem. The problem was caused by small pieces of coal which were getting through the pulverizer and classifier causing pluggage of the small coal feed lines and valves. This was solved by installing a 1/8-inch mesh screen in the bottom of the south coal feed tank and using this tank as a final screen for the pulverized coal. In actual operation the coal screening tank would be filled with pulverized coal from the storage tank above. The coal screening tank would then be pressurized, causing the coal to be forced through the screen and into the coal feed tank. Figure 2.2 shows a photograph of the lower portion of the coal screening tank.

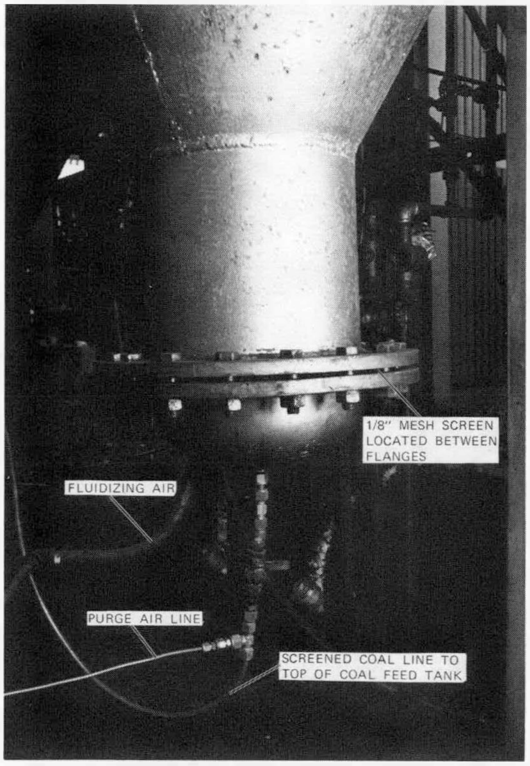


FIGURE 2.2 LOWER PORTION OF COAL SCREENING TANK

2.2.2 Coal Feed Tank and Lines

The coal feed tank was used to feed the pulverized coal to various points in the system, see Figures 2.3, 2.4, and 2.5. The two coal feed lines emanated from the fluidized section at the very bottom of the tank. This fluidized section consisted of a 12-inch long piece of 5-inch pipe which was fitted with a perforated fluidizing plate through which fluidizing air was admitted at a rate sufficient to cause fluidization of the coal.

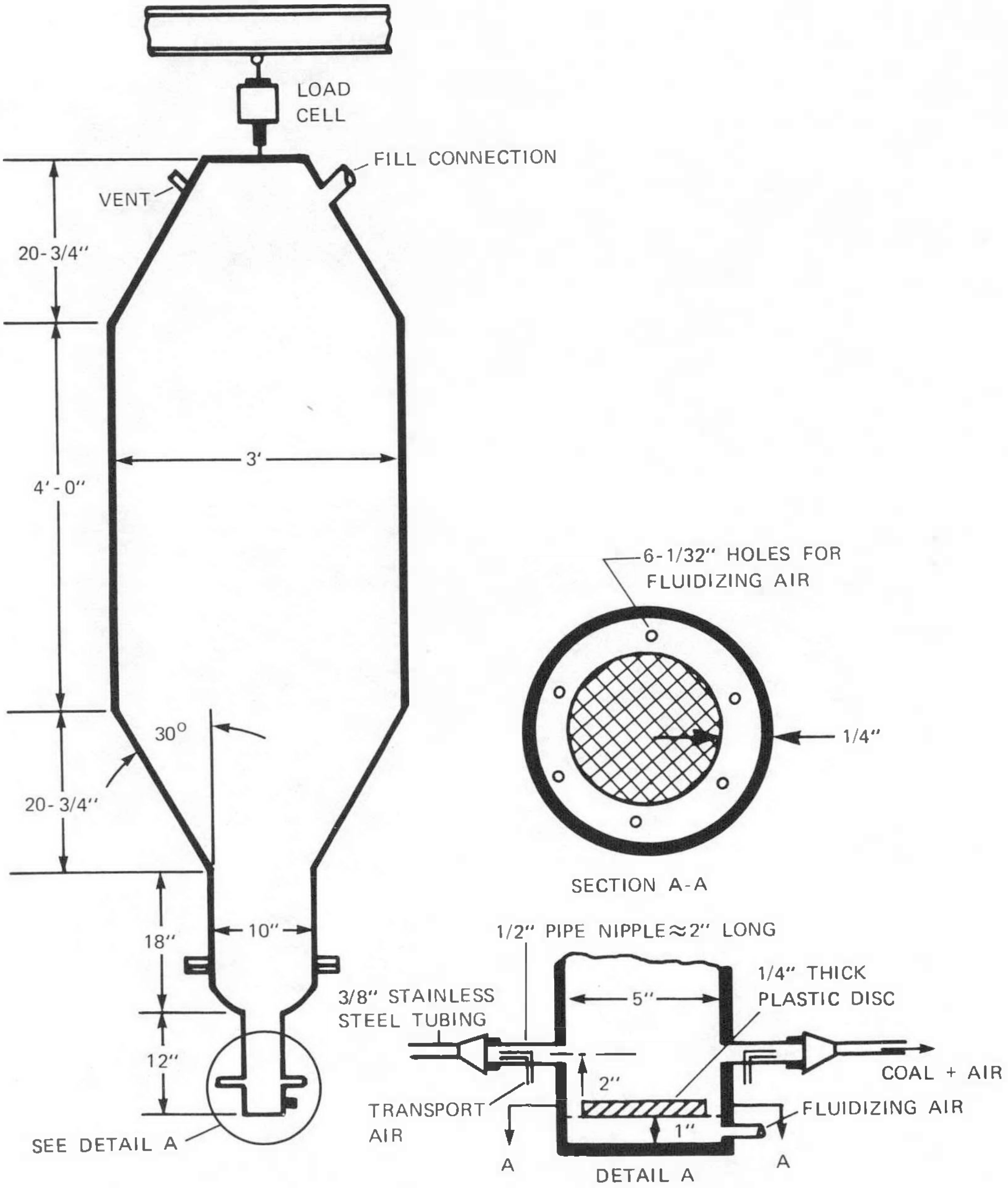


FIGURE 2.3 COAL FEED TANK

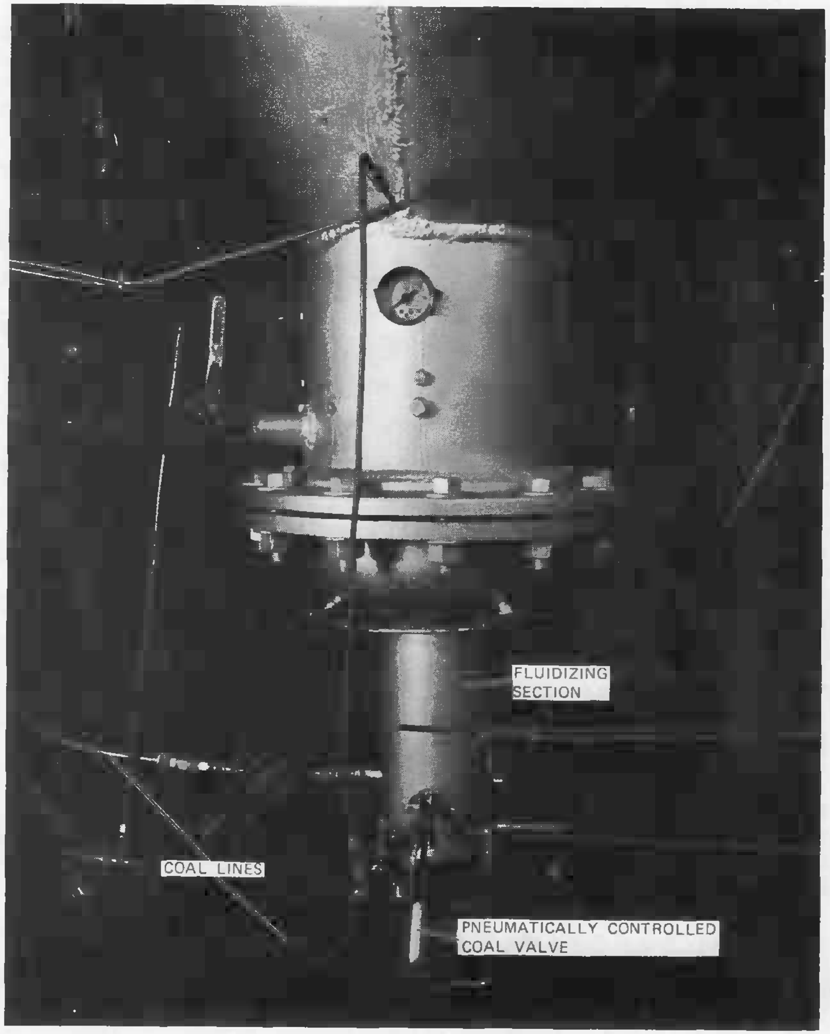


FIGURE 2.4 LOWER PORTION OF COAL FEED TANK

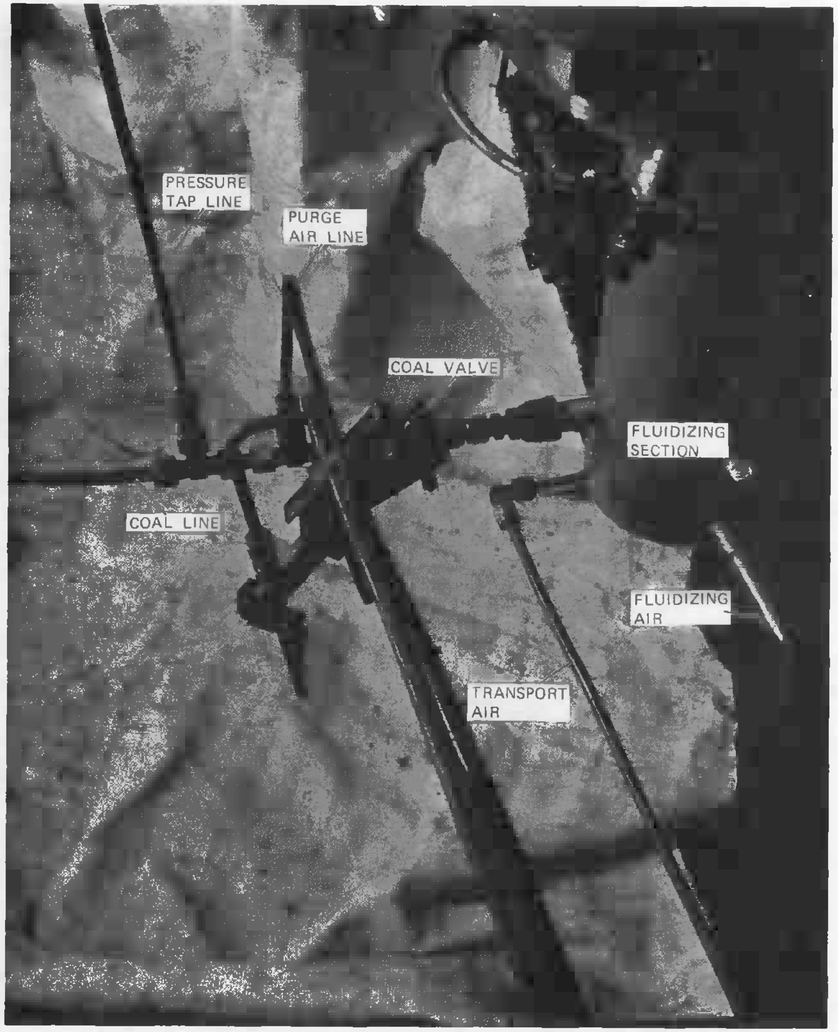


FIGURE 2.5 FLUIDIZING SECTION AND COAL LINE

The coal was fed in dense phase for a short distance at which point air was added for dilute phase transport. The feed rate and the coal flow split between each line was controlled by a combination of feed tank pressure and quantity of transport air.

2.2.3 Measurement and Control of Coal Flow

The north coal feed tank was supported from a load cell which allowed the total weight of the tank to be continuously recorded on a chart recorder, Figure 2.6. This was used as the primary determination of coal feed rate. In order to obtain an instantaneous qualitative indication of coal feed a pressure differential was measured across the length of each coal feed line.

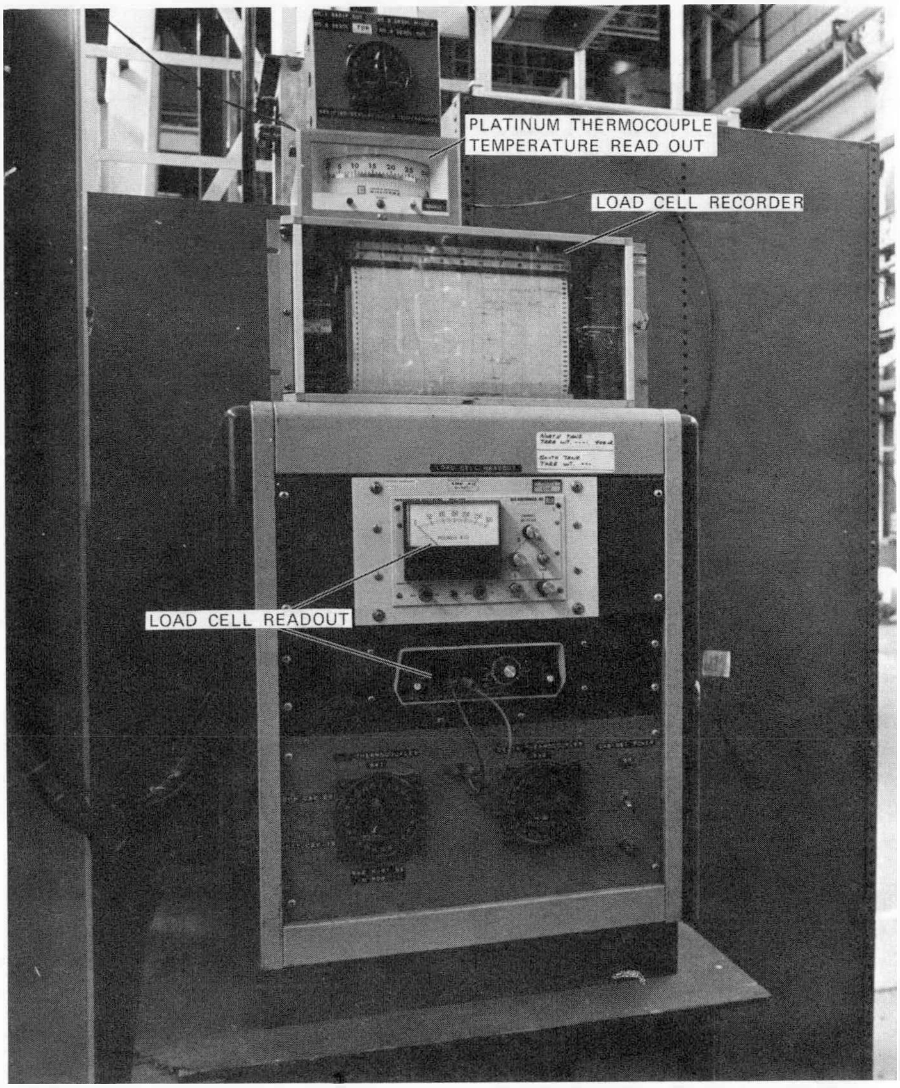


FIGURE 2.6 COAL FEED TANK LOAD CELL READOUT AND RECORDER

2.3 GASIFIER

2.3.1 Initial Design and Modifications

In the initial design of the gasifier (Figure 2.7), the gasification chamber was enclosed by a silicon carbide tube the outside of which was heated by a natural gas fired annular furnace. The purpose of this design was to control the heat losses from the gasifier. After about six hours of operation, during the initial shakedown period, the refractory in the gasifier combustion zone, which supported the silicon carbide liner, had washed out allowing the liner to slip down about 4 inches. This broke the gas seals around the ends of the liner which separated the annular fired furnace from the gasifier. In addition, the two silicon carbide liners had cracked, due either to thermal or mechanical shock.

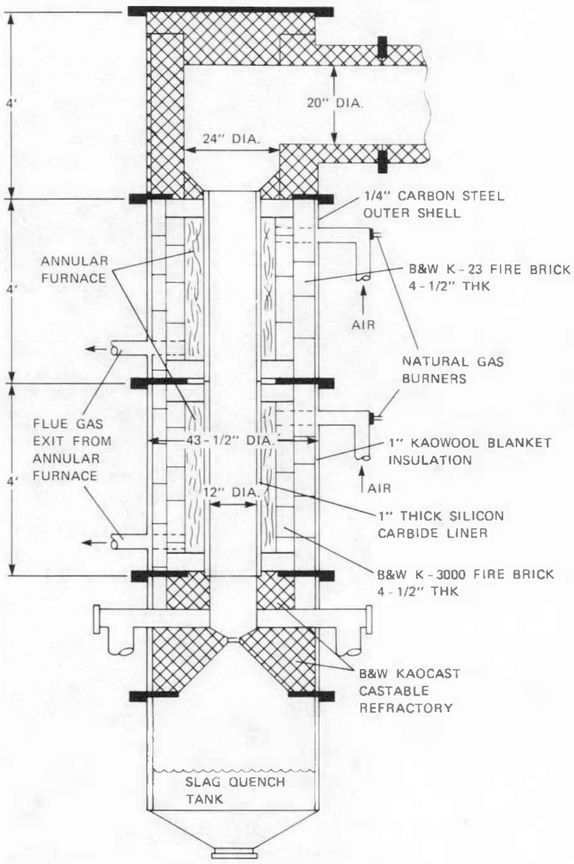


FIGURE 2.7 GASIFIER - INITIAL DESIGN

To provide a quick fix and continue the test program, the following modifications were made:

1. The volume occupied by the annular furnace was filled with refractory.
2. A water-cooled support ring was installed for the purpose of supporting the silicon carbide liner.
3. The castable refractory in the gasifier combustion zone was replaced by a high-alumina firebrick backed up by a water jacket.

2.3.2 Present Design

The present design of the gasifier incorporating the above modifications (shown in Figures 2.8 and 2.9) was used to obtain all the data. The gasifier can be considered to consist of three sections: (1) an upper section which provides the volume necessary for the reactions to take place, (2) the central section or combustion zone where the coal, char, and air are introduced through two burners, and (3) the lower portion which consists of a slag quench tank.

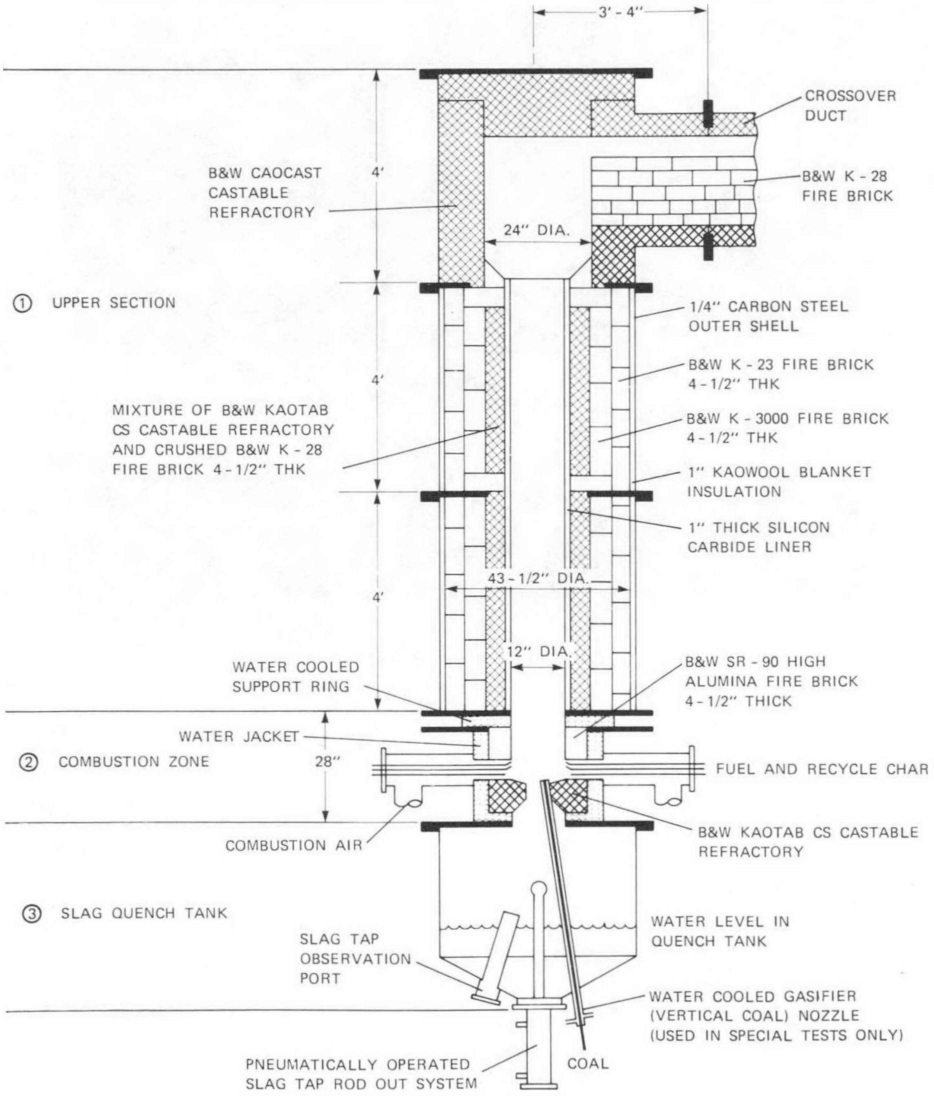


FIGURE 2.8 GASIFIER – FINAL CONFIGURATION

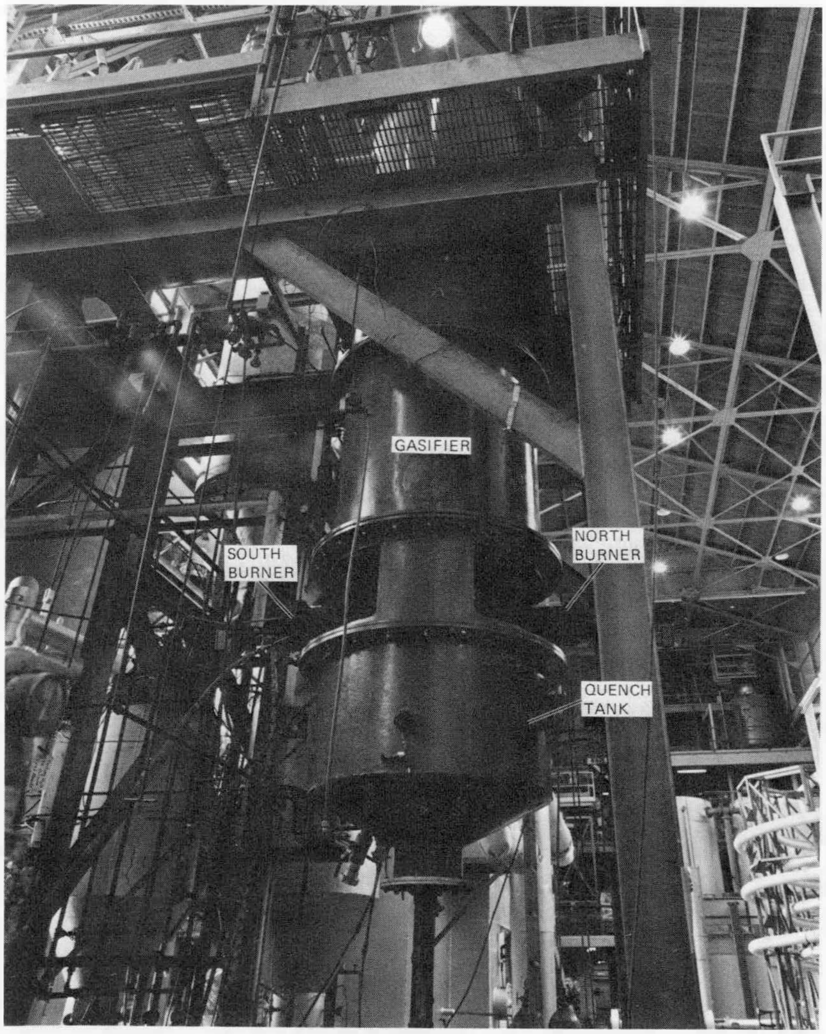


FIGURE 2.9 GASIFIER

The combustion zone is where the coal, air and recycled char are initially reacted to begin the gasification reactions. Two burners were used and were directed to fire tangentially to a 6-inch diameter circle in the combustion zone. The combustion zone was formed by high-alumina firebrick backed up by a water jacket. Figure 2.10 gives construction details of the burners and combustion zone. A photograph, Figure 2.11, of the outside of the north burner shows the location of the coal, air, and recycle char lines. Figure 2.12 shows a disassembled burner and the relative positions of the various injection nozzles. The natural gas supply line was used for two purposes: (1) to supply initial preheat to get the gasifier up to temperature quickly, and (2) during the majority of the gasification tests some amount of natural gas was fired to maintain reducing conditions in the event of char recycle interruptions.

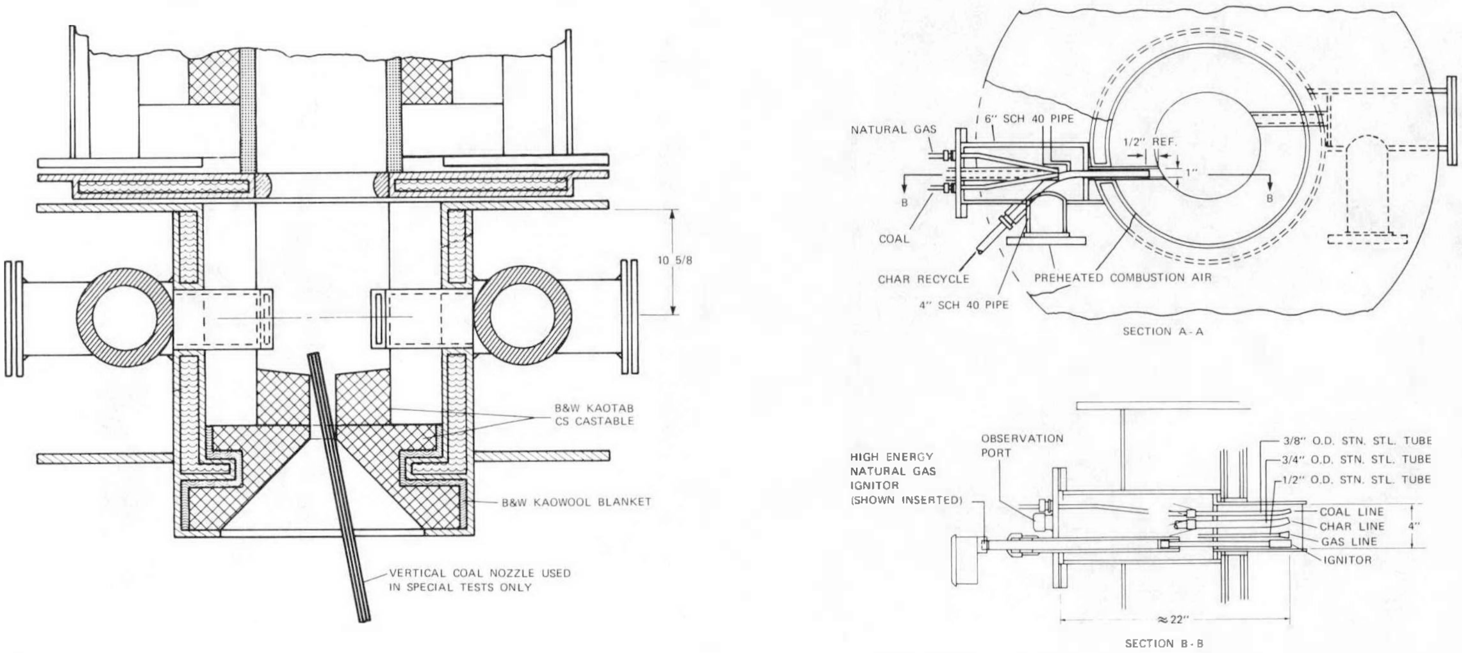


FIGURE 2.10 GASIFIER BURNERS AND COMBUSTION ZONE

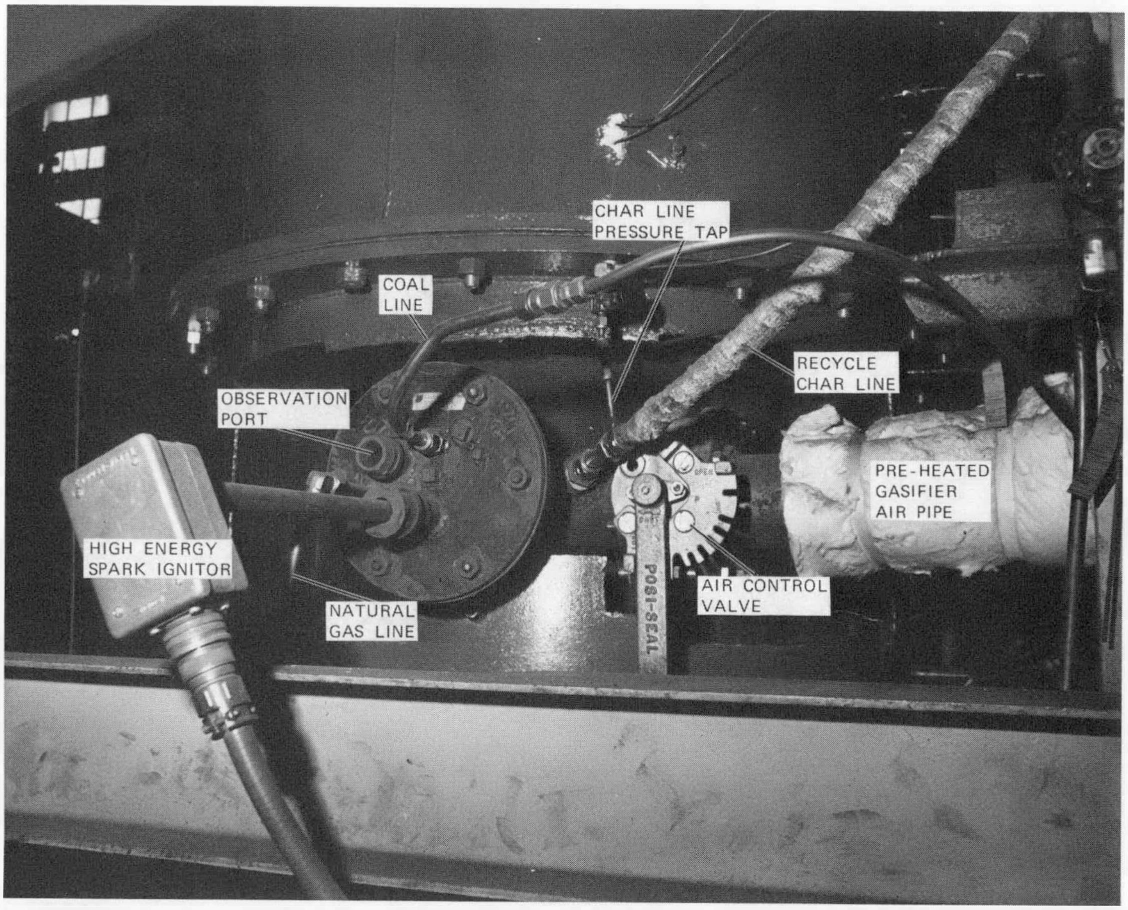


FIGURE 2.11 NORTH BURNER PIPING

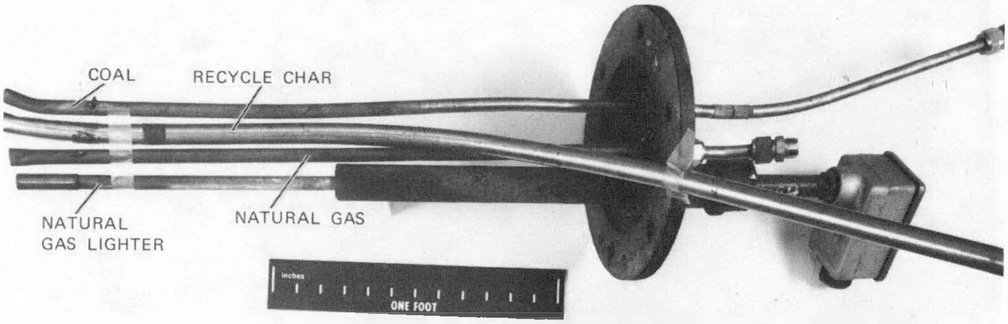


FIGURE 2.12 BURNER INJECTION LINES

The lower portion of the gasifier consisted of a water-filled slag quench tank. Its purpose was to rapidly cool the molten slag such that it shattered into small pieces making it easier to handle. Three other pieces of apparatus were affixed to and passed up through the slag tank: (1) slag tap observation port, (2) slag tap rod-out mechanism, and (3) water-cooled vertical coal injection nozzle. These can be seen in Figure 2.13. The vertical coal nozzle was used on selected tests to inject coal up into and through the hot combustion gases formed by the combustion of the air and recycled char. Figure 2.14 shows the relative location of this nozzle.

The upper part of the gasifier consisted of two silicon carbide tubes, each 12 inches in diameter by 4 feet long. These tubes were supported by a water-cooled support ring rather than supporting them from the combustion zone refractory as was done in the initial design. The silicon carbide tubes were surrounded by three layers of solid refractory and one layer of a light Kaowool blanket insulation.

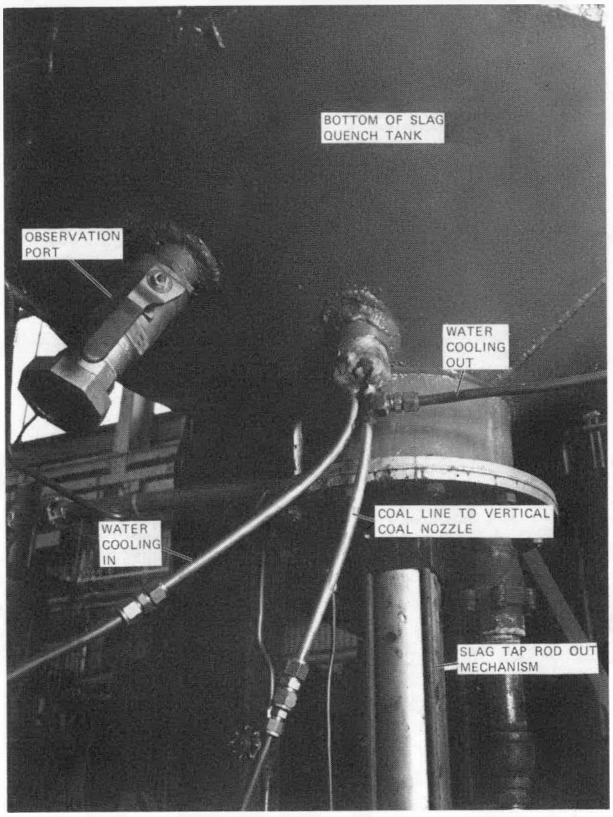


FIGURE 2.13 SLAG QUENCH TANK

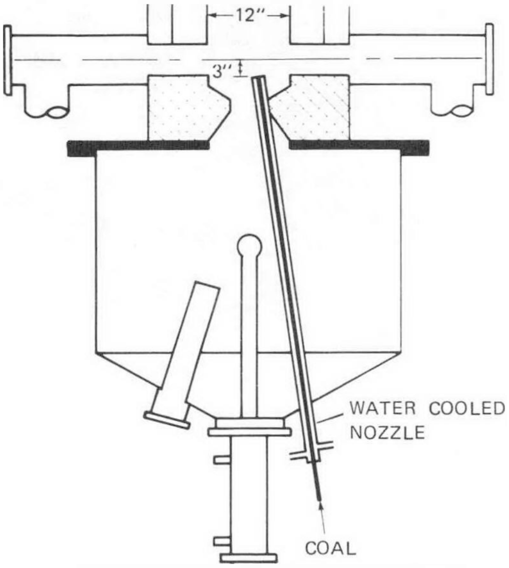


FIGURE 2.14 VERTICAL COAL NOZZLE ARRANGEMENT AT BOTTOM OF GASIFIER

2.4 CROSSOVER DUCT

The crossover duct, Figure 2.15, served only to convey the hot make gas from the gasifier over to the devolatilizer. This duct initially had an internal diameter of 21 inches but was bricked up with insulating firebrick to within 5 inches of the top. This was done to increase the velocity in this duct and thus minimize the char hide-out.

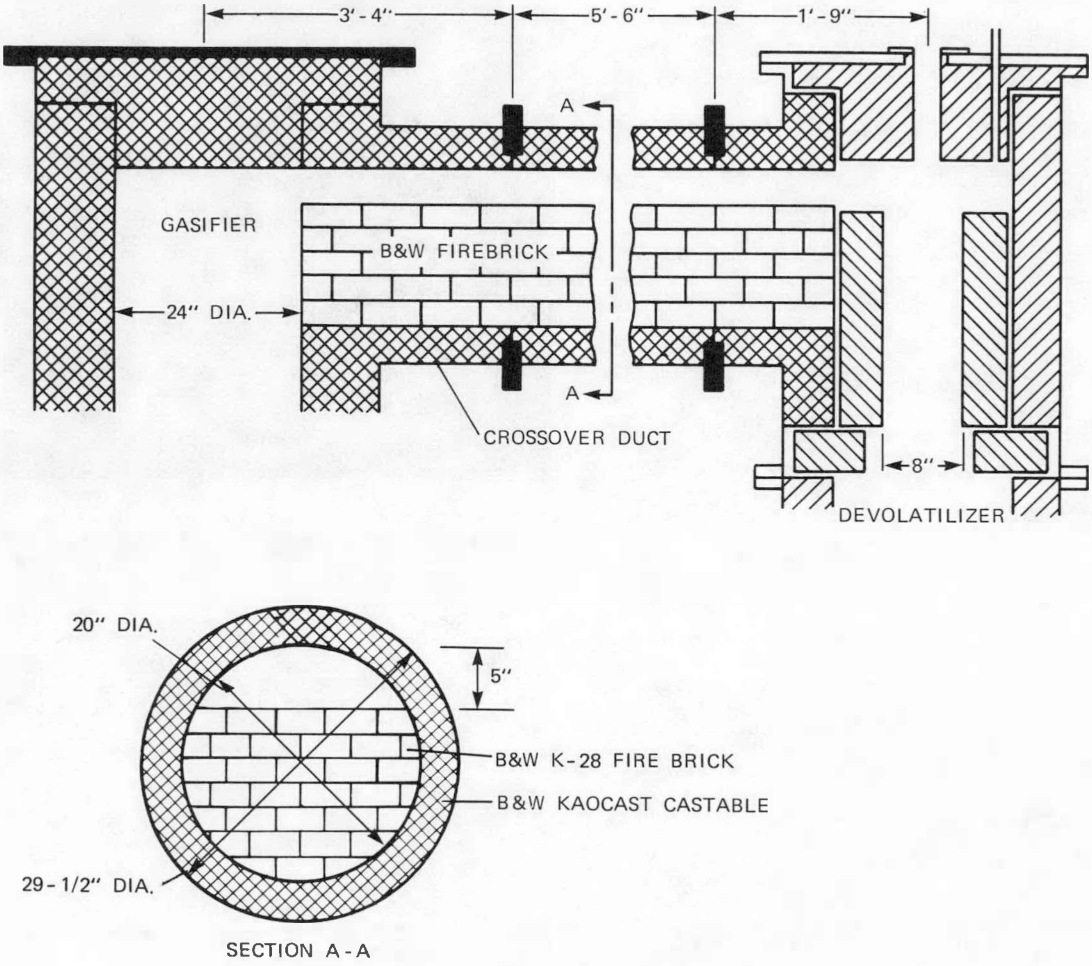


FIGURE 2.15 CROSSOVER DUCT

2.5 DEVOLATILIZER

The hot make gas from the gasifier was conveyed via the crossover duct into the top of the devolatilizer, design details of which are shown in Figures 2.16 and 2.17. The devolatilization chamber is 18 inches in diameter by about 8 feet long with approximately 5-1/2 inches of refractory on the walls.

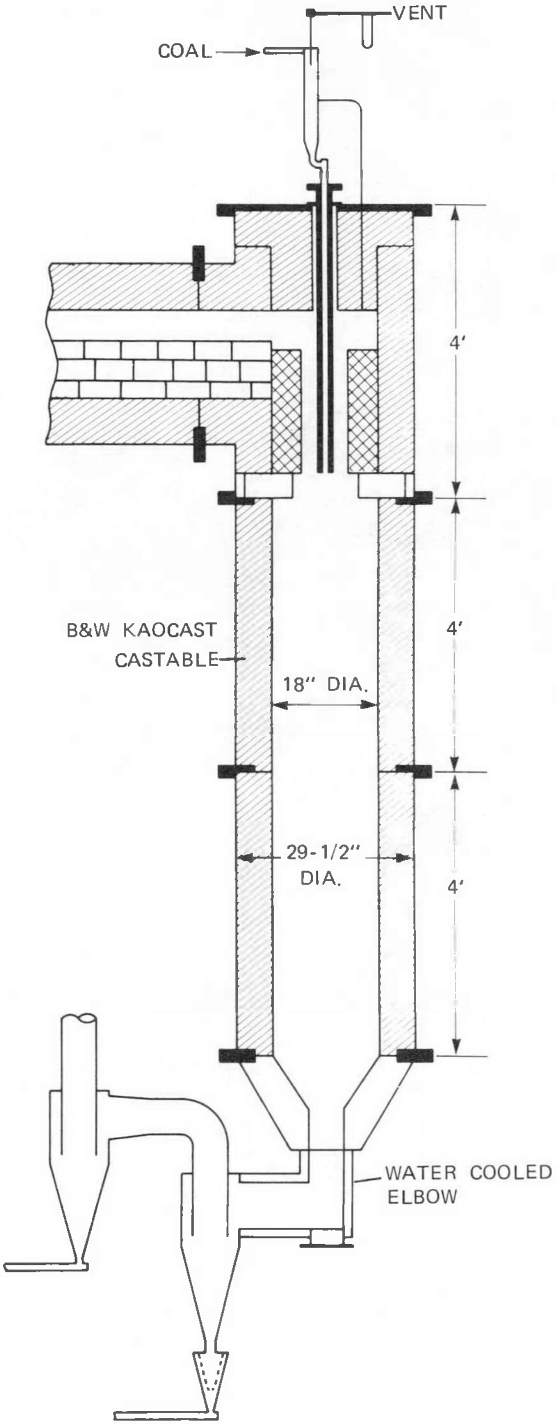


FIGURE 2.16 DEVOLATILIZER SECTIONAL VIEW

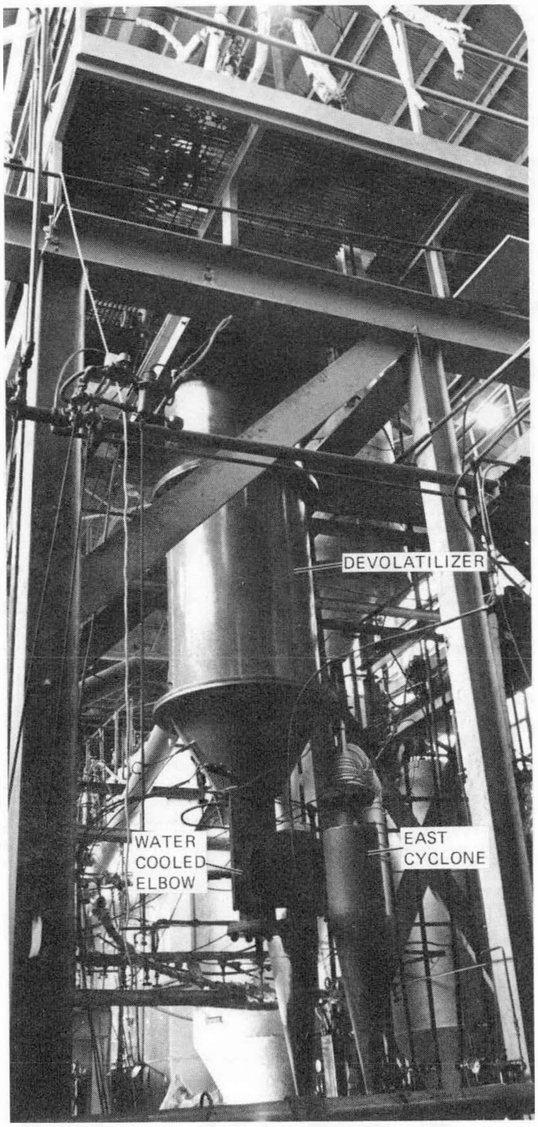


FIGURE 2.17 DEVOLATILIZER

At the very bottom of the devolatilizer was located a water jacketed elbow which directed the gases from the devolatilizer into the cyclones. The water jacketing was used to reduce the temperature of the carbon steel elbow thereby preventing its deterioration.

Figure 2.18 shows a detail of the top portion of the devolatilizer and its coal feed system. The gas flow area at the top was reduced down to an 8-inch diameter to increase the velocity in the area where the coal was injected. This was done to minimize drifting of the coal toward the walls and subsequent char buildup.

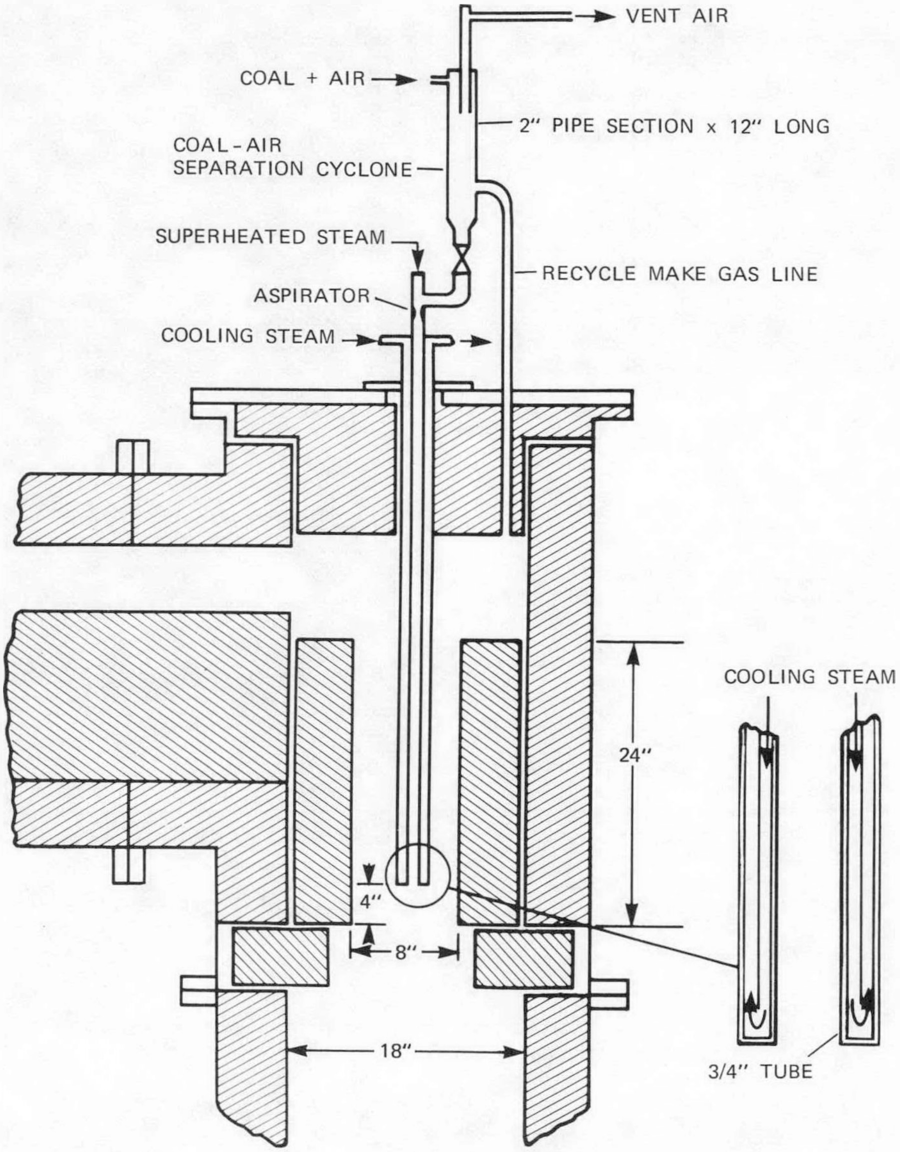


FIGURE 2.18 TOP OF DEVOLATILIZER

The coal injection system was designed to minimize the amount of transport air injected with the coal. This was achieved by bringing the coal-air mixture into a small cyclone which separated the two: the transport air was vented through a pressure relief-check valve to the atmosphere while the coal settled to the bottom. The coal was aspirated from the bottom of the cyclone by a superheated steam-operated aspirator and injected through a water-cooled nozzle into the devolatilizer. A make-gas line taken from the top of the devolatilizer enters near the bottom of the cyclone such that make gas, rather than transport air, will be preferentially aspirated.

2.6 CHAR COLLECTION AND RECYCLE SYSTEM

Char collection and recycle were effected by using two 10-inch diameter high-efficiency cyclones in conjunction with high-pressure air aspirators as shown in Figures 2.19 and 2.20. A detailed drawing of one of the cyclones is shown in Figure 2.21.

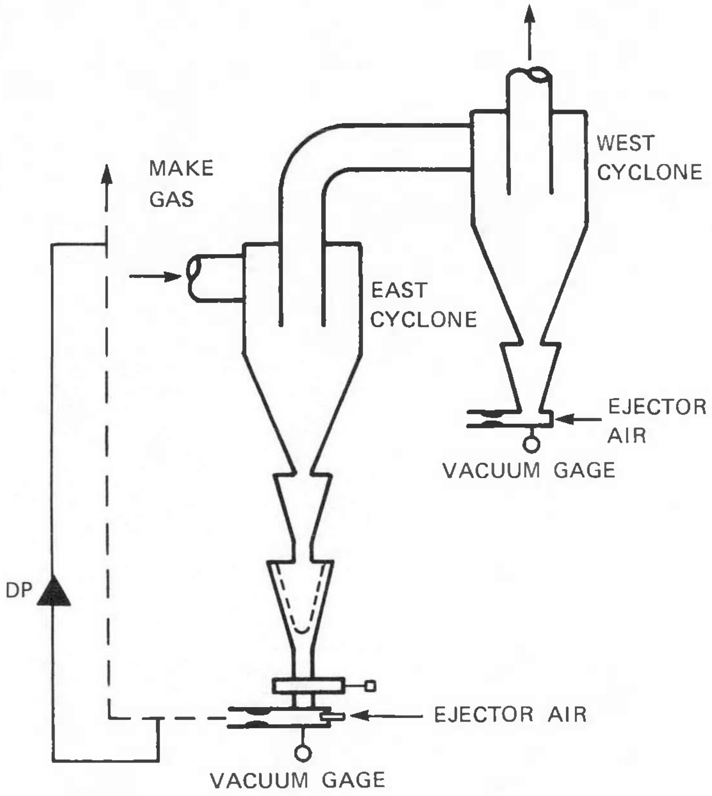


FIGURE 2.19 CHAR COLLECTION AND RECYCLE

The solid material collected by each cyclone settled to the bottom where it was reinjected back into the gasifier by an air aspirator, see Figure 2.22. It was necessary to install a 1/4-inch mesh screen at the bottom of the east cyclone to prevent the aspirator from being plugged by large pieces of slag and char. A ball valve was installed just above the screen so that a solids sample could be taken.

As an aid to indicating the relative condition of steadiness of flow or pluggage in the char recycle lines, a pressure differential was measured across the length of the char return line. A vacuum gauge was installed on the upstream side of the air aspirator to indicate pluggage in the bottom of the cyclone.

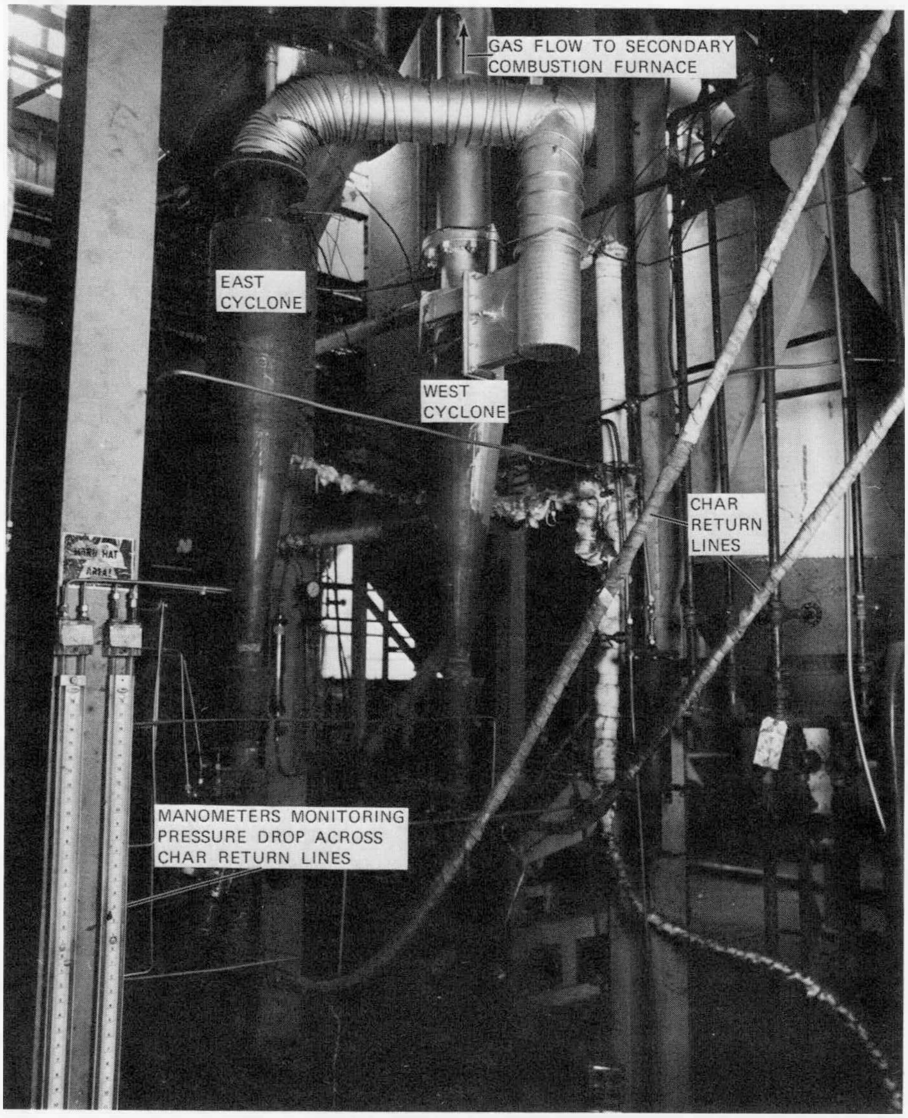


FIGURE 2.20 CYCLONE SEPARATORS

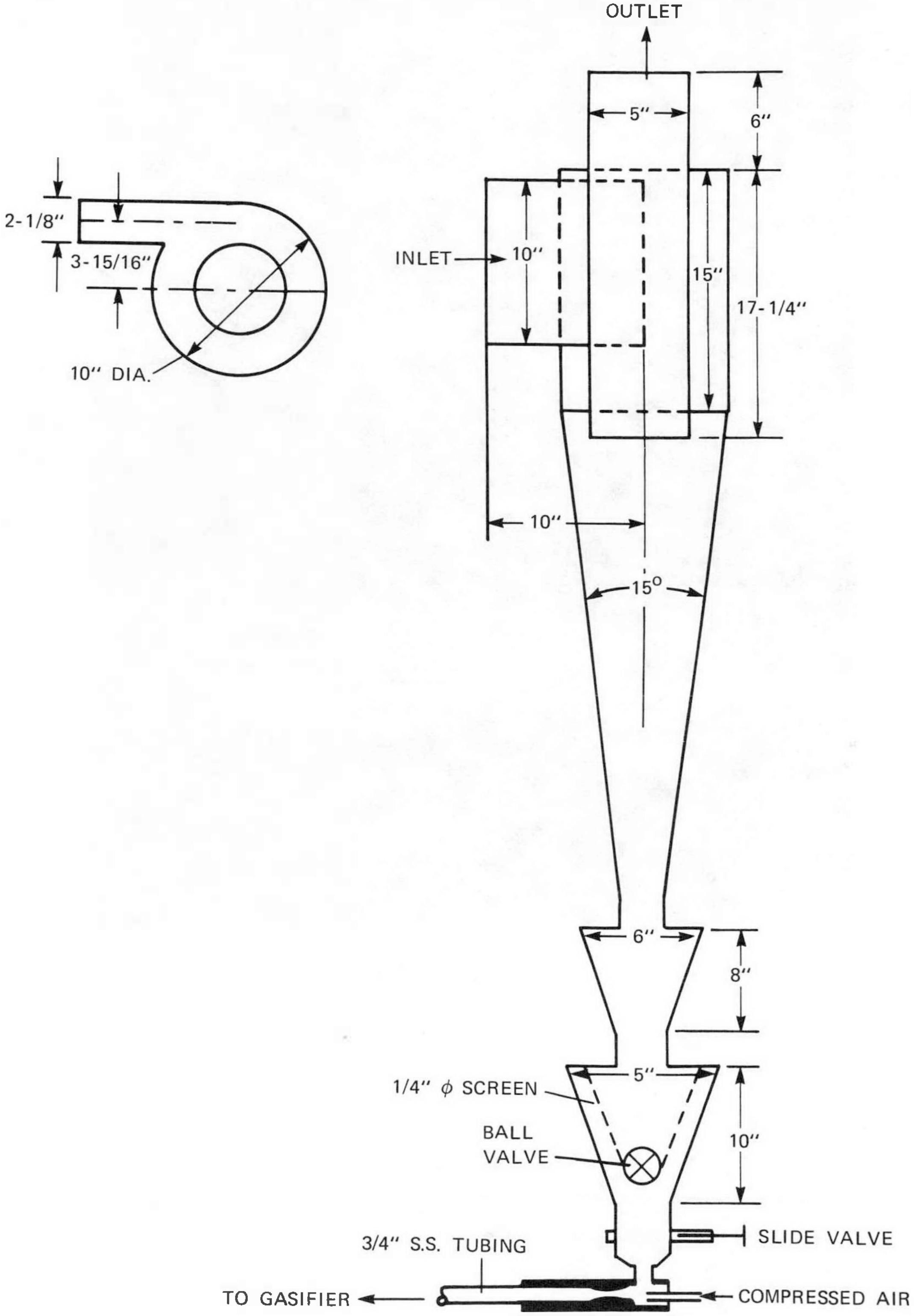


FIGURE 2.21 CYCLONE DESIGN

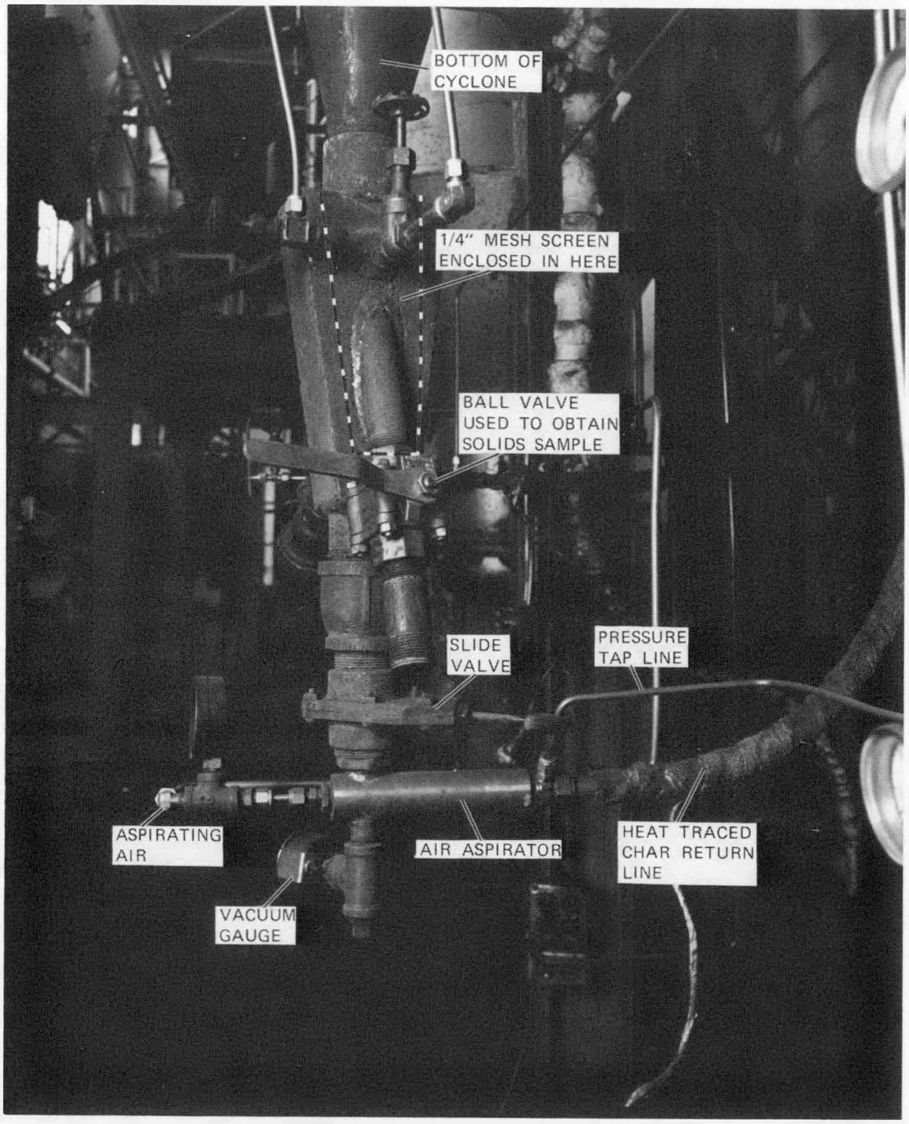


FIGURE 2.22 CHAR RECYCLE APPARATUS ON BOTTOM OF EAST CYCLONE

2.7 SECONDARY COMBUSTION FURNACE

The make gas from the gasifier-devolatilizer system was directed into an existing secondary combustion furnace; this furnace was used for combustion of the make gas and any entrained carbon particles coming from the gasifier. The forced draft fan and air heater on the secondary combustion furnace served as a source of preheated air for the gasifier. Provision was also made to burn supplemental natural gas to help control air preheat temperature.

2.8 CONTROL PANEL

The main control panel for the pilot plant is shown in Figure 2.23. Most of the operations of the pilot plant were controlled and monitored from this panel. All pressure and pressure differential measurements in the system were made using manometers. The majority of the temperatures were measured with chromel-alumel thermocouples and recorded on a Speedomax recorder. Temperature measurements at the gasifier outlet, the devolatilizer inlet, the middle of devolatilizer, and the devolatilizer outlet were measured using platinum thermocouples because of the high temperature involved. These four temperatures were read out on a Leeds & Northrup Millitemp meter as shown in Figure 2.6.

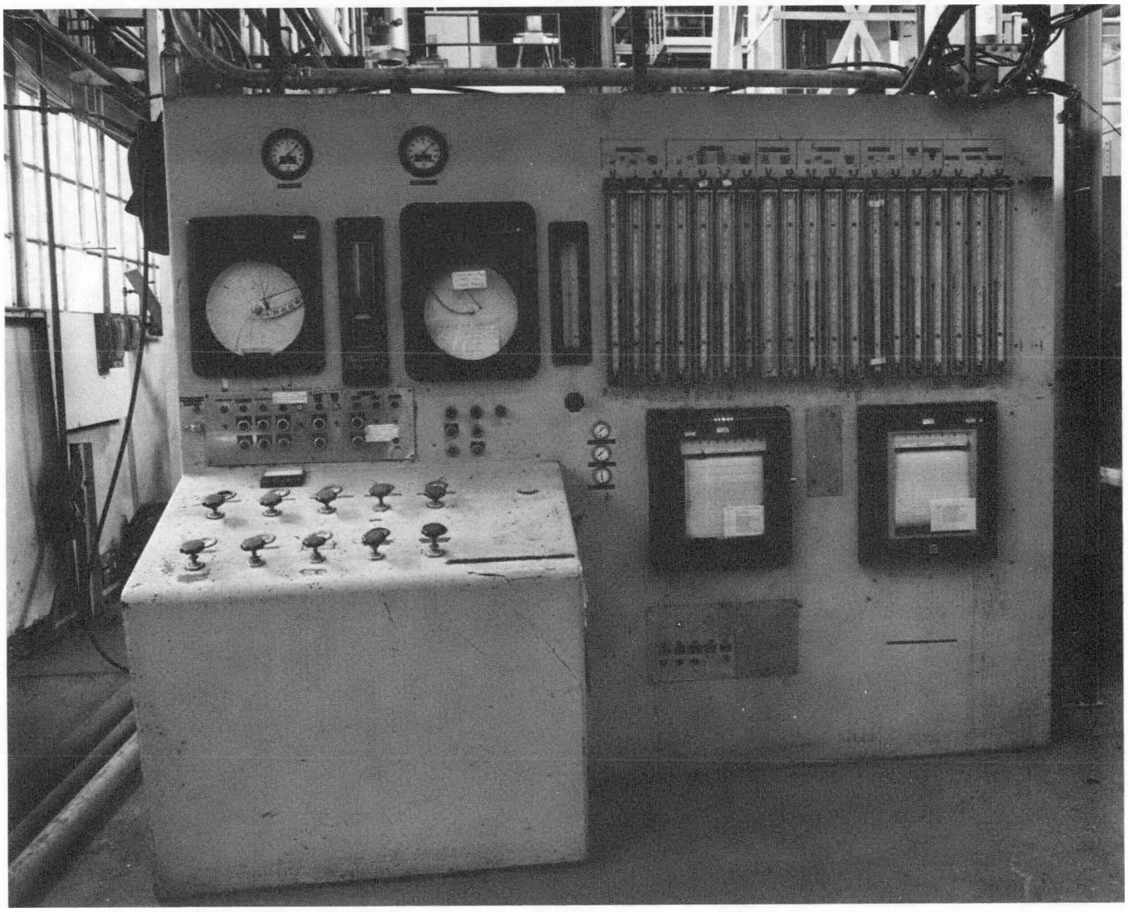


FIGURE 2.23 MAIN CONTROL PANEL

2.9 COAL

Two coals were used during the test period:

1. Pittsburgh No. 8 coal, classed as a high volatile bituminous B coal. This was a caking coal.
2. Western Coal from Belle Ayr mine, Campbell County, Wyoming, classed as a sub-bituminous B coal. This was a non-caking coal.

The analysis of these coals is shown in Table 2.1.

TABLE 2.1 COAL ANALYSIS

	PITTSBURGH NO. 8 COAL ANALYSIS	WESTERN COAL ANALYSIS
MOISTURE, %	1.5	15
PROXIMATE ANALYSIS (DRY), %		
VOLATILE MATTER	40.6	41.1
FIXED CARBON	48.9	51.1
ASH	10.5	7.8
BTU PER LB. (DRY)	13,100	11830
ULTIMATE ANALYSIS (DRY), %		
CARBON	72.7	69.4
HYDROGEN	5.1	4.7
NITROGEN	1.0	0.9
ASH	10.5	7.8
SULFUR	3.2	0.4
OXYGEN (BY DIFF.)	7.5	16.8
SIZING		
% THROUGH #50 MESH	99.6	99.7
#100 MESH	96.7	94.8
#140 MESH	91.8	
#200 MESH	84.9	81.3
#270 MESH	72.5	
#325 MESH	67.9	

Section 3

TEST APPARATUS AND PROCEDURES

3.1 TEST PROCEDURE

3.1.1 Method of Start-Up

At the start of each testing period the gasifier was fired on natural gas at about 115% theoretical air for about two hours to bring the gasifier up to gasification temperature quickly. Gasification tests were started at the end of this time; i.e., when the gasifier outlet temperature reached about 2000-2200°F.

3.1.2 Gasification Testing

After start-up with coal, operating parameters were changed to those required for the first test. Steady state was assumed when the following measurements remained relatively constant over a period of about one-half hour:

1. Gas temperatures in the gasifier and devolatilizer.
2. Oxygen analysis of the flue gas leaving the secondary combustion furnace.

At this point the taking of data was initiated which included the following:

1. Panel board data
2. Gas samples and gas analysis
3. Solids loadings
4. Sample of material collected by east cyclone.

The collection of the above data required about one-half hour to one hour, after which time operating conditions were changed in preparation for the next test.

3.2 GAS SAMPLING APPARATUS

3.2.1 Cyclone Outlet Gas Sampling Apparatus

A schematic diagram of the cyclone outlet gas sampling apparatus is shown in Figure 3.1. The make gas was tapped off the top of the 6-inch makegas line, and particulate material was filtered out with a glass wool filter. A condensate trap served to remove water from the gas sample at this point. This was followed by a tubing pump which pumped the gas sample into and through the gas sampling bottle. The gas sampling bottle consisted of a 300 cc glass bottle with stopcocks at each end.

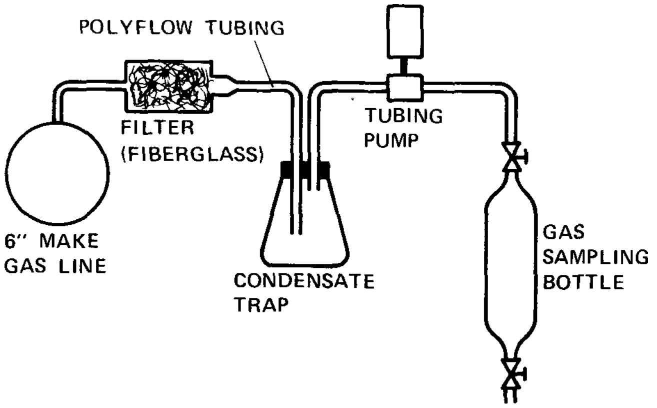


FIGURE 3.1 CYCLONE OUTLET GAS SAMPLING SYSTEM

3.2.2 Gasifier Outlet Gas Sampling Apparatus

Figure 3.2 shows a schematic diagram of the gasifier outlet gas sampling apparatus. A water-cooled stainless steel probe was required at this location because of the high temperature involved. After leaving the probe the make-gas sample was directed to a combination condensate-particulate trap to remove water vapor and particulate material. From here the gas went to the sampling bottle. A gas pump was not required at this location since the system pressure was sufficient to force the gas sample through the apparatus.

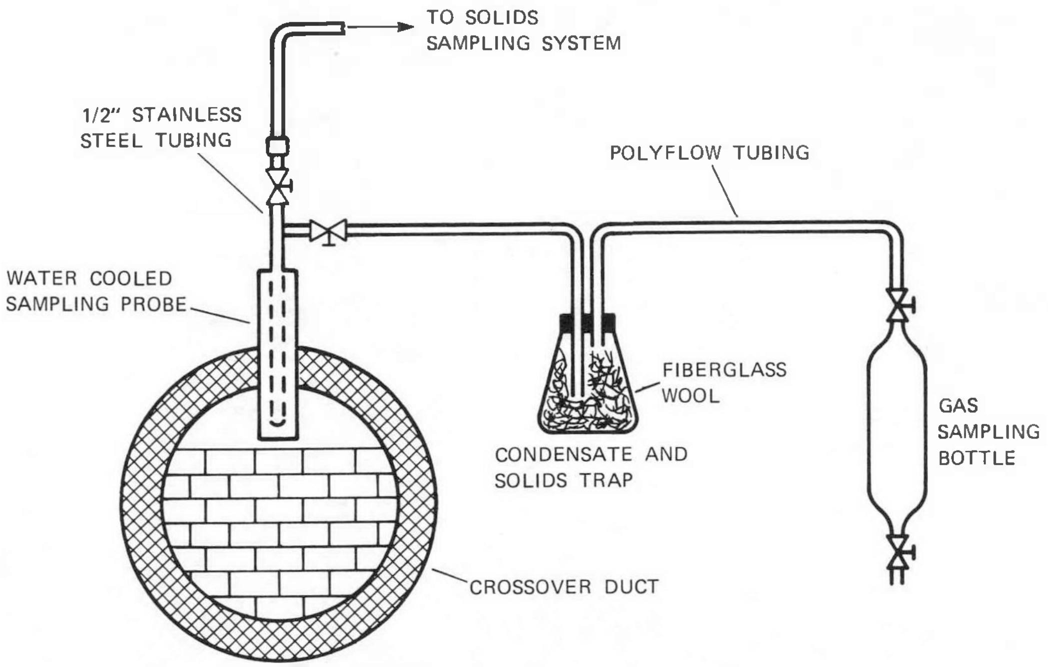


FIGURE 3.2 GASIFIER OUTLET GAS SAMPLING SYSTEM

3.2.3 Oxygen Analysis at Secondary Combustion Furnace

An oxygen analysis of the flue gas leaving the secondary combustion furnace was obtained using a Bailey Meter Company Oxygen and Combustibles Analyzer. This was a continuous analysis and was recorded on a time chart. The probe used to obtain the gas sample was a fixed probe, hence no traverses were made. This analysis was used to calculate the carbon balance designated "C". This will be discussed later.

3.3 GAS SAMPLING PROCEDURE

Prior to starting any gas sampling the gas sampling bottles were purged and filled with helium under a slight positive pressure. Helium was used since it was also the carrier gas for the gas chromatograph.

The gas sampling procedure at the above locations was essentially the same and was accomplished as follows:

1. Gas flow was started through the sampling system without the gas sample bottle connected. The system was allowed to purge for about 2-5 minutes.

2. After this purge period the gas sample bottle was connected via surgical tubing to the sampling apparatus; both stopcocks were still closed at this time.

3. The inlet valve was opened first and then the outlet valve. The make gas was allowed to flow into and through the sample bottle for a period of 5-10 minutes.

4. After this sampling period the stopcocks were closed; outlet first, inlet second.

5. The gas samples were then taken to our lab and analyzed on a Beckman GC-4 gas chromatograph.

3.4 SOLIDS LOADING APPARATUS

3.4.1 Gasifier Outlet Solids Loading

A solids loading was taken at the gasifier outlet using the apparatus shown in Figure 3.3. The pressure at this point was again sufficient to force a make-gas sample through the system without the need for a pump. An isokinetic sampling rate was maintained by adjusting the flow control valve.

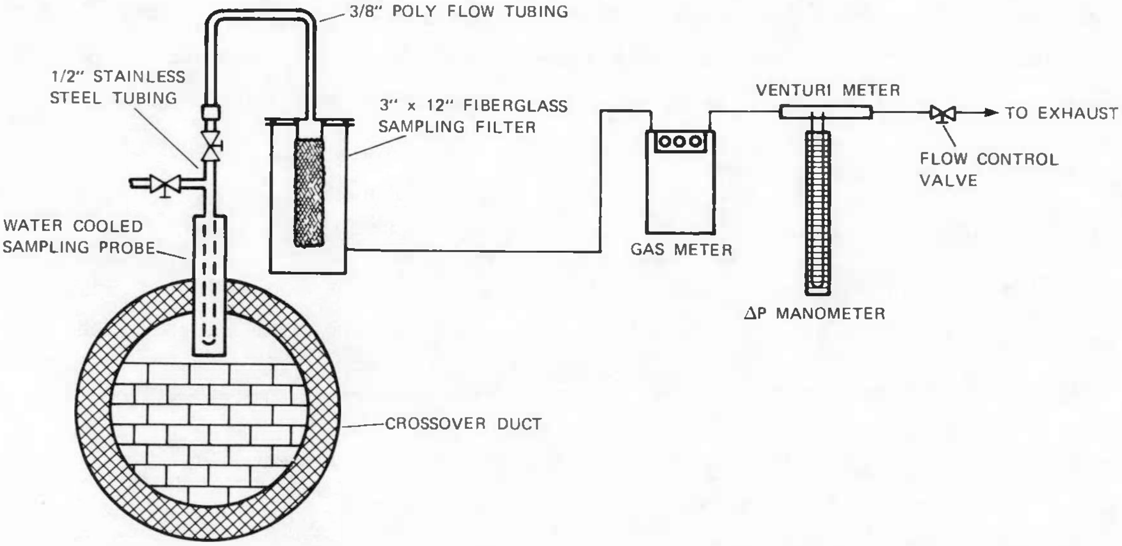


FIGURE 3.3 GASIFIER OUTLET SOLIDS SAMPLING SYSTEM

3.4.2 Solids Loading at Exit of Cyclones

A solids loading was taken at the exit of the cyclones using the apparatus shown in Figure 3.4. Because of low static pressure at this point, it was necessary to aspirate the make-gas sample through the sampling apparatus. An isokinetic sampling rate was maintained by adjusting the aspirating rate.

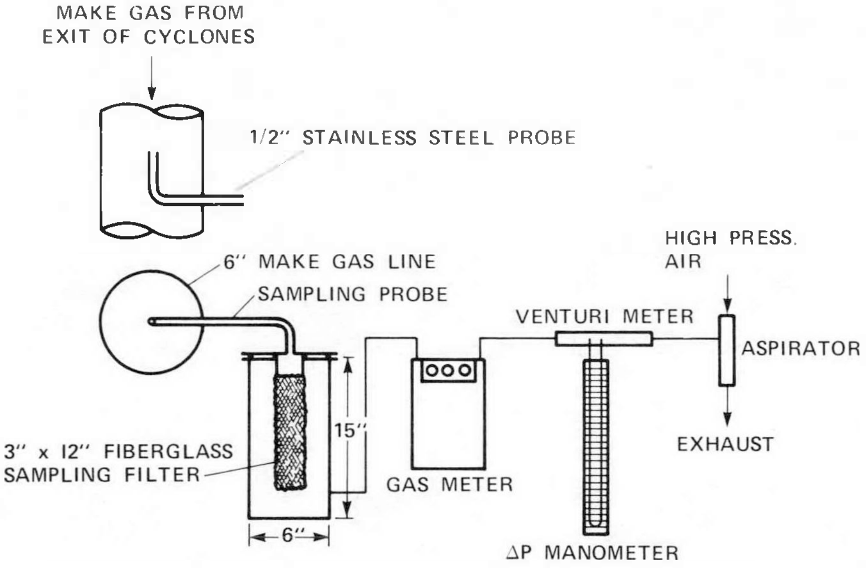


FIGURE 3.4 CYCLONE OUTLET SOLIDS SAMPLING SYSTEM

3.5 SOLIDS LOADING PROCEDURE

The fiberglass filters used for filtering the solid material out of the make gas were first dried in a drying oven and then immediately weighed to obtain an initial weight. A filter was then secured in the filter holder and the apparatus checked for leaks.

Immediately after initiating the sampling procedure the necessary adjustments were made to obtain an isokinetic sampling rate. Sampling time was in the order of 10-15 minutes, whereupon approximately 10 cubic feet of make gas had been sampled. The filter bag was removed from the filter holder immediately after sampling was complete and then weighed to obtain a final weight.

3.6 SOLIDS SAMPLE AT EAST CYCLONE

A ball valve was located at the very bottom of the first cyclone just ahead of the air ejector and was used to obtain a solids sample at this point. The procedure used to obtain a sample was to secure a fiberglass bag at the exit of the ball valve. The valve was then opened permitting gas and solids to enter the bag. The gas flowed through the bag leaving solids behind.

3.7 SOLIDS ANALYSIS

The material collected in a solids loading sample was subjected to a number of analyses:

- Proximate Analysis
- Ultimate Analysis
- Toluene Extraction - for tar determination, as described in Section 3.8.
- Thermogravimetric Analysis - see Section 4.6.1.

The results of the first three analyses are presented in Appendix A under the specific test for which they were run.

The solids sample obtained from the first cyclone was subjected to the following analyses, results of which are given under specific test data in Appendix A:

- Proximate Analysis
- Ultimate Analysis
- Toluene Extraction
- Screen Sizing.

3.8 TAR FORMATION DETERMINATION

Determination of the amount of tars produced by the system was accomplished by toluene extraction of the solid material collected in the fiberglass bag during a solids loading sampling. The toluene extraction procedure was carried out in a Soxlet extraction column and the material which was extracted was defined as tars.

A Soxlet extraction column is shown in Figure 3.5. A small amount of toluene (100 ml) is placed in a heated flask. The toluene distills off and is condensed in the upper portion of the apparatus by a water-cooled condenser. The condensed toluene then runs down into a porous ceramic cup in which the material to be extracted is contained. The toluene with the extracted material flows through the porous cup and back into the heated flask to complete the cycle.

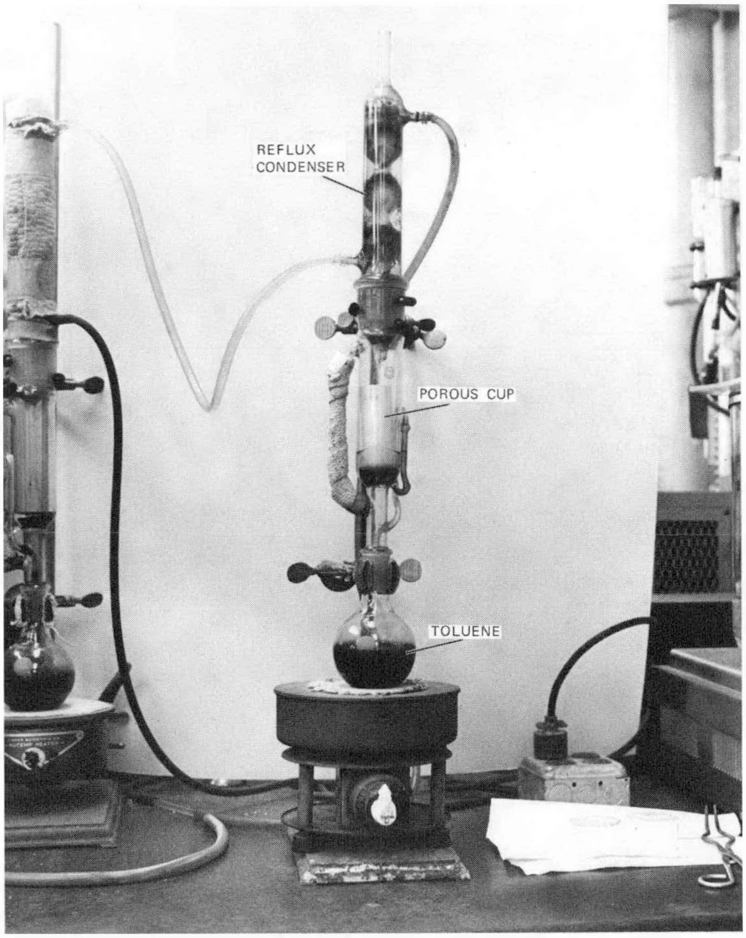


FIGURE 3.5 SOXLET EXTRACTION COLUMN FOR TAR EXTRACTION

The gas temperature was about 800°F at the point where the solids loading was conducted and measurements indicate that the fiberglass filter reached a temperature of 300-400°F within 2 minutes from the start of sampling. This may mean that tars which vaporize below a temperature of 300-400°F may have passed through the filter and were therefore not accounted for. This will be discussed further in a subsequent section.

3.9 PROCESS MEASUREMENTS AND LOCATIONS

The relative locations of previously described gas analysis and solids or particulate loadings are indicated in Figure 3.6. In addition to these measurements other process measurements were made:

- Air and gas temperature
- Air flows by orifice
- Natural gas flows by orifice.

The relative positions of these measurements are shown in Figure 3.6.

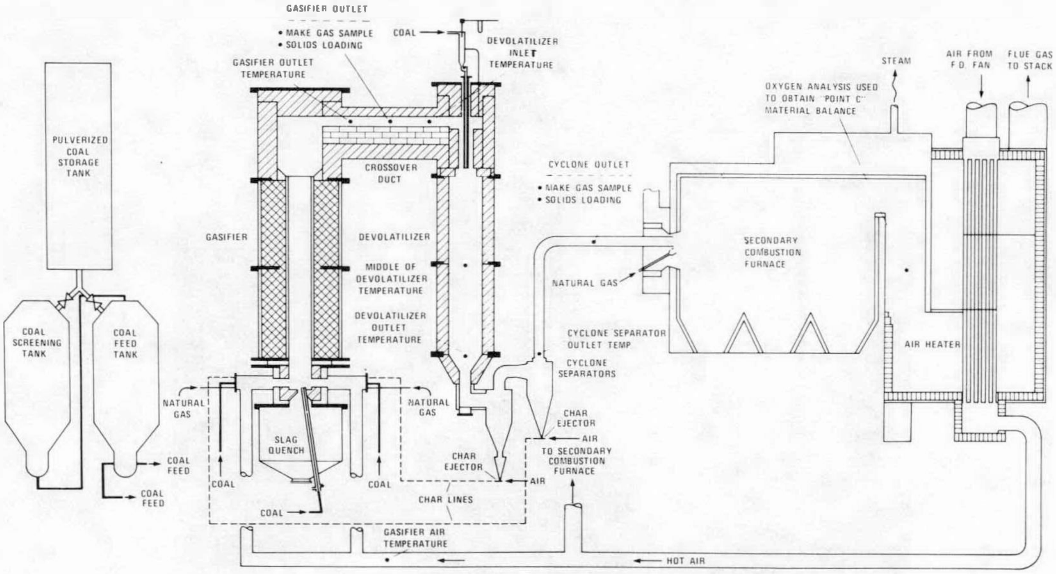


FIGURE 3.6 LOCATION OF PROCESS MEASUREMENTS

3.10 GAS ANALYZER - GAS CHROMATOGRAPH

A Beckman GC-4 gas chromatograph was used to analyze the gas samples. The chromatograph was equipped with a thermal conductivity detector, dual flow controller, temperature programmer, gas sampling valve system and a switching valve arrangement for column switching. A 13-foot x 1/8-inch Teflon column with Poropak QS packing (Waters Associates, Inc.) and a 8-foot x 1/8-inch stainless steel column with molecular sieve packing (Analabs, Inc. 5A Type, 80/90 mesh) was used to separate the gases. Helium was used as the carrier gas.

The data readout system consisted of an electronic integrator with a teletype printout. In addition, a Beckman Recorder was used for a visual display of data. Calibration curves were prepared for each gas by running known concentrations of the gas through the chromatograph. These standards were prepared using the partial pressure technique for gases.

The arrangement and selection of the gas detection columns were chosen based on the following criteria:

1. Short turnaround time for gas analysis
2. Ability to detect all gases of interest.

These criteria were met, but gas concentrations below 3000 ppm were not detectable. Table 3.1 presents a list of the chemical species which the chromatograph was able to detect.

TABLE 3.1 GAS ANALYSIS BY CHROMATOGRAPH

CHEMICAL SPECIES

PARAFFIN SERIES	OLEFIN SERIES	OTHER GASES
METHANE ETHANE PROPANE	ETHYLENE PROPYLENE	HYDROGEN OXYGEN CARBON DIOXIDE CARBON MONOXIDE NITROGEN SULFUR DIOXIDE HYDROGEN SULFIDE CARBONYL SULFIDE ACETYLENE

Section 4

RESULTS AND DISCUSSION

The data obtained during this test program are presented in computer output form in Appendix A. A total of 43 tests were run during the period of October 1975 to April 1976. Of these 43 tests, the data from 32 tests were chosen for analysis because they could be grouped into only four categories of equipment configurations. The eleven omitted tests involved some oxygen enrichment, some employed steam addition, and some test results were obviously erroneous.

Details of the energy and material balances are presented in Appendices B and C, respectively. Appendix D contains a detailed description of a very simple mathematical model that assumes rate control by gas-phase diffusion.

4.1 PRECISION OF MEASUREMENTS

A rather large scatter is evident when make gas heating value is plotted versus percent theoretical air, as in Figure 4.1. Since some of this scatter might be attributed to the precision of measurement, a study was conducted to estimate this for the relevant variables.

4.1.1 Make-Gas Heating Value

Table 4.1 summarizes the precision of measuring make-gas composition. Values of standard deviation were estimated for the concentration of all the gaseous species. The corresponding contributions of each species to total heating value were combined to produce an estimated standard deviation for that quantity using the rule of weighted variances.

4.1.2 Air-Fuel Ratio

It is conventional and convenient to express the air-fuel ratio as "Percent Theoretical Air," or the ratio (expressed in percentage) of the actual air flow rate to that which would be required in order to burn the fuel to its theoretical combustion products of CO_2, H_2O, SO_2, and N_2, with zero O_2, CO, and H_2. Thus coal flow rate, air flow rate, and coal composition could enter into the precision of measuring "Percent Theoretical Air."

Table 4.2 summarizes the results of this particular study. The precision to which the various air flows and coal flow could be determined were estimated based on our judgement of the precision of determination of the manometer differentials, rotameter float position, chart pen position, and time increment.

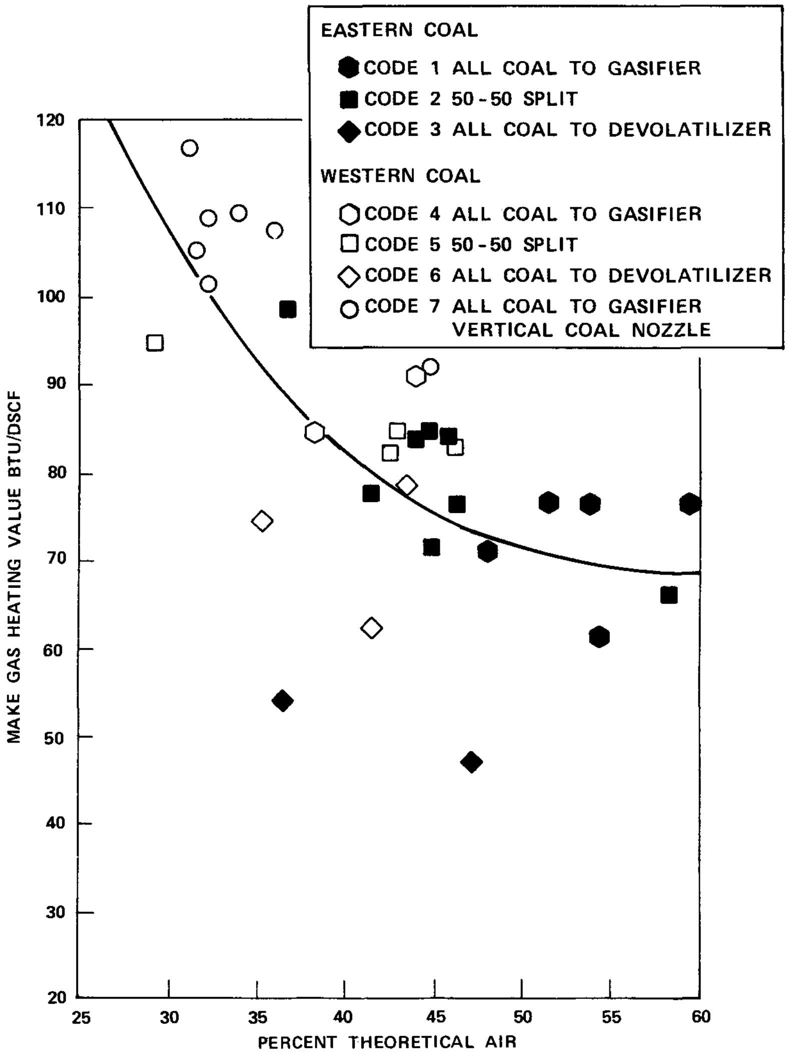


FIGURE 4.1 MAKE GAS HEATING VALUE VERSUS PERCENT THEORETICAL AIR

The variation in the composition of the two coals was estimated based on two complete analyses for each coal. The estimated standard deviation for the Western coal is larger because of the greater uncertainty as to its moisture content; this difference is carried through to the precision of measurement for the air-fuel ratio.

TABLE 4.1 ESTIMATED PRECISION OF MEASUREMENT OF MAKE GAS COMPOSITION

	EST σ, %	H, BTU/SCF	$(\sigma H)^2$
H_2	.20	325	14225
O_2+A	.23	0	
CO_2	.23	0	
C_2H_4	(.1)	1614	26009
C_2H_2	(.1)	1499	22470
C_2H_6	(.1)	1792	32112
H_2S	(.1)	647	4186
N_2	.21	0	
CH_4	(.1)	1013	10261
CO	.26	322	18009
			106,314

$$\hat{\sigma} = \left[\sum (\sigma H)^2\right]^{1/2} = 326\left(\% \times \frac{\text{BTU}}{\text{DSCF}}\right) = \boxed{3.26\,\frac{\text{BTU}}{\text{DSCF}}}$$

TABLE 4.2 PRECISION OF MEASUREMENTS

MEASUREMENT	ESTIMATED STD. DEV.	
	ENGR. UNITS	%
AIR FLOWS		
GASIFIER COMBUSTION AIR	10 LB/HR	1.1*
COAL TRANSPORT AIR	4 LB/HR	0.4*
CHAR EJECTION AIR	3 LB/HR	0.3*
COAL FLOW (AS FIRED)	6 LB/HR	2.1
COAL COMPOSITION ASH, MOISTURE & HEATING VALUE		0.8/2.2**
AIR TO FUEL RATIO***		2.6/3.3**

NOTES: *AS % OF TOTAL AIR FLOW

**EASTERN COAL/WESTERN COAL; THE DIFFERENCE IS DUE TO MOISTURE

***AS % OF RATIO, i.e., 40% THEORETICAL AIR WOULD BE 40 ± 40 (.049) OR 40 ± 2.0% FOR THE ONE-STANDARD-DEVIATION BAND

4.2 EFFECT OF NATURAL GAS FIRING PRIOR TO TESTING

4.2.1 Test Procedure

As preliminary tests have shown (Figure 4.2), the gasifier has a rather long thermal time constant — roughly two hours or more. Therefore, to get it up to gasification temperature quickly, each day's testing was started by firing natural gas at about 115% theoretical air for about two hours. Gasification tests were started at the end of this time; i.e., when the gasifier outlet temperature reached about 2000-2200°F.

Although coal flow to the system was started at this time the natural gas was not completely shut off. In fact during the majority of these tests, about 8 to 51 lb/hr of natural gas was fired in the gasifier at the same time as the coal. This was done to insure that a reducing atmosphere would be present in the event of possible coal or char recycle interruptions. If not for the natural gas, the interruptions would suddenly cause the gas composition to become oxidizing, which might precipitate an explosion or cause very large excursions in temperature.

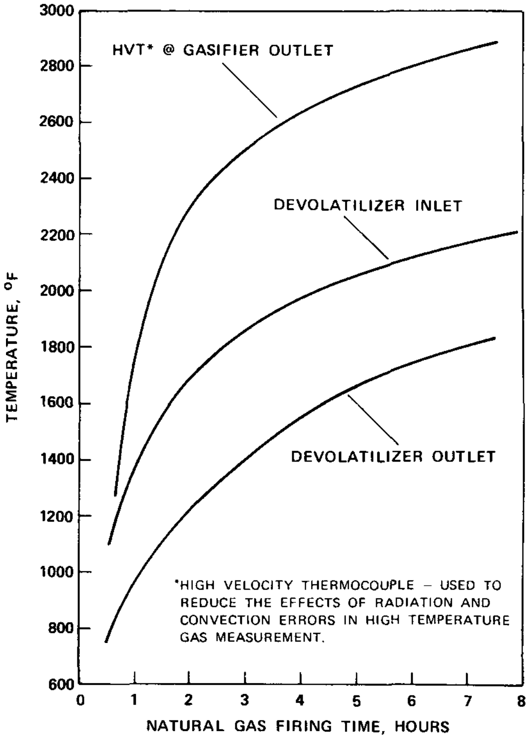
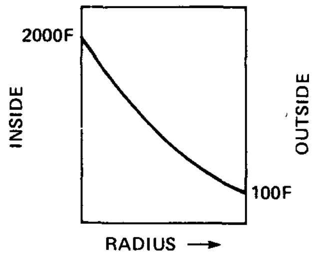


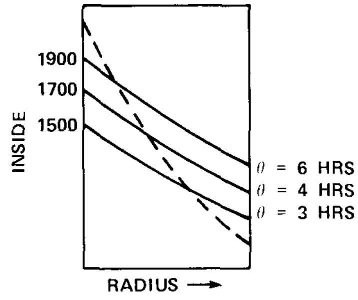
FIGURE 4.2 GAS TEMPERATURE DATA FOR FIRING NATURAL GAS ONLY

4.2.2 Hypothetical Temperature Distribution in Gasifier Wall

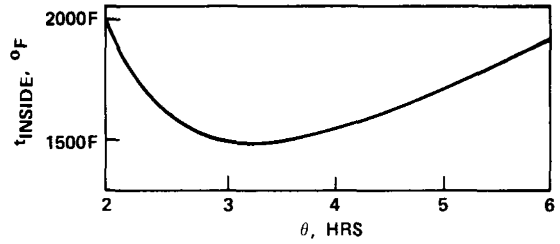
As a result of this method of startup, it is conceivable that the gasifier heat losses could vary systematically during the balance of the day. They might even go through a maximum. How this might happen is illustrated in Figure 4.3, which shows hypothetical temperature distributions in the gasifier wall. For example, Figure 4.3A shows a steep gradient with a high inner-wall temperature immediately on completion of preheating. In Figure 4.3B, after an hour of gasification, the gradient has decreased substantially and, with it, the inner-wall temperature. However, the vessel wall is still not up to steady-state temperature in its entirety. So, at successively longer times, the inner-wall temperature rises again, although the lower gradient is maintained (consistent with the slower heating due to gasification compared with combustion). Figure 4.3C shows the resulting inner-wall temperature as a function of time. Heat losses from the gasification reactions would, of course, follow a complementary path, peaking at some intermediate time. Accordingly, time after startup of the gasifier ("Time of Day") was included as one of the initial correlating variables to be considered in statistical analysis.



A. AT θ = 2 HRS CH_4 FIRING



B. AT LATER TIMES, GASIFYING



C. t_{INSIDE} VS TIME

FIGURE 4.3 POSSIBLE TEMPERATURE PROFILES IN GASIFIER WALL

4.2.3 Statistical Correlation Including "Time of Day"

A non-linear regression analysis was made using make-gas heating value as the dependent variable and "Time of Day," air-fuel ratio, expressed as a fraction of the amount of air that is theoretically required to burn the fuel (coal and natural gas included) completely to CO_2 and H_2O and operating mode as independent variables. Operating mode was broken down into seven cases, coded as follows:

Code No.	Description
1	Eastern Coal, all to gasifier, horizontal burners
2	Eastern Coal, 50-50 split
3	Eastern Coal, all to devolatilizer
4	Western Coal, all to gasifier, horizontal burners
5	Western Coal, 50-50 split
6	Wester Coal, all to devolatilizer
7	Western Coal, all to gasifier, vertical upward nozzle

The functional dependencies on "Time of Day" and air-fuel ratio were required to be the same for all seven cases, but the parameter expressing the mean heating value was allowed to seek a different value for each case.

Results are summarized in Table 4.3. The relative importance of any parameter in the correlation is measured by the "F to remove" value. This value is a ratio of the value of that parameter to the random error associated with the data points about the curve. Thus, if the value contributed by a particular parameter is less than twice the random error about the curve, the parameter can be regarded as relatively unimportant. Therefore, we used a value of 2 as an approximate cut-off point; parameters with an "F to remove" value much less than 2 can be considered unimportant. Based on this criteria the parameters containing the time function (coefficients K_3, K_4, K_5) are relatively unimportant and hence the coefficients can be considered equal to zero for practical purposes.

A plot of the data points based on the above correlation is shown in Figure 4.4. On the vertical axis is plotted make-gas heating value with mode of coal injection and air-fuel ratio taken into account. On the horizontal axis is plotted the elapsed time as measured from the beginning of natural gas firing up until the time the data for that particular test was taken ("Time of Day"). Time was measured from the beginning of natural gas firing for preheat purposes because this time would also contribute to the gasifier inner wall temperature. As confirmed in this plot, no significant correlation exists as far as the time function is concerned.

TABLE 4.3 STATISTICAL CORRELATION OF DATA: AIR-FUEL RATIO, GROUP, AND "TIME OF DAY"

$$H = C_o + \sum_{n=1}^{7} C_n X_n + K_1 A + K_2 A^2 + K_3 \theta + K_4 \theta^2 + K_5 \theta^3$$

A = AIR-TO-FUEL RATIO

H = HEATING VALUE, BTU/DSCF

C_o = CONSTANT

C_n = COEFFICIENT EXPRESSING RELATIVE POSITION OF n-th DATA GROUP

X_n = "DUMMY" VARIABLE HAVING VALUE OF UNITY FOR n-th GROUP AND ZERO FOR ALL OTHERS

K'S = COEFFICIENTS AS ABOVE

θ = TIME OF DAY MEASURED FROM MORNING LITE-OFF

COEFFICIENT	F TO REMOVE	SENSIBLE VALUE
K_1	1.77	-1.589
K_2	0.676	0.0103
K_3	0.418	0
K_4	0.674	0
K_5	1.014	0

CONCLUDE: NO CONSISTENT TREND WITH TIME OF DAY

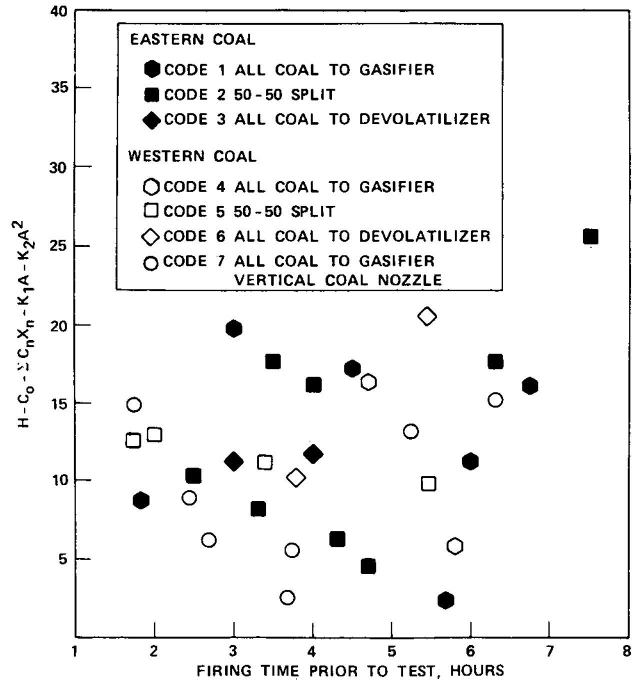


FIGURE 4.4 EFFECT OF TIME OF DAY

4.3 EFFECT OF NATURAL GAS FIRING DURING TESTING

Natural gas was fired in the gasifier during the majority of these tests because of possible interruptions of char recycle. If not for the natural gas, these interruptions would suddenly cause the gas composition to become oxidizing, which might precipitate an explosion or cause very large excursions in temperatures.

Only during the code 7 tests were we confident enough of char recycle to shut off the natural gas. Oddly enough it was during these tests that the highest Btu contents were obtained. So we asked the question, "Could it be possible that the firing of natural gas into the gasifier tended to produce lower Btu values?" To answer this question, two statistical analyses were made. The first is depicted in Figure 4.5 where we have fit the data to an equation of the general form indicated. This general form, quadratic in air-fuel ratio and linear in the amount of natural gas fired, was fitted to the data without regard to the effect of code. Plotted against the amount of natural gas fired is heating value less the effect of air-fuel ratio. From this, it indeed appears that there is a trend for the Btu content to go down as the amount of natural gas increases. However, upon closer examination, there is also a trend as far as code is concerned in that different codes tend to have different amounts of natural gas, e.g., code 1 employed 8-12 lb/hr natural gas, and codes 2, 5, and 6 employed 27 lb/hr natural gas.

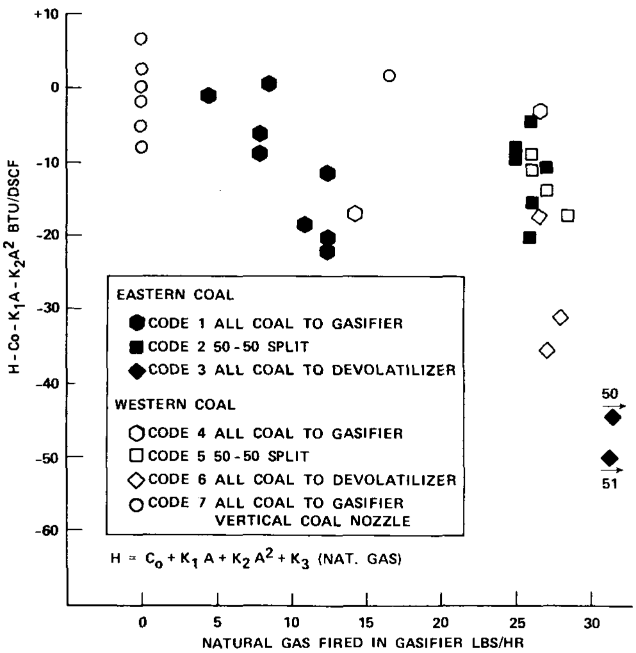


FIGURE 4.5 EFFECT OF NATURAL GAS FIRED IN GASIFIER

Therefore, the correlation was done again. This time, each code was allowed to "float" (so to speak) through the addition of the terms $\sum_{1}^{7} C_n X_n$. In other words the same functional dependencies with respect to air-fuel ratio and amount of natural gas are forced upon each code, but each code is allowed to "seek its own level." Figure 4.6 presents this analysis showing a plot of heating value less the effect of air-fuel ratio and code as a function of the amount of natural gas fired. This analysis indicates that there is no correlation. In other words, although admitting inherent differences among the codes due to equipment arrangement or coal fired, natural gas firing had no effect on the heating value.

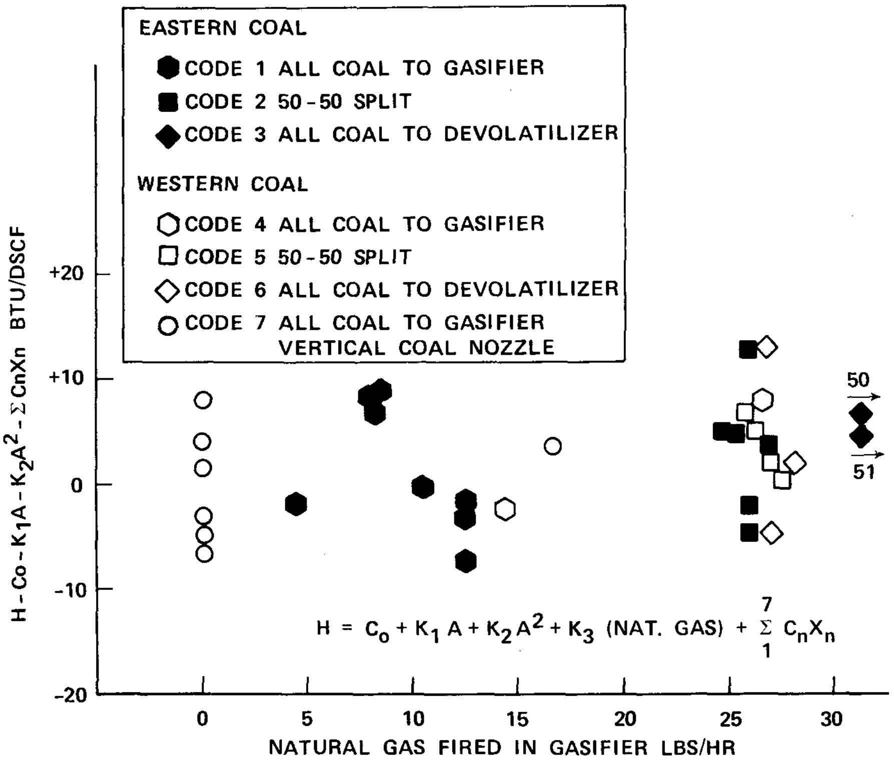
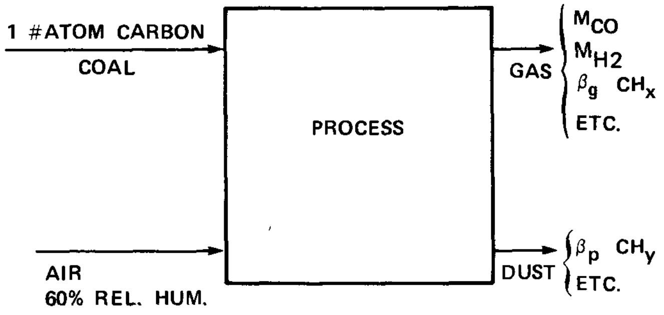


FIGURE 4.6 EFFECT OF NATURAL GAS FIRED IN GASIFIER

4.4 MATERIAL BALANCE

4.4.1 Basis for Material Balance

Figure 4.7 shows the basis for the material balances that were made. The general gasification stoichiometry can be explained as follows. We assume that into the process goes one pound atom of carbon in the form of coal along with some amount of air to give a value of air-fuel ratio, A, defined as moles of air fed per mole of air theoretically required to burn the coal all the way to CO_2, H_2O, and SO_2. The gas produced in the process consists of some quantity of carbon monoxide, hydrogen, and an amount β_g of hydrocarbon gas with an average formula of CH_x. The value of β_g will range up to 0.10. Also coming out of the process is a certain amount of dust, β_p, defined as the fraction of inlet carbon which escapes from the process as char with an average formula CH_y. Thus, the process of Figure 4.7 will give a gas with a heating value which is a function of the A, β_p, and β_g — or approximately just of the air-fuel ratio and the β_p, since, over the range of values encountered, β_g has only a slight effect upon heating value.



A = MOLS AIR/MOL AIR THEORETICAL

HEATING VALUE, $H = f(A, \beta_p, \beta_g) \cong f(A, \beta_p)$

FIGURE 4.7 GASIFICATION STOICHIOMETRY

Table 4.4 shows the various values of β_g, x, β_p, y, and the amount of methane fired that were observed in the tests under consideration. For the material balance calculations, the value of β_g was taken to be 0.06. This choice was made so as to favor code 7 data a little more than the rest. However, the next figure will show that the value of β_g is not very important, anyhow. From Table 4.4 it is obvious that the x value runs at about 2.5, except for codes 4 and 5 where it is equal to 4.0 (indicating that methane was the major hydrocarbon produced). As a typical value for all material balance calculations, we have chosen a value of 2.5.

TABLE 4.4 MATERIAL BALANCE PARAMETERS

CODE NO.	TEST NO.	β_g	x	β_p (MEASURED)	y	PERCENT ASH IN DUST	$\beta'_{N.G.}$ $\frac{\#CH_4\ \text{FIRED}}{\#\text{COAL (WET)}}$
1	1	0	–	–	–	13.08	.06
	2	0	–	–	–	13.08	.06
	3	0	–	.032	–	13.08	.045
	4	0	–	.033	–	13.08	.046
	5	0	–	.122	–	13.08	.052
	6	0	–	.020	–	13.08	.032
	20	.0553	2.5	.119	.110	9.7	.083
	21	0475	2.29	096	–	11.5	.06
	22	0	–	0506	–	13.08	.077
2	9	0366	2.33	–	–	32.8	.15
	10	.0714	2.40	.148	.142	6.7	.144
	11	.0923	2.50	094	–	13.08	.163
	13	.0649	2.40	.114	.446	2.6	.126
	14	.0486	2.29	.129	.386	13.4	.154
	16	.0588	2.50	.096	–	34.6	.17
3	7	.0417	3.57	–	–	13.08	.417
	8	.0556	3.33	–	–	13.08	.28
4	27	.0192	4.0	.127	–	24.7	.122
	32	.0062	4.0	.162	–	24.7	.049
5	24	.0053	4.0	.0919	–	19.9	.119
	28	.0117	4.0	.086	–	24.7	.111
	29	.0128	4.0	.085	.405	26.2	.115
	35	.0204	4.0	.180	–	26.6	.08
6	26	.0194	2.67	.104	–	20.6	.114
	31	.0409	2.67	.118	.576	19.4	.101
	36	.0470	2.91	.066	–	21.8	.12
7	33	.1446	2.60	.125	–	25.5	.050
	34	.1255	2.64	.150	–	26.7	0
	38	.0443	2.50	.051	–	27.05	0
	39	.0705	2.86	.088	.208	29.0	0
	40	.0541	2.00	.144	–	27.05	0
	42	.0412	2.50	.104	–	27.05	0
	43	.0886	2.25	.096	.220	27.0	0

The value for β_p, Table 4.4, varied so much that we felt we couldn't pick an average, so we retained the individual values for each run. The value of y, the hydrogen-to-carbon ratio in the char, was chosen as a typical value of 0.22, again favoring the code 7 data.

The last column in Table 4.4 represents the methane fired in the gasifier in terms of pounds of methane per pound of coal fired. The individual values were used in calculating the air-fuel ratio; that is, the amount of methane fired was counted as part of the fuel in calculating air-fuel ratio.

4.4.2 Effect of Amount of Hydrocarbons on Heating Value

As we have already noted, within the range, 0-0.10, the value of β_g is relatively unimportant as far as heating value is concerned. This is shown in Figure 4.8 where the calculated heating value of the make gas is plotted against air-fuel ratio. This plot assumes 100% carbon utilization, i.e., no carbon loss from system. A fictitious hydrocarbon, $CH_{2.5}$, has been assumed and its amount, β_p, has been varied from 0 to 0.10. As will be seen there is only a small effect. Thus, a value of 0.05 or 0.06 could represent the entire range. It is interesting to note that, at a given air-fuel ratio, the more hydrocarbon in the gas, the lower the resulting Btu value. The reason for this is that the formation of hydrocarbons from CO_2 and hydrogen is exothermic, as is demonstrated by the heating value formulas of Figure 4.9.

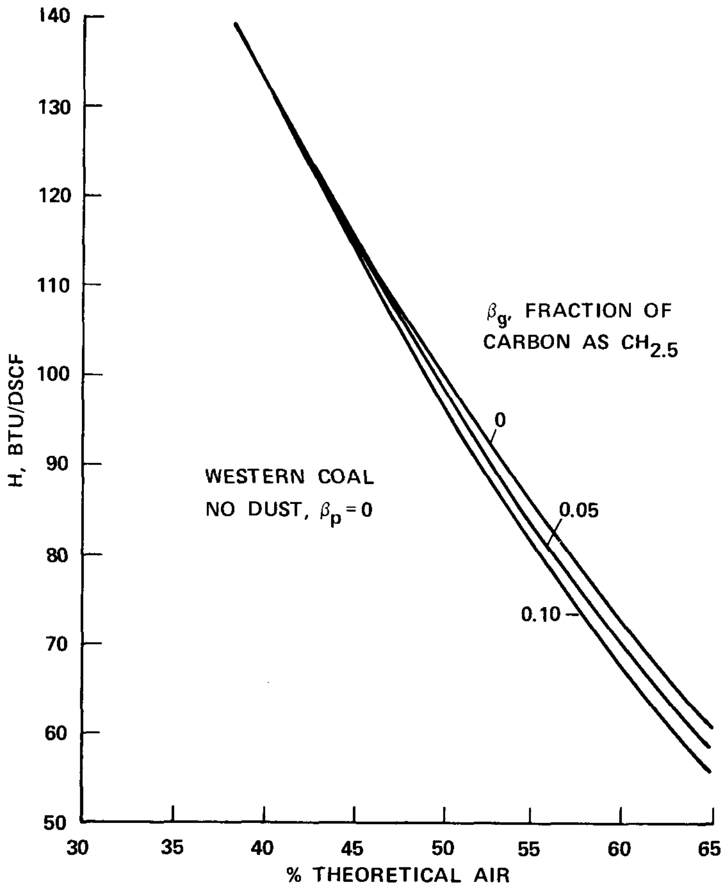


FIGURE 4.8 EFFECT OF AMOUNT OF HYDROCARBONS ON STOICHIOMETRIC HEATING VALUE

$$H = \frac{121{,}675\ M_{CO} + 122{,}891\ M_{H_2} + 284{,}287\ M_{H_2S} + (240200 + 20160X)\ M_{CH_x}}{387\ (\Sigma\ M - M_{H_2O})}$$

$$M_{CO} + M_{CO_2} + M_{CH_x} = \frac{W_c}{12} \quad \frac{\text{MOLS}}{\#\text{DRY COAL}}$$

$$\frac{\partial H}{\partial M_{CH_x}} = [290{,}600 - 2(121{,}675) - \frac{2.5}{2}(122{,}891)]/387\ (\Sigma\ M - M_{H_2O})$$

$$= -106{,}364/387\ (\Sigma\ M - M_{H_2O})$$

FIGURE 4.9 COMPUTATION OF GAS HEATING VALUE

4.4.3 Check of Heating Value and Particulate Loading

Figure 4.10 is a plot of heating value against air-fuel ratio with lines of constant percentage of carbon appearing as char. Put another way, these are lines of constant carbon utilization. The data from the code 7 tests has been plotted on this graph, and beside each data point is the "actual" amount of char in the gas as measured by sampling the gas. It will be noted that the percentage of carbon dictated by stoichiometry (i.e., by the position of the point with respect to the β_p graph) and that actually measured do not generally agree. For example, the point located at about 45% theoretical air lies on a 15% carbon line; however, only 6% was actually measured by sampling. This kind of discrepancy is also evident for all of the other data. The implication is, of course, either that we measured the heating value of the gas wrong or that we measured too little char in the gas.

We made several checks in an effort to verify the heating value data. The first of these is summarized in Figure 4.11. We attempted to condense out in a flask all of the low boiling hydrocarbons in the sample stream. As indicated, most of the condensed liquid appeared to be water as determined by distillation tests with little, if any, tars or oils. This implies that we did not miss low-boiling hydrocarbons in our gas analysis because there were none. Figure 4.12 summarizes the results of a second test of this nature. A solid residue was condensed out in this case, and infrared analysis showed it to be naphthalene. The quantity, however, was very small and would account for only about 0.5 Btu in heating value. A check was also made on the ability of our gas chromatograph to detect gaseous species present in significant quantities (>3000 ppm). This was done by sending duplicate samples out to another lab for analysis (Gollob Analytical Service). The results of these analyses agreed closely with our own, Table 4.5. In neither case did the outside lab find significant quantities of hydrocarbons which we did not detect.

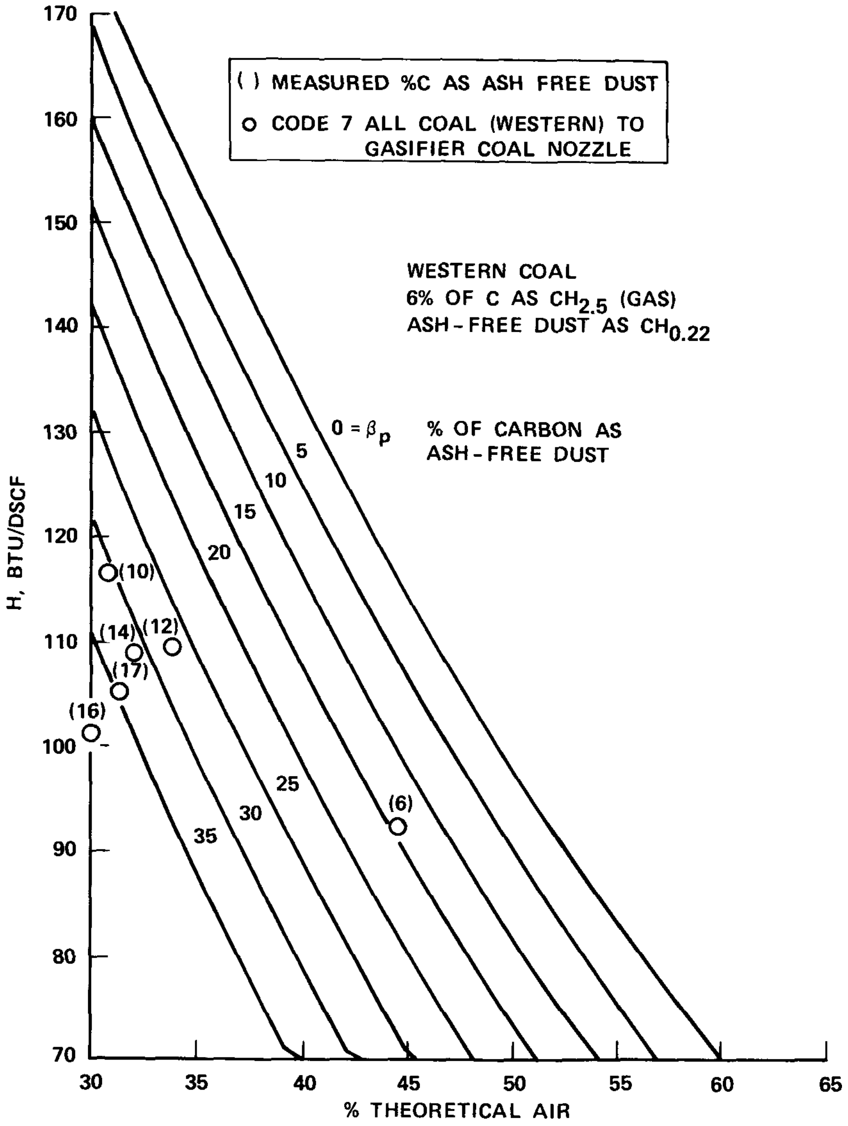


FIGURE 4.10 COMPARISON OF CODE 7 DATA WITH THEORY

DATE / TIME	VOLUME GAS SAMPLED	SOLIDS CAUGHT IN GLASS BAG	MATERIAL CONDENSED
5/14/76 / 0949	14.35 FT^3	10.24g.	21.01g.
5/14/76 / 1035	17.18 FT^3	28.06g.	25.54g.

ALL COAL BEING FED TO VERTICAL GASIFIER NOZZLE

A DISTILLATION TEST ON THIS LIQUID SHOWED THAT ALL OF IT DISTILLED OFF AT 100°C INDICATING THAT IT WAS WATER. VERY LITTLE TARS, OILS, OR OTHER MATERIAL WAS EVIDENT IN EITHER SAMPLE.

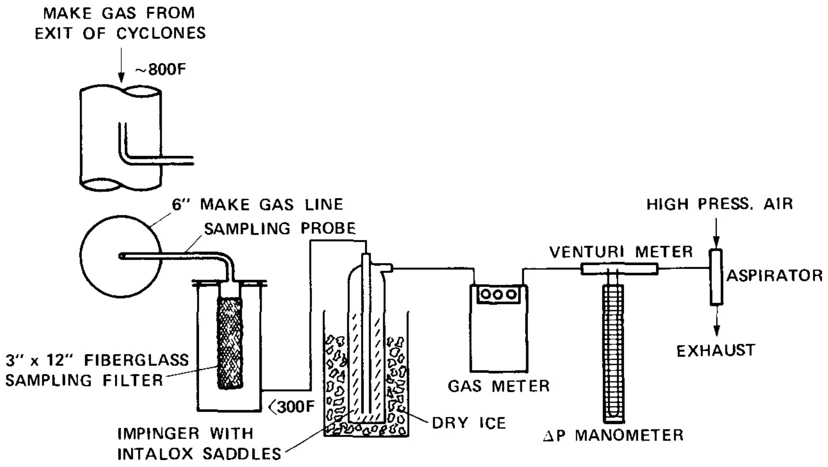


FIGURE 4.11 DRY ICE CONDENSATION TESTS

TEST #	VOLUME GAS SAMPLED	SOLIDS CAUGHT IN GLASS BAG	SOLID RESIDUE COLLECTED BY ICE BATH	SOLIDS FROM GLASS BAG #/HR	SOLIDS FROM ICE BATH #/HR	HEATING VALVE OF RESIDUE (ASSUME NAPHTHALENE)	ICE BATH RESIDUE AS % OF SOLIDS CAUGHT IN BAG FILTER
43	18.1 FT^3	18.08g	0.27 grams*	34.06	0.51	$0.54 \frac{BTU}{SCf}$	1.5%

*IDENTIFIED BY IR AS PRIMARLY NAPHTHALENE

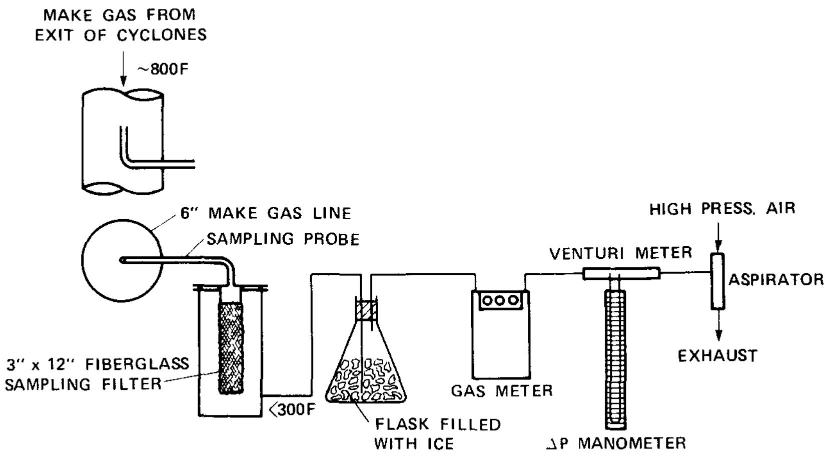


FIGURE 4.12 ICE BATH COLLECTION TEST

TABLE 4.5 GAS ANALYSES – COMPARISON OF ARC AND GOLLOB ANALYTICAL SERVICE

SAMPLE DESCRIPTION	DEVOLATILIZER* OUTLET TEST 29 GOLLOB ANALYTICAL SERVICE	DEVOLATILIZER** OUTLET TEST 29 ARC	DEVOLATILIZER* OUTLET TEST 30 GOLLOB ANALYTICAL SERVICE	DEVOLATILIZER** OUTLET TEST 30 ARC
NITROGEN (N_2)	BALANCE (65.7)	65.1	BALANCE (62.0)	60.1
OXYGEN + ARGON (O_2 + Ar)	0.132	0.9	0.582	0.9
CARBON MONOXIDE (CO)	15.0	15.1	19.4	18.0
CARBON DIOXIDE (CO_2)	8.7	8.4	7.7	9.5
HYDROGEN (H_2)	9.7	10.2	9.6	11.3
HELIUM (He)	0.015	(1)	0.057	(1)
CARBONYL SULFIDE (COS)	0.026	0	0.023	0.3
SULFUR DIOXIDE (SO_2)	–	0	–	0.3
METHANE (CH_4)	0.49	0.3	0.41	0.3
ACETYLENE (C_2H_2)	–	0	–	0.3
ETHYLENE (C_2H_4)	–	0	–	0.3
ETHANE (C_2H_6)	0.14	0	0.17	0.3
PROPENE (C_3H_6)	–	0	–	0.3
PROPANE (C_3H_8)	0.018	0	N.D.	0.3
BENZENE (C_6H_6)	0.013	(2)	0.0090	(2)
TOLUENE (C_7H_8)	0.0085	(2)	0.0045	(2)
ORGANICS (C_4-C_6 MIXTURE)	0.058	(2)	0.052	(2)

*ALL ANALYSES BY MASS SPECTROMETER EXCEPT CARBON MONOXIDE (GAS CHROMATOGRAPH).

**ALL GAS CHROMATOGRAPH.

(1) CHROMATOGRAPH CARRIER GAS

(2) NOT MEASURED

In the area of particulate measurement, we ran two checks on the effectiveness of the fiberglass sampling bag. The experimental setup and results of these checks are shown in Figure 4.13. It will be noted that less than 2% of the material got through the fiberglass fiber.

From the results of these checks, we concluded that:

1. The measured heating values are substantially correct.
2. The missing particulate was probably flowing around the sampling tube in the make-gas line.

TEST =	FIBERGLASS FILTER BAG CATCH, GMS	BACK-UP FILTER CATCH, GMS	= SOLIDS/HR BASED ON BAG FILTER	= SOLIDS/HR CAUGHT BY BACK-UP FILTER	% OF SOLIDS GETTING THRU BAG FILTER
11	4.65	0.07	15.88	0.24	1.5%
12	5.23	0.03	14.17	0.08	0.60%

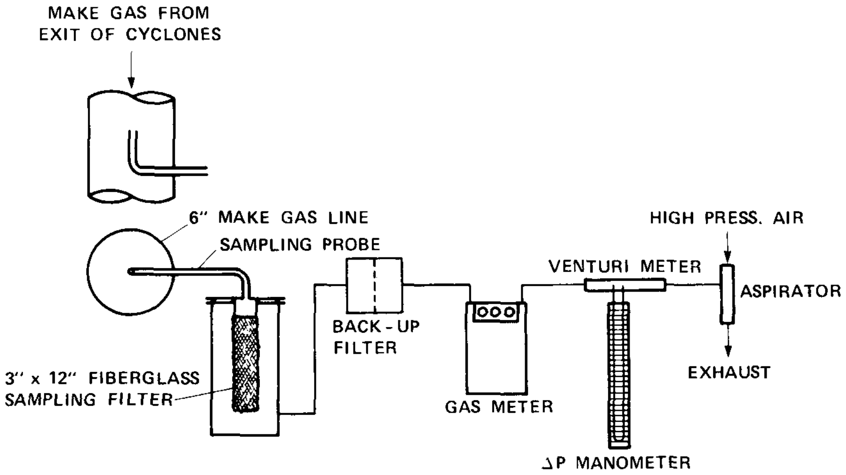


FIGURE 4.13 BACK-UP FILTER TESTS

4.4.4 Comparison of Data with Theory

Figures 4.14 through 4.17 present all 32 runs on H-A type plots, grouped according to code. As previously noted in connection with code 7 data, the measured amounts of particulates are far below what they must be if the heating values and air-fuel ratio are correct (which we believe they are). These plots can be used to read off the correct β_p values.

4.4.5 Carbon Balance at Cyclone Exit

The information from the previous four figures can be presented in another form as shown in Figures 4.18 and 4.19. Here we have plotted stoichiometrically required amounts of particulate versus that found by measurement at point B, the exit of the cyclones. Theoretically, the points should fall on a 45-degree line; however, as seen for the Eastern coal, the points are scattered above such a line with a few points below. The data for the Western coal are somewhat better in that there is a fairly good empirical correlation. Still, it is far from a 45-degree line.

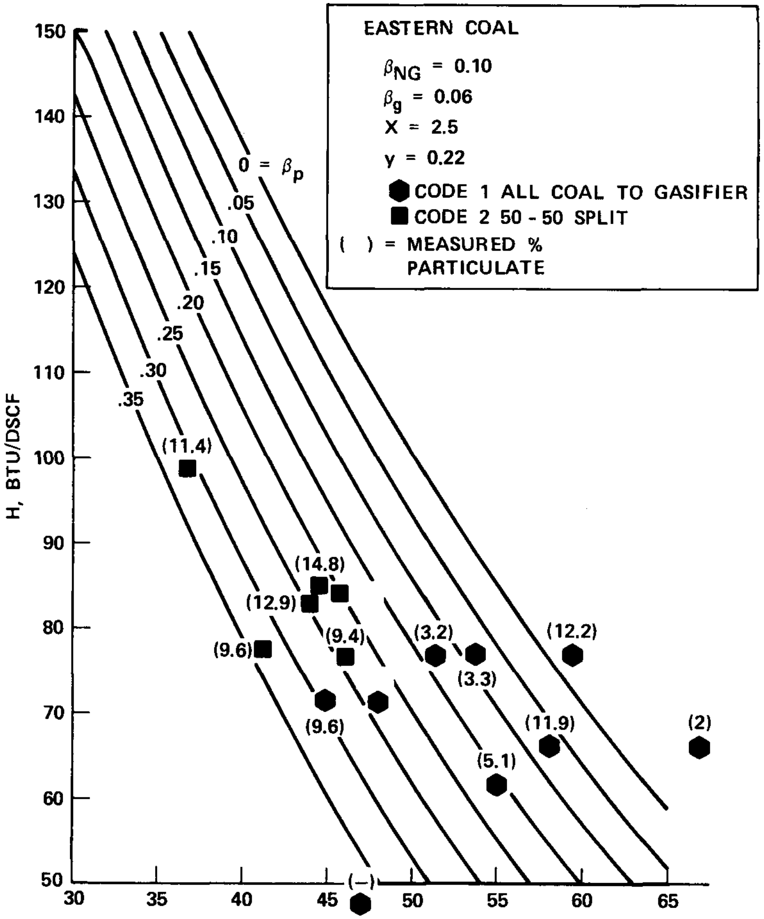


FIGURE 4.14 COMPARISON OF CODE 1 & 2 DATA WITH THEORY

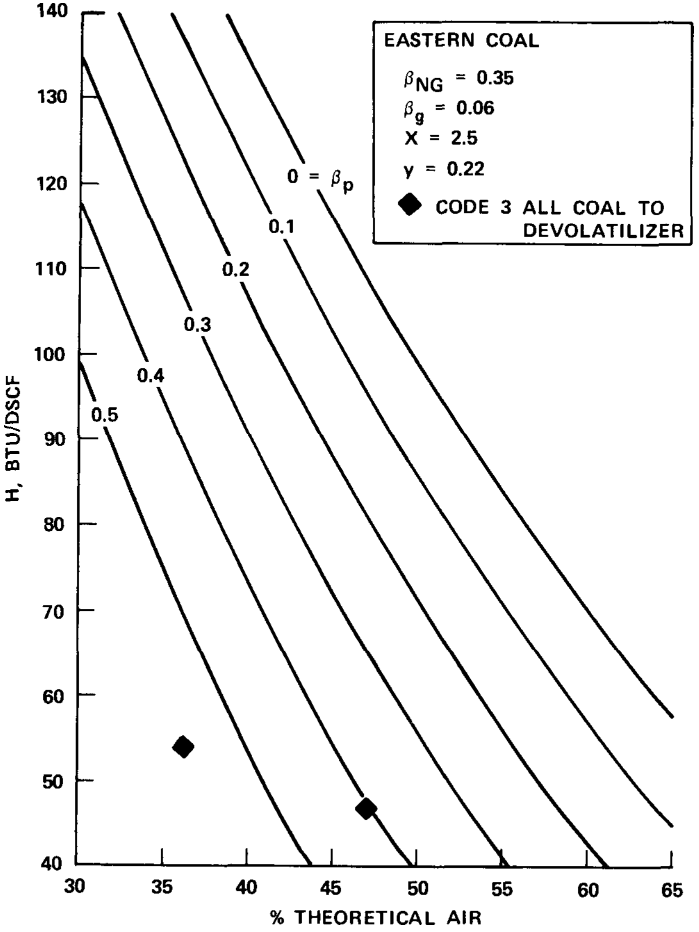


FIGURE 4.15 COMPARISON OF CODE 3 DATA WITH THEORY

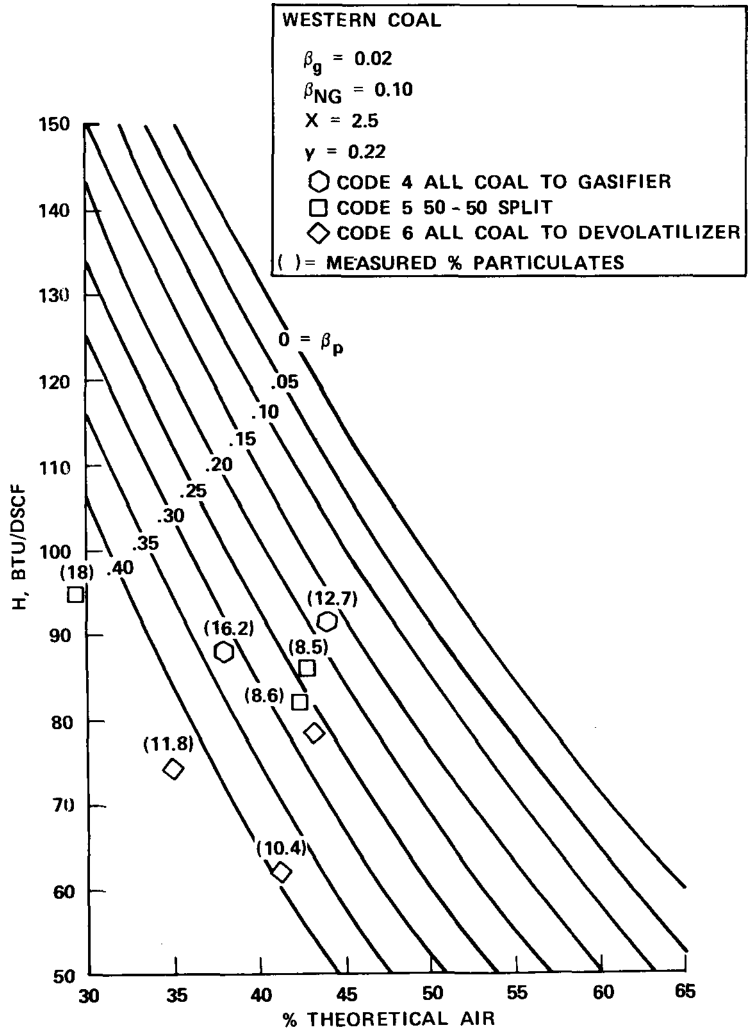


FIGURE 4.16 COMPARISON OF CODE 4, 5, 6 DATA WITH THEORY

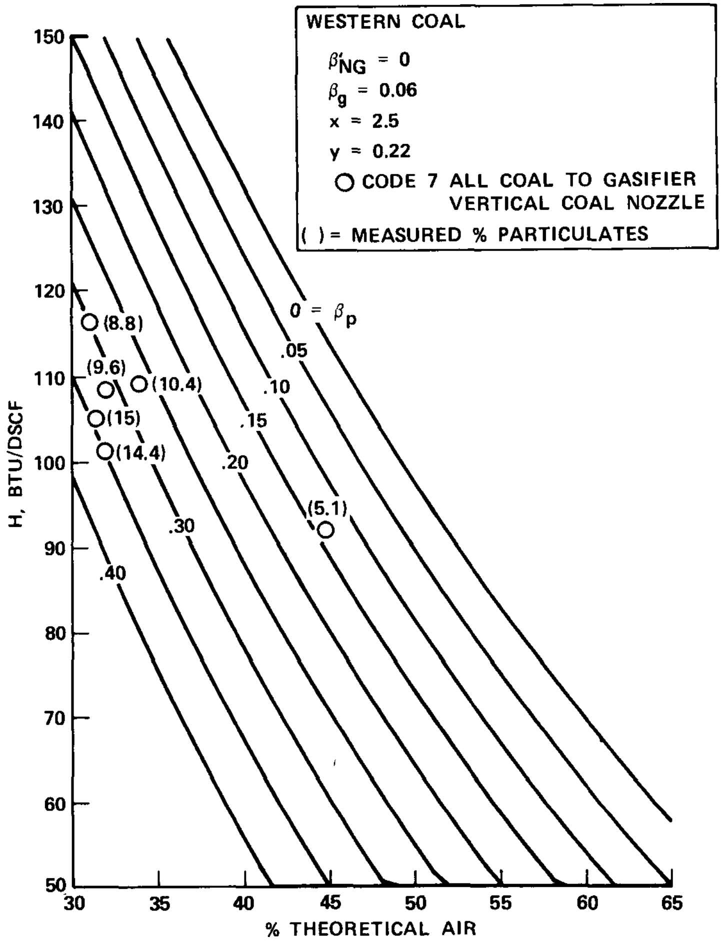


FIGURE 4.17 COMPARISON OF CODE 7 DATA WITH THEORY

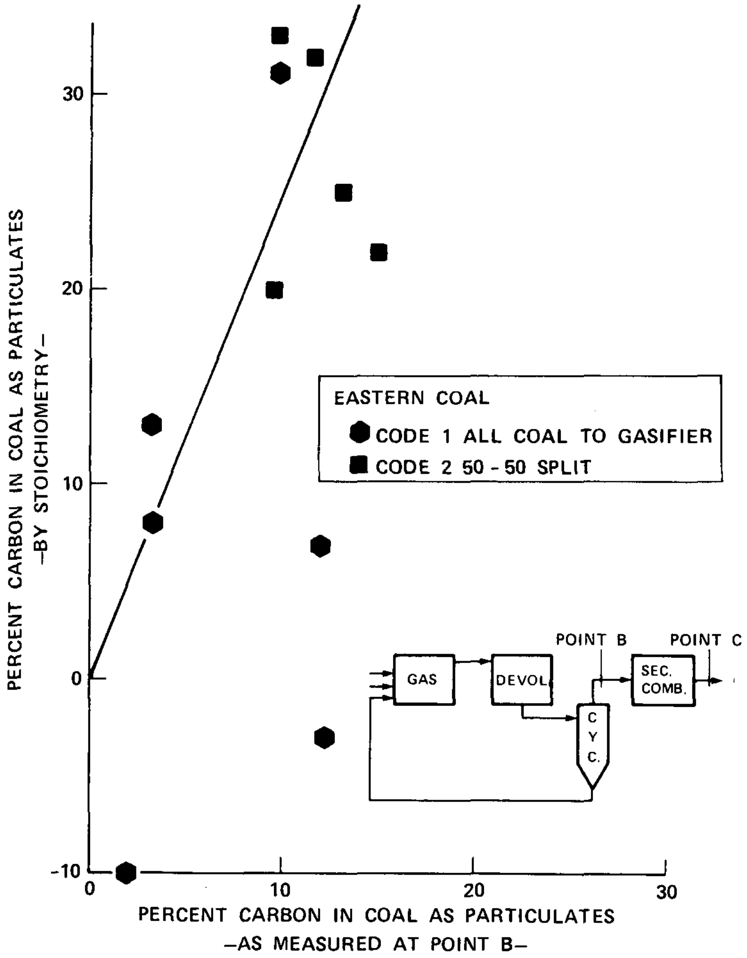


FIGURE 4.18 CARBON BALANCE AT POINT B — EASTERN COAL

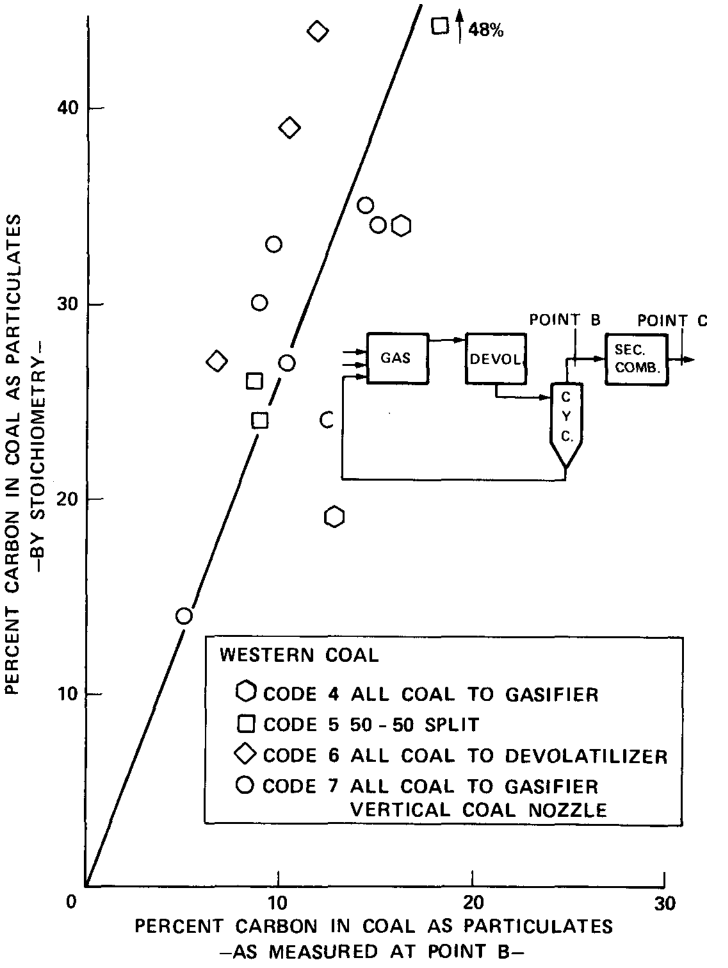


FIGURE 4.19 CARBON BALANCE AT POINT B — WESTERN COAL

4.4.6 Carbon Balance at Secondary Combustion Furnace

A second kind of carbon balance was made at point C, the exit of the secondary combustion furnace. For this balance we took the percent carbon as particulates which we found experimentally at point B and corrected it for the additional carbon found at point C. This new carbon balance is shown in Figures 4.20 and 4.21 for the Eastern and Western coals, respectively. For the Eastern coal, the data points are still widely scattered. For the Western coal, Figure 4.21, the correlation is better but all the carbon is still not accounted for.

4.4.7 Carbon Balance as a Function of Air-Fuel Ratio

Perhaps a more revealing way of presenting the carbon balances is that represented by Figures 4.22 and 4.23. Percent carbon accounted for at points B and C is plotted against air-fuel ratio. The open points represent the carbon balance at point B, and the solid points represent the carbon balance at point C.

Looking first at the data for Eastern coal, Figure 4.22, it is evident that in the majority of the tests more carbon was found at point C than at point B. However, sometimes when the points are close together the reverse is true. In any event, there is a definite tendency to miss carbon at points B and C at the lower air-fuel ratios. This implies more and more carbon was lost from the system as the air-fuel ratio decreased.

There are three possibilities that might account for our inability to account for all of the carbon:

1. Deposition of carbon within the system.
2. The carbon actually went through the secondary combustion furnace but did not burn completely. (There is some evidence that the solids slugged through the system which may account for its not all being burned.)
3. The oxygen analyzer at point C may have been inaccurate or subject to flow stratification causing a higher than actual oxygen reading. (If this were the case, however, one wouldn't expect a trend with air-fuel ratio.)

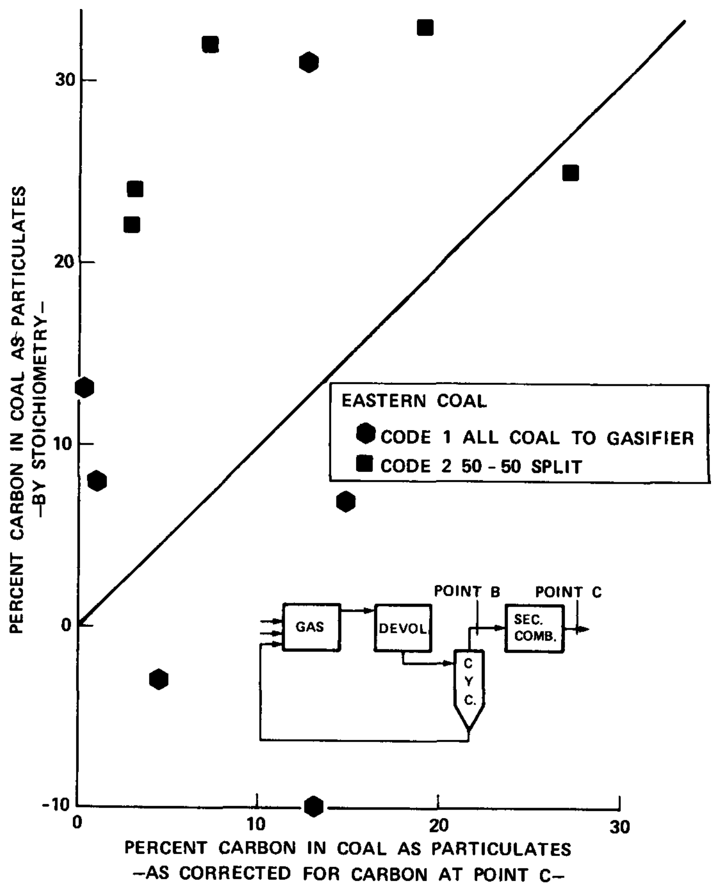


FIGURE 4.20 CARBON BALANCE AT POINT C

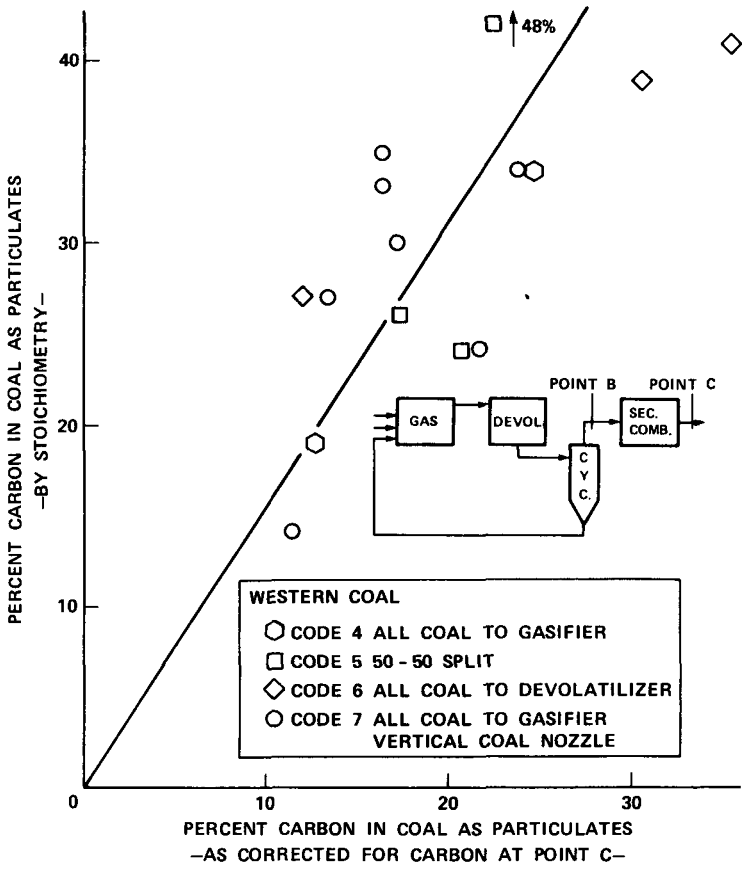


FIGURE 4.21 CARBON BALANCE AT POINT C — WESTERN COAL

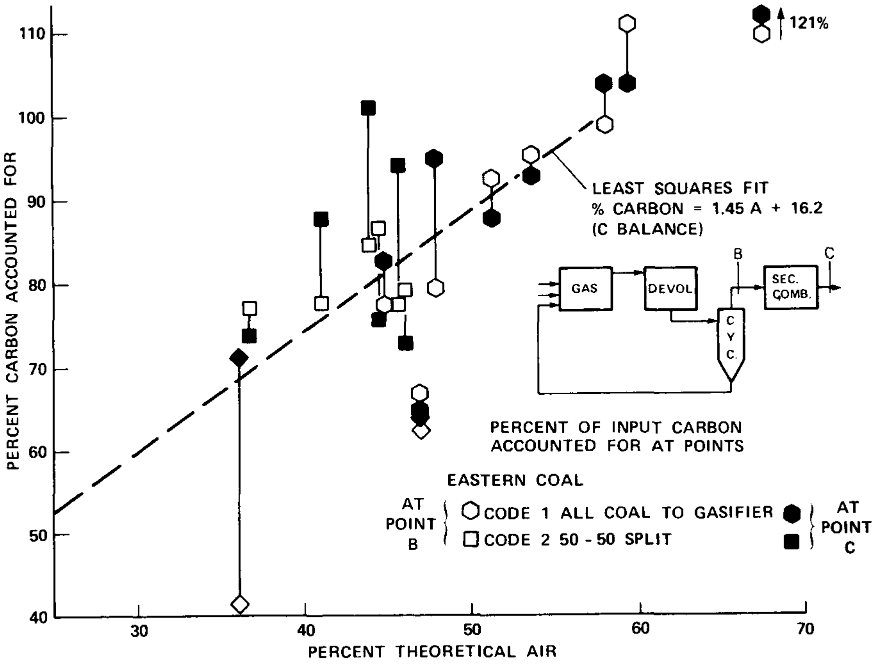


FIGURE 4.22 EFFECT OF THEORETICAL AIR ON CARBON BALANCE

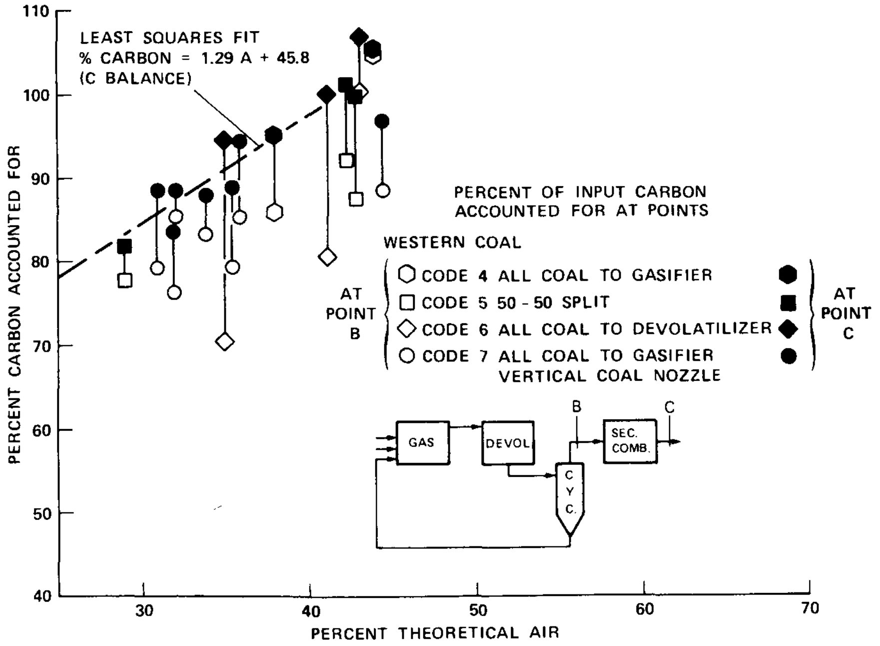


FIGURE 4.23 EFFECT OF THEORETICAL AIR ON CARBON BALANCE

In any event, the solid points in Figure 4.22, carbon balance at point C, indicate that at about 58% theoretical air we should be able to get 100% carbon utilization in this apparatus.

The data for western coal, Figure 4.23, are a little more consistent in that the point-C balance always indicates more carbon accounted for than the point-B balance. As for the Eastern coal data, the same trend is evident as far as a decrease in carbon accounted for at lower air-fuel ratios. A least-squares fit through the point-C data indicates that 100% carbon utilization might be achieved in this apparatus at an air-fuel ratio of about 43%.

4.5 ENERGY BALANCE

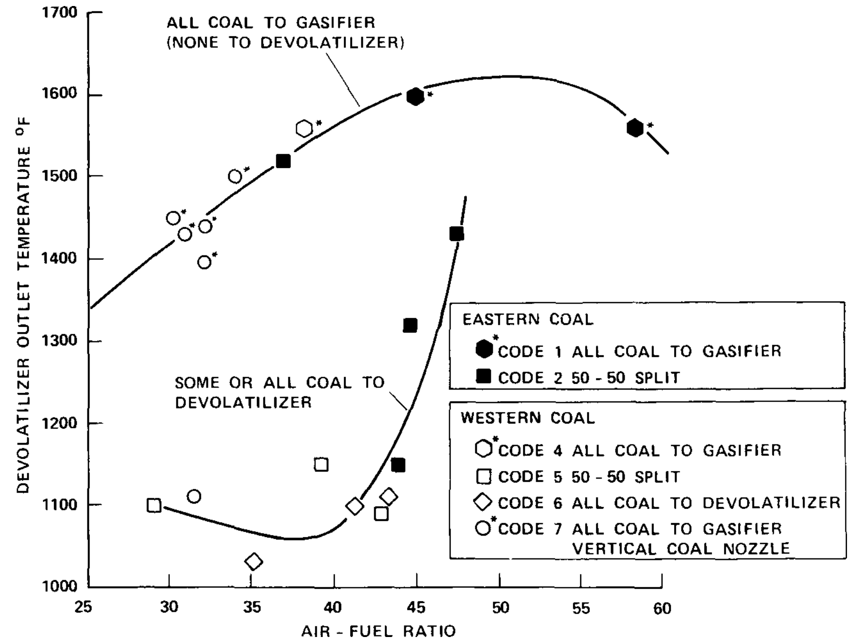
4.5.1 Devolatilizer Outlet Temperature Versus Air-Fuel Ratio

The curves shown in Figure 4.24 represent the measured devolatilizer outlet temperature as a function of air-fuel ratio. One curve (the upper one) applies where no coal was fed to the devolatilizer. The other applies where some coal was fed to the devolatilizer. Considering for a moment that the devolatilizer outlet temperature is virtually the same as the process outlet temperature (to a first approximation), then at a given air-fuel ratio, the devolatilizer outlet temperature should be unaffected by the point of coal injection. However, this expectation is not borne out by the data. This strongly suggests that the thermocouple at the devolatilizer outlet was getting fouled by tars and, therefore, reading low when coal was fed to the devolatilizer. True, there are other factors that might affect this situation, but they are best analyzed via energy balance.

4.5.2 Energy Balance Boundaries

Figure 4.25 shows the gasifier process and boundaries that were used to make the various energy balances. Three pieces of equipment are involved:

1. Gasifier
2. Devolatilizer
3. Cyclone Separators.



*AIR-FUEL RATIO IS EXPRESSED AS A FRACTION OF THE AMOUNT OF AIR THAT IS THEORETICALLY REQUIRED TO BURN THE FUEL (NATURAL GAS AND COAL INCLUDED) COMPLETELY TO CO_2 AND H_2O.

FIGURE 4.24 EFFECT OF AIR-FUEL RATIO ON MEASURED DEVOLATILIZER OUTLET TEMPERATURE

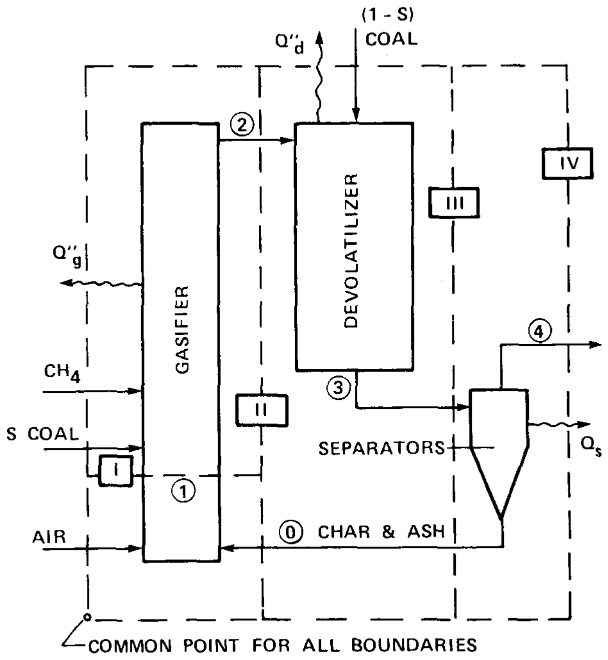


FIGURE 4.25 ENERGY BALANCE BOUNDARIES

Four different energy balances were made and these are described below:

Balance IV	This balance is around the whole process and is useful for calculating the exit temperature, T_4, leaving the cyclone separators.
Balance III	This balance is cut just ahead of the cyclone separators and is useful for calculating T_3, the temperature at the devolatilizer exit.
Balance II	This is just around the gasifier and is used for calculating the gasifier outlet temperature, T_2.
Balance I	This balance is around the bottom portion of the the gasifier. The assumption is made that at the bottom of the gasifier all of the oxygen is used for forming CO_2 and H_2O with no further H_2 nor CO reactions taking place. This permits the calculation of the maximum temperature that might be achieved in the gasifier.

4.5.3 Energy-Balance Assumptions

A number of assumptions were made for simplicity:

1. No chemical reactions occur in the cyclone separators; their only function is to separate the char from the gas.
2. Separator efficiency was assumed to lie between 80 and 95%, since data was not available to calculate this parameter.
3. The material balance closes. (This may appear to be questionable since it has been shown that the material balance rarely closed, often by a wide margin. However, it will be shown later that this assumption is justifiable.)
4. The make gas contains N_2, CO_2, CO, H_2O, and H_2 in water-gas shift equilibrium (down to 1700°F) plus a small amount of CH_x (gas) and CH_y (solid). All sulfur appears as H_2S. Note that the water-gas shift reaction has very little enthalpy change associated with it.)
5. Steady state. (This assumption was found to be not true and later abondoned.)

6. No reaction in the devolatilizer other than devolatilization; e.g., no char is gasified. (From our gas-composition data we believe that this is not quite right; no other assumption is feasible at this point. The result is that our calculated values of T_2 should be a little lower than reality. In other words, there should be a temperature drop across the devolatilizer due to actual gasification reactions which we are neglecting for analysis purposes.)

7. At T_1 all the oxygen reacts with char to form only CO_2 and H_2O; no CO, H_2, H_2S, or CH_x are formed.

4.5.4 Summary of Steady-State Heat-Loss Calculations

Figure 4.26 presents a summary of heat-loss calculations. As indicated in this figure, all the heat losses were broken up and assigned to the three major pieces of equipment: (1) gasifier, (2) devolatilizer, and (3) cyclone separators.

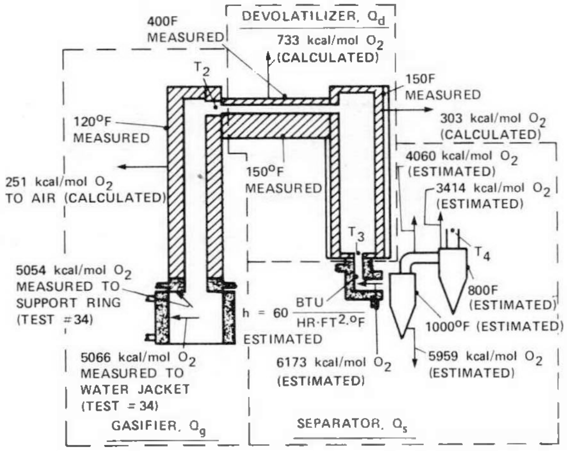


FIGURE 4.26 SUMMARY OF STEADY-STATE HEAT-LOSS CALCULATIONS

A brief description of these heat losses and their method of calculation follows:

Gasifier Water Jacket - This heat loss was calculated from measured water flow rates and inlet and outlet temperatures.

Water-Cooled Support Ring - This heat loss was calculated using measured water flow rates and inlet and outlet temperatures. (Note: This support ring was removed just prior to Test 39 and was not reinstalled.)

Gasifier Surface - The outside surface temperature of the gasifier was measured at various times and at various positions along its length. The heat loss was estimated using an average overall temperature and an estimated convection coefficient to the surrounding air.

Crossover Pipe - Heat loss was calculated using measured surface temperatures taken during a couple of tests and an estimated convection coefficient to the surrounding air.

Devolatilizer Surface - Heat loss was calculated using measured surface temperatures and an estimated heat transfer coefficient of the surrounding air.

Water-Cooled Elbow at Devolatilizer Exit - The heat loss at this point presented a problem because neither water flow nor temperature was measured. We estimated the heat transfer coefficient from the gas to the metal wall via the Colburn equation and assumed the metal temperature to be 212°F. Actually, the Colburn equation should underestimate the heat transfer coefficient 1) because the equation applies for fully developed flow, whereas the elbow represents an entrance condition; 2) because the elbow is curved, whereas the Colburn equation presumes a straight pipe; and 3) because the particulate should tend to raise the coefficient over and above that for a clean gas. On the other hand, as a result of the low surface temperature of the elbow, considerable buildup of sticky tars and char might occur, and these could decrease the heat transfer coefficient by as much as an order of magnitude. Thus, the calculated value of the heat transfer coefficient (60 $\mathrm{Btu/hr\text{-}ft^2\text{-}^\circ F}$) is quite uncertain. The possible effect of this uncertainty will be discussed later.

Cyclone Separators - A heat loss by convection and radiation was estimated from an estimated surface temperature. The surface temperature estimate was based on a measured inlet gas temperature and the fact that the cyclones were not hot enough to give off visible radiation. This put an upper limit on the temperatures.

4.5.5 Effects of Assumptions

4.5.5.1 Carbon Balance Study. One of the assumptions made in the energy balance calculations was that the material balance closes, i.e., all the input carbon is accounted for at the exit of the system. However, this was rarely the observed case; and we would like to discuss here the effect of this assumption.

Two runs (runs 40 and 43) were selected that display a relatively large carbon imbalance. To estimate the effect of the imbalance, the air-fuel ratio was "corrected" so as to make the carbon into the system equal to the carbon out. This had the effect of raising the air-fuel ratio as indicated in Table 4.6. For example, the actual air-fuel ratio for run 43 was 0.321 while the "corrected" value for run 43.1 was 0.397. We then computed the energy balances using these "corrected" values of A, and the results are as shown in Table 4.6. (In all cases, temperatures, T_4, were forced to equal the measured values by adding additional heat losses. We'll discuss the reason for doing this later.) Comparing the T_3 values of Table 4.6, we note that the "corrected" values are a little over 100°F higher than the uncorrected. The T_2 temperature (into the devolatilizer) went up about 200°F in both cases. We can conclude from this that, in spite of the fact that the material balances didn't always close, the calculated temperatures are fairly accurate.

4.5.5.2 Cyclone Efficiency Study. Table 4.7 presents the results of a study to determine the effect of the assumed value of cyclone efficiency upon the results of the energy balance. We've taken run 43 and varied the cyclone efficiency from 80 to 90 to 95%, holding everything else constant. Here again the system outlet temperature, T_4, has been forced to equal the measured outlet temperature by the addition of heat losses. The effect of going from 80 to 90% and 90 to 95% cyclone efficiency is about 100°F for T_3 and about 150°F for T_2, the devolatilizer outlet and inlet temperatures, respectively. Since we feel that the actual cyclone efficiency was probably somewhere in this range, we conclude that the actual value used is not of crucial importance in making the energy balances.

TABLE 4.6 CARBON BALANCE STUDY

RUN NO.	43	43.1	40	40.1
A	.321	.397	.321	.407
β_p	.32	.17	.35	.17
S	1	1	1	1
H_m, $\frac{BTU}{DSCF}$	108.9	108.9	101.2	101.2
$(\mu_{CHAR})_0$	8.14	3.50	8.9	3.41
$(\mu_{ASH})_0$	34.3	27.8	34.3	27.1
β_g #/#	.06	.06	.06	.06
$\beta'_{N.G.}$ #/#	0	0	0	0
η_c	.90	.90	.90	.90
Q''_g $\frac{kcal}{mol\ O_2}$	19,700	20,800	22,000	22,300
Q''_d $\frac{kcal}{mol\ O_2}$	9,900	10,800	11,800	12,000
Q''_s $\frac{kcal}{mol\ O_2}$	19,600	19,600	19,600	19,600
COAL	WESTERN	WESTERN	WESTERN	WESTERN
T_4, °F	1000	1000	970	970
H_{g4}, $\frac{BTU}{DSCF}$	107.6	105.4	100.9	101.7
$(\mu_{CHAR})_4$	.90	.388	.989	.378
$(\mu_{ASH})_4$	3.82	3.09	3.82	3.01
T_3, °F	1316	1425	1278	1402
$(\mu_{CHAR})_3$	9.04	3.90	9.89	3.79
$(\mu_{ASH})_3$	38.2	30.85	38.16	30.1
T_2, °F	1469	1647	1454	1654
$(\mu_{CHAR})_2$	9.04	3.89	9.9	3.79
$(\mu_{ASH})_2$	38.2	30.85	38.16	30.1
T_1, °F	2718	3377	2639	3392
$(\mu_{CHAR})_1$	7.19	2.55	7.96	2.46
$(\mu_{ASH})_1$	34.3	27.77	34.34	27.08

TABLE 4.7 η_c STUDY

RUN NO.	43	43	43
A	.321	.321	.321
β_p	.32	.32	.32
S	1	1	1
H_m, $\frac{BTU}{DSCF}$	108.9	108.9	108.9
$(\mu_{CHAR})_0$	3.62	8.14	17.18
$(\mu_{ASH})_0$	15.3	34.3	72.5
β_g #/#	.06	.06	,06
$\beta'_{N.G.}$ #/#	0	0	0
η_c	.80	.90	.95
Q''_g $\frac{kcal}{mol\ O_2}$	19,700	19,700	19,700
Q''_d $\frac{kcal}{mol\ O_2}$	9,900	9,900	9,900
Q''_s $\frac{kcal}{mol\ O_2}$	19,600	19,600	19,600
COAL	WESTERN	WESTERN	WESTERN
T_4, °F	1000	1000	1000
H_{g4}, $\frac{BTU}{DSCF}$	107.6	107.6	107.6
$(\mu_{CHAR})_4$	.904	.904	.904
$(\mu_{ASH})_4$	3.82	3.82	3.82
T_3, °F	1412	1316	1216
$(\mu_{CHAR})_3$	4.52	9.04	18.1
$(\mu_{ASH})_3$	19.07	38.16	76.3
T_2, °F	1612	1469	1321
$(\mu_{CHAR})_2$	4.52	9.04	18.1
$(\mu_{ASH})_2$	19.08	38.15	76.3
T_1, °F	3472	2719	2096
$(\mu_{CHAR})_1$	2.67	7.19	16.24
$(\mu_{ASH})_1$	15.26	34.34	72.49

NOMENCLATURE

SYMBOL

A = AIR-FUEL RATIO EXPRESSED AS A FRACTION OF THE AMOUNT OF AIR THAT IS THEORETICALLY REQUIRED TO BURN THE FUEL (COAL AND NATURAL GAS INCLUDED) COMPLETELY TO CO_2 AND H_2O, DIMENSIONLESS.

β_p = CHAR OUTPUT EXPRESSED AS ATOMS CARBON PER ATOM CARBON INPUT IN COAL, DIMENSIONLESS.

S = FRACTION OF COAL FED TO GASIFIER, DIMENSIONLESS.

H_m = MEASURED HEATING VALUE OF THE MAKE GAS, BTU/DSCF.

μ = MOLECULAR FLOW RATES OF INDIVIDUAL SPECIES, kg MOLS/kg MOL O_2 FED AS AIR.

β_g = FRACTION OF THE TOTAL INPUT CARBON APPEARING AS HYDROCARBONS, CH_x, IN STREAM LEAVING SYSTEM. THE VALUE OF X IS APPROXIMATELY 2.5, DIMENSIONLESS.

$\beta'_{N.G.}$ = NATURAL GAS (METHANE) FEED RATE EXPRESSED AS kg OF METHANE PER kg OF AS-FIRED COAL, DIMENSIONLESS.

η_c = OVERALL EFFICIENCY OF PARTICULATE COLLECTOR (BOTH CYCLONES IN SERIES TAKEN TOGETHER AS A SINGLE DEVICE), DIMENSIONLESS.

SYMBOL

Q''_g = TOTAL HEAT LOSS FROM GASIFIER, kcal/kg MOL O_2 FED AS AIR.

Q''_d = TOTAL HEAT LOSS FROM DEVOLATILIZER, kcal/kg MOL O_2 FED AS AIR.

Q''_s = TOTAL HEAT LOSS FROM CYCLONE SEPARATORS (INCLUDES HEAT LOSS FROM WATER JACKETED ELBOW AT DEVOL. EXIT), kcal/kg MOL O_2 FED AS AIR.

T_1, T_2, T_3, T_4 = CALCULATED TEMPERATURES AT COMBUSTOR OUTLET, GASIFIER OUTLET, DEVOLATILIZER OUTLET AND CYCLONE SEPARATOR OUTLET, RESPECTIVELY, °F.

H_{g4} = CALCULATED HEATING VALUE OF THE MAKE GAS, BTU/DSCF.

SUBSCRIPTS

0, 1, 2, 3, 4 = COMBUSTOR INLET, COMBUSTOR OUTLET, GASIFIER OUTLET, DEVOLATILIZER OUTLET AND CYCLONE SEPARATOR OUTLET, RESPECTIVELY.

4.5.5.3 Heat Loss Study. One of the largest uncertainties in the energy balance calculations was the heat loss in the water-cooled elbow (which is considered as part of the separator heat loss). Therefore, a study was made to determine the magnitude of the effect of these uncertainties. Table 4.8 presents the results of this study. The heat loss from the cyclone separators, Q_2'', was cut in half (a change of about 10,000 kcal/mol O_2) in going from run 42 to 42A and from 28 to 28A. This is probably a little more of a change than the uncertainty in the loss from the water-cooled elbow. It will be seen that the effect of T_4, the separator outlet temperature, is in the order of 200°F between runs 42 and 42A. In the case of runs 26 and 26A, the outlet temperature, T_4, was forced to be equal to the measured temperature of 840°F. This required the overall heat loss to be the same and hence the reduction in heat loss in the separator was distributed as additional heat loss in the gasifier and devolatilizer. The effect on T_3 is about 200°F and on T_2 about 100°F. Thus, the uncertainty in separator heat loss is significant, but not decisive, in its effect upon calculated temperatures.

4.5.6 Overall Heat Balance

Table 4.9 summarizes the results of overall heat balances (IV). For each run, we used as input to the calculation the fraction of unconsumed carbon (β_p) as previously obtained for the material-balance calculations, the air-to-fuel ratio, and the estimated steady-state heat losses. The resulting values of T_4 were calculated for each run and compared with the corresponding measured values. The entries in the column labeled ΔT_4 in Table 4.9 represent measured differences, arranged according to code. It will be noted that the differences, ΔT_4, are far larger than could possibly be explained by the various approximations we have had to make in the calculations.

The third column in Table 4.9, labeled Q', represents the amount of additional heat loss that would have to be present in the process in order to explain the T_4 differences. The rates in the fourth column, $dT/d\theta$, represent the average rate of change of refractory temperature required to provide this heat loss if transient heating up of refractory is the cause of the additional heat loss. (In making this calculation, we calculated the total mass of refractory in the gasifier, crossover pipe, and devolatilizer. We also estimated the mean temperature of each kind of refractory and its corresponding specific heat.)

TABLE 4.8 HEAT LOSS STUDY

RUN NO.	42	42A	26	26A
A	.339	.339	.413	.413
β_p	.27	.27	.39	.39
S	1	1	0	0
H_m, $\frac{BTU}{DSCF}$	109.3	109.3	62.1	62.1
$(\mu_{CHAR})_0$	6.503	6.503	7.0	7.0
$(\mu_{ASH})_0$	32.5	32.5	21.2	21.2
β_g #/#	.06	.06	.02	.02
$\beta'_{N.G.}$ #/#	0	0	.114	.114
η_c	.90	.90	.90	.90
Q''_g $\frac{kcal}{mol\ O_2}$	9500	9500	33,300	38,800
Q''_d $\frac{kcal}{mol\ O_2}$	1000	1000	19,500	23,800
Q''_s $\frac{kcal}{mol\ O_2}$	19,600	9,800	19,600	9,800
COAL	WESTERN	WESTERN	EASTERN	EASTERN
T_4, °F	1524	1790	840	840
H_{g4}, $\frac{BTU}{DSCF}$	109.9	110.3	67.0	67.0
$(\mu_{CHAR})_4$	.723	.723	.78	.78
$(\mu_{ASH})_4$	3.61	3.61	2.35	2.35
T_3, °F	1836	1939	1216	1032
$(\mu_{CHAR})_3$	7.23	7.23	67.0	67.0
$(\mu_{ASH})_3$	36.1	36.1	7.77	7.77
T_2, °F	1852	1955	2512	2410
$(\mu_{CHAR})_2$	7.23	7.23	6.51	6.51
$(\mu_{ASH})_2$	36.1	36.1	21.2	21.2
T_1, °F	3109	3226	2841	2841
$(\mu_{CHAR})_1$	5.56	5.56	6.05	6.05
$(\mu_{ASH})_1$	32.5	32.5	21.2	21.2

NOMENCLATURE

SYMBOL

A = AIR-FUEL RATIO EXPRESSED AS A FRACTION OF THE AMOUNT OF AIR THAT IS THEORETICALLY REQUIRED TO BURN THE FUEL (COAL AND NATURAL GAS INCLUDED) COMPLETELY TO CO_2 AND H_2O, DIMENSIONLESS.

β_p = CHAR OUTPUT EXPRESSED AS ATOMS CARBON PER ATOM CARBON INPUT IN COAL, DIMENSIONLESS.

S = FRACTION OF COAL FED TO GASIFIER, DIMENSIONLESS.

H_m = MEASURED HEATING VALUE OF THE MAKE GAS, BTU/DSCF.

μ = MOLECULAR FLOW RATES OF INDIVIDUAL SPECIES, kg MOLS/kg MOL O_2 FED AS AIR.

β_g = FRACTION OF THE TOTAL INPUT CARBON APPEARING AS HYDROCARBONS, CH_x, IN STREAM LEAVING SYSTEM. THE VALUE OF X IS APPROXIMATELY 2.5, DIMENSIONLESS.

$\beta'_{N.G.}$ = NATURAL GAS (METHANE) FEED RATE EXPRESSED AS kg OF METHANE PER kg OF AS-FIRED COAL, DIMENSIONLESS.

η_c = OVERALL EFFICIENCY OF PARTICULATE COLLECTOR (BOTH CYCLONES IN SERIES TAKEN TOGETHER AS A SINGLE DEVICE), DIMENSIONLESS.

Q''_g = TOTAL HEAT LOSS FROM GASIFIER, kcal/kg MOL O_2 FED AS AIR.

Q''_d = TOTAL HEAT LOSS FROM DEVOLATILIZER, kcal/kg MOL O_2 FED AS AIR.

Q''_s = TOTAL HEAT LOSS FROM CYCLONE SEPARATORS (INCLUDES HEAT LOSS FROM WATER JACKETED ELBOW AT DEVOL. EXIT), kcal/kg MOL O_2 FED AS AIR.

T_1, T_2, T_3, T_4 = CALCULATED TEMPERATURES AT COMBUSTOR OUTLET, GASIFIER OUTLET, DEVOLATILIZER OUTLET AND CYCLONE SEPARATOR OUTLET, RESPECTIVELY, °F.

H_{g4} = CALCULATED HEATING VALUE OF THE MAKE GAS, BTU/DSCF.

SUBSCRIPTS

0, 1, 2, 3, 4 = COMBUSTOR INLET, COMBUSTOR OUTLET, GASIFIER OUTLET, DEVOLATILIZER OUTLET AND CYCLONE SEPARATOR OUTLET, RESPECTIVELY.

TABLE 4.9 OVERALL HEAT BALANCE (IV)

CODE	ΔT_4, °F	Q' kcal/mol O_2	$(dT/d\theta)$ FOR Q' °F/HR
1	1412	41,634	114
2	1158	35,695	97
3	1522	49,043	134
4	880	29,123	79
5	1014	33,368	91
6	1162	38,938	106
7	611	21,093	58

$\Delta T_4 \overset{\Delta}{=} (T_4)_{CALC.} - (T_4)_{MEAS.}$

Q' = AMOUNT OF ADDITIONAL HEAT LOSS THAT WOULD HAVE TO BE PRESENT IN THE PROCESS IN ORDER TO EXPLAIN THE ΔT_4 DIFFERENCES.

$\frac{dT}{d\theta}$ = RATE OF CHANGE OF REFRACTORY TEMPERATURE REQUIRED TO ACCOUNT FOR Q' ASSUMING THAT THE TRANSIENT HEATING OF THE REFRACTORY IS THE CAUSE OF THE ADDITIONAL HEAT LOSS.

When all of the coal is fed to the gasifier, the local air-fuel ratio in the gasifier is equal to the overall process air-to-fuel ratio. But when, as in codes 3 and 6, all coal is fed to the devolatilizer (at the same overall air-fuel ratio), the local air-fuel ratio in the gasifier is quite a bit higher than the overall value. This situation should produce a gasifier temperature that is higher than the case of all coal to the gasifier (codes 1, 4, and 7). Interestingly, in Table 4.9 the Q' values are highest for the condition of high gasifier temperature (codes 3 and 6). This is consistent with the inference that transient heat losses are the cause of the T_4 discrepancies.

Since, for the majority of the tests, the pilot plant was started up at about the same time every morning one might expect an unsteady state condition to reveal itself via a gradual heating up of the unit throughout the day. If this were the case the system outlet temperature (cyclone separator outlet) would be affected the most and conceivably would be a function of the "time of day". Admittedly although each test was run under different conditions and hence would produce different outlet temperatures a general trend might be expected to appear. A plot of cyclone outlet temperature T_4 as a function of "Time of Day", Figure 4.27, confirms the fact that the system was not at steady state, but was slowly heating up throughout the day. The slope of the least-squares fit through the data is about 60°F/hr. This is consistent with the required range of 58-134°F when one considers that the rate of rise of exit gas temperature will probably be less than that of the refractory and that we have not included the mass of the steel shells and their rate of temperature rise in estimating the required $dT/d\theta$'s.

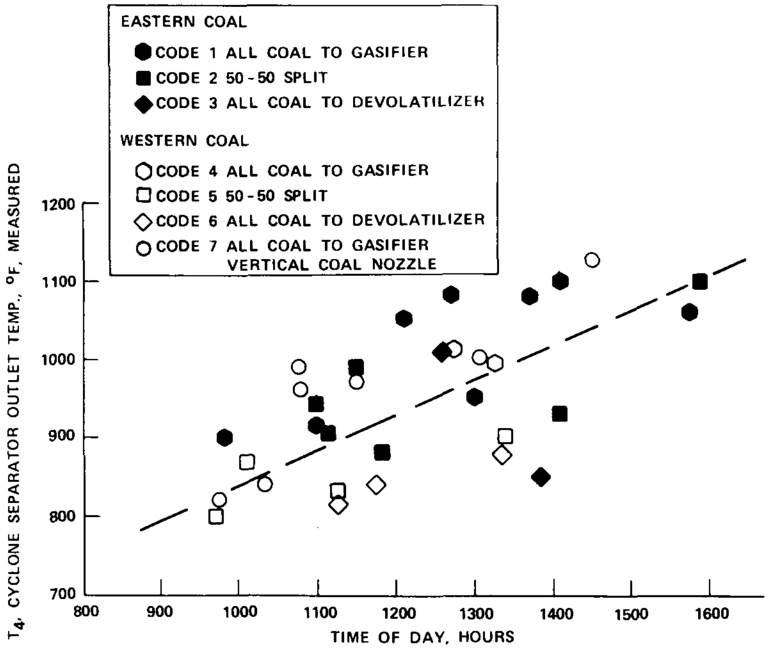


FIGURE 4.27 SEPARATOR OUTLET TEMPERATURE AS A FUNCTION OF "TIME OF DAY"

4.5.7 T_3 and T_2 Study

Having established that transient heat losses were significant, we repeated the energy balance calculations, this time forcing the separator outlet temperature, T_4, to be equal to the measured value, i.e., we assumed that the measured separator outlet temperature was correct and calculated the required additional heat losses. These transient heat losses were distributed in the gasifier-devolatilizer on the basis of the weight-specific heat product. This amounted to roughly a 50/50 split.

Table 4.10 summarized the results of the T_2 (gasifier exit) and T_3 (devolatilizer exit) calculations. The table contains the average values of the differences, grouped according to code and differentiated according to the assumed value of separator efficiency, η_c. In comparing the ΔT_3 values for code 1 with codes 2 and 3 and code 4 with codes 5 and 6, it will be noted that the ΔT_3 tends to be higher for the cases where any coal at all is fed to the devolatilizer. This is consistent with the hypothesis that the measured T_3 values are low in this circumstance due to fouling by tars and soot. These changes are also consistent with the hypothesis of an actual heat loss below that estimated due to fouling of the water-cooled elbow. If in actuality the elbow had been fouled with tar deposits, thereby reducing separator heat losses, temperatures T_3 and T_4 (cyclone exit) would tend to approach each other; in the extreme with no separator heat loss, T_3 would equal T_4. However, the calculated value of T_3 does not take into account possible fouling (reduced heat loss). Therefore, T_3 tends to be calculated high since it must maintain a given heat loss across the separator.

TABLE 4.10 GASIFIER AND DEVOLATILIZER EXIT – AVERAGE DIFFERENCE BETWEEN CALCULATED AND MEASURED TEMPERATURES

η_c	CODE	1	2	3	4	5	6	7
.90	ΔT_3 AVG. (DEVOL. EXIT)	-22	+100	+84	-74	+117	+140	-10
	ΔT_2 AVG. (GASIFIER EXIT)	-96	+175	+542	-311	+183	+538	-182
.95	ΔT_3 AVG.	-86	-15	-32	-180	+13	+31	-110
	ΔT_2 AVG.	-262	-199	-62	-430	-139	-17	-332

$\Delta T \triangleq T_{CALCULATED} - T_{MEASURED}$

Comparing the values of ΔT_2 in Table 4.10 — code 1 with codes 2 and 3, code 4 with codes 5 and 6 — reveals that the codes where some coal is fed to the devolatilizer (codes 2, 3, 5, 6) give higher values of ΔT_2 than do the corresponding codes where all the coal goes to the gasifier. This is consistent with our picture of the devolatilization process; that is, for purposes of energy balances, we assumed that devolatilization is instantaneous, and the devolatilizer products are immediately reformed to carbon monoxide and hydrogen. As a matter of fact, devolatilization takes time, the reforming may not be completed in the devolatilizer, and both devolatilization and reforming are endothermic. Thus, failure of these assumptions would have the same effect as an exothermic reaction within the devolatilizer, tending to raise T_3 with respect to T_2. Or, which amounts to the same thing, it would tend to make the actual value T_2 lower than that calculated. However, some of the ΔT_2 values seem a little too large (in the absolute sense) for this explanation. Bearing in mind that the ΔT_2 should be negative (because of the assumption of no reaction in the devolatilizer) the too large values of ΔT_2 would be, for $\eta_c = 0.9$, +175, +542, +183, and +538 — or precisely those where some coal goes to the devolatilizer. For $\eta_c = 0.95$, these values become -262, -430, and -332, — or just the values for no coal to the devolatilizer.

This leads us to conclude (somewhat tenuously, we admit) that $\eta_c = 0.90$ for runs wherein all the coal was fed to the gasifier (codes 1, 4, 7) and $\eta_c = 0.95$ when some coal was fed to the devolatilizer (codes 2, 3, 5, 6). With this choice, all of our a priori predictions are satisfied, and the largest discrepancy is about 300°F in absolute magnitude.

Thus, an explanation for the low measured values of T_3 when feeding coal to the devolatilizer (Figure 4.25) might be fouling of the thermocouple, or it might be just that the separator efficiency improves under this condition. Consequently, one can use the measured values of T_3 as characteristic of devolatilization — although this should be done with some reservations.

4.5.8 Summary of Effects of Steady-State and Transient Heat Losses

Table 4.11 presents a summary of the effects of steady-state and transient heat losses. The first column enumerates the various codes while the second, third, and fourth columns list the steady-state heat losses in the gasifier, devolatilizer, and separators respectively. The total of these steady-state heat losses, Q, is listed in the fifth column. The total heat loss, which is the sum of both steady-state and transient, is listed in the column labeled BOTH Q". It is evident that the transient heat loss is a major part of the total.

TABLE 4.11 SUMMARY OF EFFECTS OF STEADY STATE AND TRANSIENT HEAT LOSSES

CODE	STEADY STATE kcal/kg·mol O_2 in				TRANSIENT ONLY Q'	BOTH Q''	$\Delta T'_4$ °F
	Q_g	Q_d	Q_s	Q			
1	9242	1036	19606	29,884	41,634	71,477	2358
2	10271	1036	19606	30,913	35,695	66,608	2069
3	9635	1036	19606	30,277	49,043	79,320	2362
4	8999	1036	19606	29,641	29,123	58,764	1996
5	8958	1036	19606	29,600	33,368	62,968	2021
6	9635	1036	19606	30,277	38,938	69,215	2183
7	8283	1036	19606	28,925	21,093	50,018	1756

$Q \overset{\Delta}{=} Q_g + Q_d + Q_s$

$Q'' \overset{\Delta}{=} Q + Q'$

Q′ IS DIVIDED 56% TO GASIFIER, 44% TO DEVOLATILIZER

$\Delta T'_4 \overset{\Delta}{=} (T_4)_{\text{CALC., ZERO HEAT LOSS}} - (T_4)_{\text{MEASURED}}$

Q_g = TOTAL HEAT LOSS FROM GASIFIER

Q_d = TOTAL HEAT LOSS FROM DEVOLATILIZER

Q_s = TOTAL HEAT LOSS FROM CYCLONE SEPARATORS

T_4 = CYCLONE SEPARATOR OUTLET TEMPERATURE

The last column, labeled $\Delta T_4'$, is the difference between the adiabatic value of T_4 (i.e., without any heat losses whatever) and the measured values of T_4. Obviously, complete elimination of all heat losses could produce very significant temperature increases (1700-2400°F), and even elimination of only the transient losses would produce much higher temperatures (roughly 700-1800°F). For example, in the case of code 1, the transient heat loss amounts to about 4/7 of the total, and elimination of it would raise the temperature 4/7 of 2358°F, which is about 1350°F.

4.6 TAR FORMATION

As described previously, "tars" are defined in this report as that material which is extracted from a particulate-loading sample by a toluene wash. These tars are condensed at temperatures above the temperature of the particulate filter, about 400°F. They are removed from the gases that pass through the particulate probe whose total quantity is measured. Assuming these tars are uniformly distributed throughout the gas volume, the total quantity captured in the filter will actually represent their quantity in the gas, even if much of the particulate escapes the sampling probe (as we believe it often did).

4.6.1 TGA Analysis of Captured Particulate

The data of Figure 4.28 help to establish the possible magnitude of the error in tar measurement due to missing particulate. The Thermogravimetric Analysis (TGA) apparatus permits determination of the weight of a sample as a function of the temperature to which it is exposed. Assuming that condensation of tars is reversible, then the "dust" sample contained a total of about 28% tars. This agrees well with the 25.9% extracted by the toluene wash. Of this total, the curve of Figure 4.28 implies that roughly 2/3 would have condensed at temperatures above 800°F and, therefore, presumably on the dust particles before they were drawn from the gas stream into the particulate filter via the dust-sampling probe. The amount of this portion might be low by as much as a factor of two, if half of the dust in the gas stream was actually missed due to stratification. The other 1/3 of the total must have condensed at temperatures between 800°F and 400°F, that is, after the gas sample was drawn out of the make-gas line. The concentration represented by this amount is, presumably, accurate because prior to condensation the tars should have been uniformly distributed through the gas stream. Thus, the nominal tar concentration of 26% possibly should have been: 26 (1/3) + 2 (26) 2/3 = 43%. In other words, our tar determinations might be low inasmuch as a factor of 43/26 = 1.67, but probably not more than that.

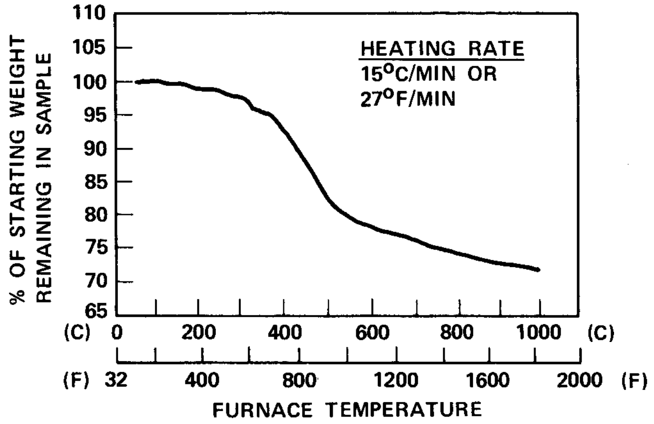


FIGURE 4.28 THERMOGRAVIMETRIC ANALYSIS (TGA) OF PARTICULATE FROM CYCLONE OUTLET TEST 26 – % TOLUENE EXTRACTED 25.9

4.6.2 Air-Fuel Ratio and Temperature Effect

The effects of air-fuel ratio and devolatilizer temperature are interrelated. With this in mind, Figure 4.29 shows the effect of air-fuel ratio on tar formation. Two curves are shown, one for all coal fed to the gasifier (points with an asterisk) and the other for some coal or all the coal fed to the devolatilizer. When all the coal is fed to the gasifier, relatively little tar is produced above an air-fuel ratio of 40%. Below this point, tar production rises dramatically. On the other hand, if any amount of coal is fed to the devolatilizer, relatively large amounts of tar are produced regardless of the air-fuel ratio.

Tar formation is plotted versus devolatilizer inlet temperature, T_2, and devolatilizer outlet temperature, T_3, in Figures 4.30 and 4.31 respectively. Again, the points corresponding to all the coal fed to the gasifier are denoted by an asterisk. As in the previous figure, the data seems to fall into two groups: (1) with all coal to the gasifier, tar production is low until the devolatilizer inlet temperature drops below 1700°F, and (2) when any amount of coal is fed to the devolatilizer, tar production is high regardless of temperature.

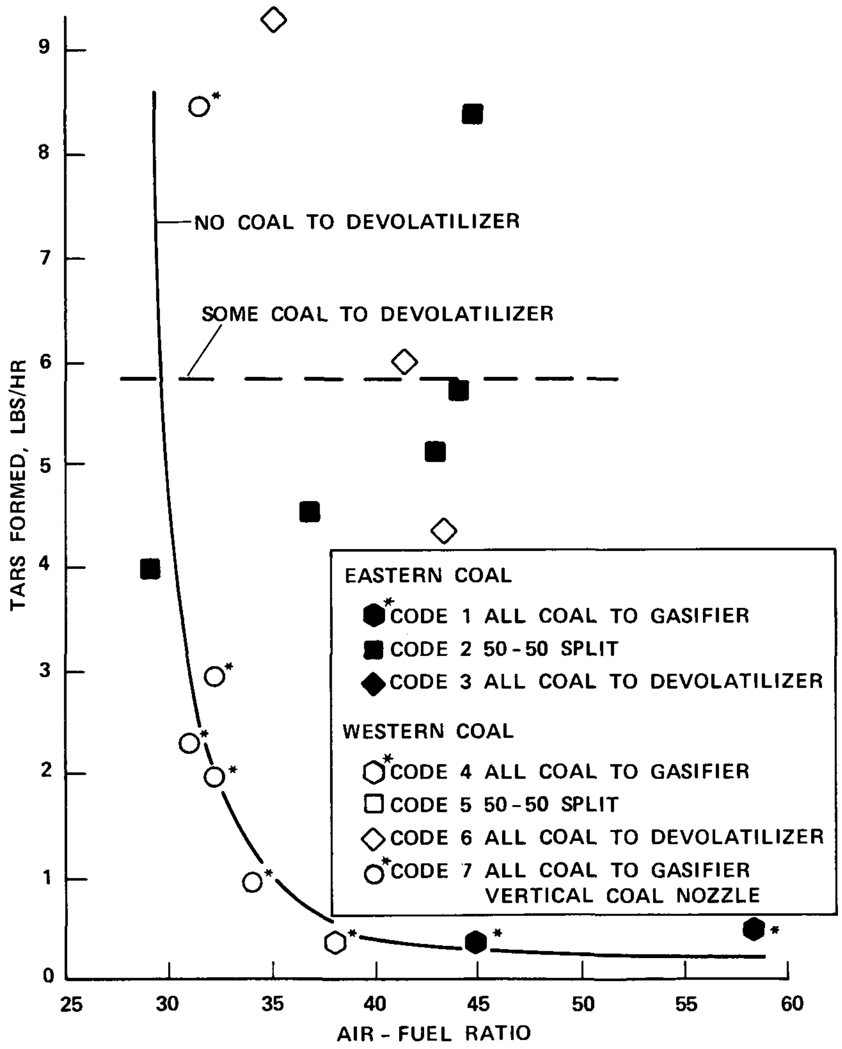


FIGURE 4.29 EFFECT OF AIR-FUEL RATIO ON TAR FORMATION

4.6.3 Residence Time

Residence times are shown along each data point in Figure 4.30. These were calculated from the point of coal injection to the devolatilizer outlet. For the codes 2 and 5, 50-50 split, the residence time was calculated as though all the coal was fed to the devolatilizer.

It will be noted that all of the longer residence times fall on the "no coal-to-devolatilizer" curve and all of the shorter on the "some-coal-to-devolatilizer" curve. This is due primarily to the fact that air flows to the gasifier were

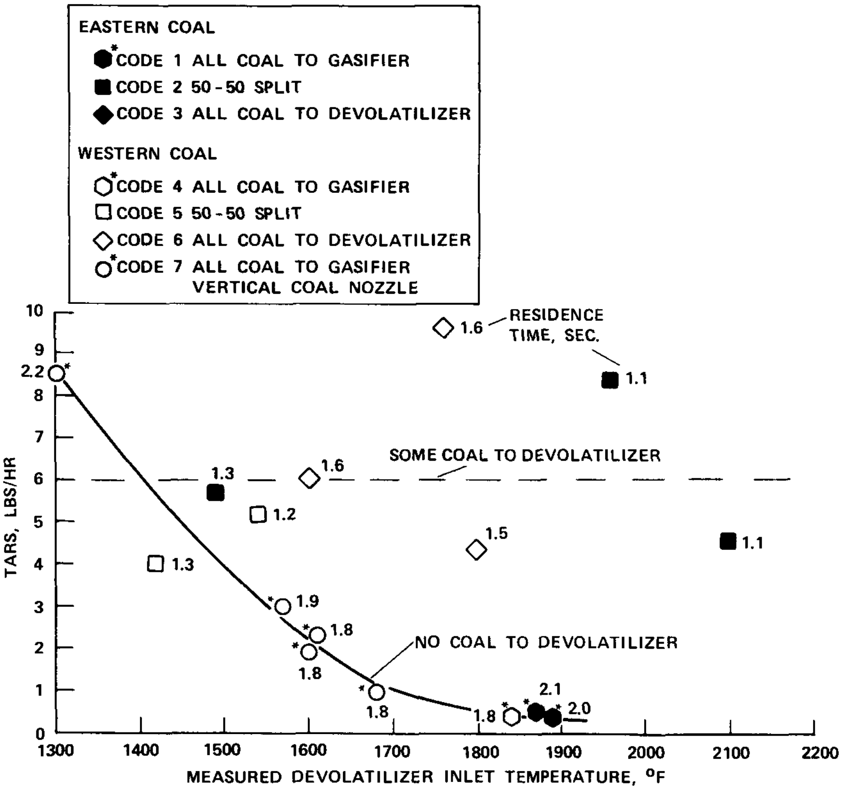


FIGURE 4.30 TAR FORMATION AS A FUNCTION OF MEASURED DEVOLATILIZER INLET TEMPERATURE

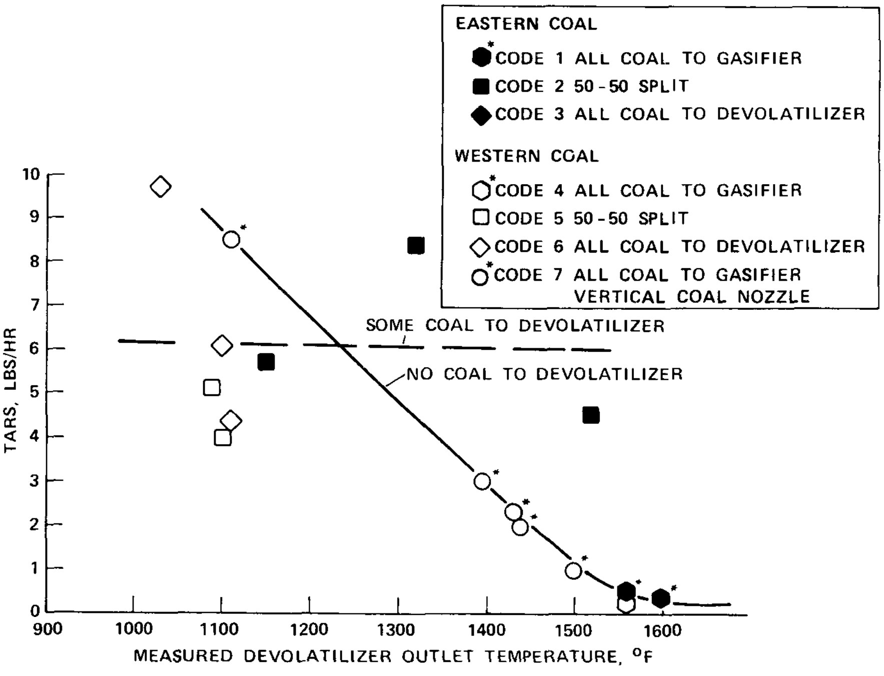


FIGURE 4.31 TAR FORMATION AS A FUNCTION OF MEASURED DEVOLATILIZER OUTLET TEMPERATURE

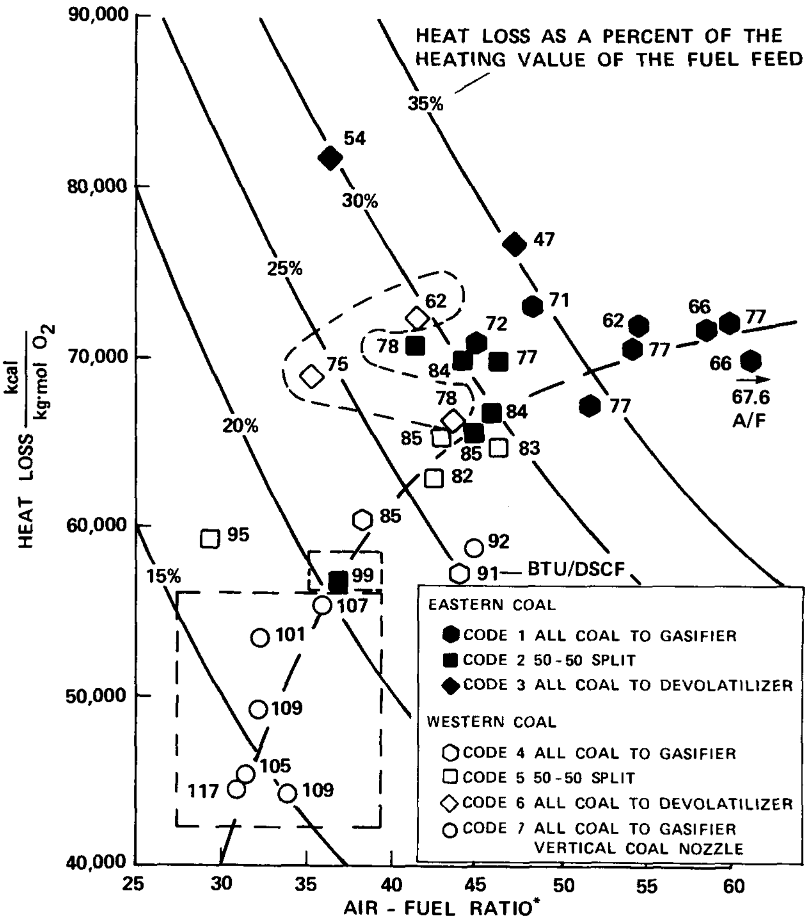
held constant. Thus, it is not possible to say with certainty whether the higher tars in the devolatilizer case were due to the equipment configuration or to the short residence times. However, the fact that the two curves intersect — giving the same tar production for the same devolatilization inlet temperature with different residence times and different conditions — does seem to suggest that tar production is a more complicated phenomenon than can be described in terms of these three variables alone.

4.7 STATISTICAL ANALYSIS

4.7.1 Heating Value as a Function of Heat Loss and Air-Fuel Ratio

It seems obvious from stoichiometric considerations, etc., that air-to-fuel ratio (expressed as a fraction of the amount of air that is theoretically required to burn the fuel [coal and natural gas included] completely to CO_2 and H_2O, dimensionless) must be an important variable controlling make-gas heating value. It is not so obvious whether or not heat losses should have a similarly important effect, since the energy they represent might, in effect, simply come out of the sensible heat of the make gas. However, in spite of this limitation, our modeling study does suggest that heat losses may be important. Thus, it is of interest to investigate the question empirically.

Before we attempt to do this, however, we think it important to point out that, in our experiments, the "independent" variables heat loss and air-to-fuel ratio are interrelated (in the statistical sense). This situation is illustrated in Figure 4.32 where heat loss is plotted against air-fuel ratio for all 32 runs that were analyzed. It will be noticed that the points fall in a curved line that rises, at first steep, then more slowly with increasing air-fuel ratio. (In all probability, this is due to the fact that temperatures tend to rise with rising air-fuel ratio, leading to greater transient heat loss in the refractory of the gasifier.) Thus, one must be very careful of his interpretation of statistical analysis. That is, if the points were to lie along a precise curve in the heat loss-air fuel ratio domain, it would become impossible to say whether variations in heating value were due to heat loss or air-fuel ratio. Fortunately, this is not quite the case, so some inferences can perhaps be drawn, if tenuously.



*AIR-FUEL RATIO IS EXPRESSED AS A FRACTION OF THE AMOUNT OF AIR THAT IS THEORETICALLY REQUIRED TO BURN THE FUEL (NATURAL GAS AND COAL INCLUDED) COMPLETELY TO CO_2 AND H_2O.

FIGURE 4.32 TEST DATA PLOTTED AS A FUNCTION OF HEAT LOSS, AIR-FUEL RATIO, AND HEATING VALUE

Also shown in Figure 4.32 are values of heating value of the make gas. These permit a few inferences, as follows:

1. The three points for code 6 data, showing heating values of 62, 75, and 78 Btu/dscf, suggest a tilt of the make gas heating value surface that is downward as heat loss increases. In other words, a strong effect of heat loss is revealed.

2. The one point for code 2 data at 99 Btu/dscf, when compared with the rest of the code 2 data at 78, 84, 84, 77 Btu/dscf, could include either a heat loss effect or an air-to-fuel ratio effect, since it is displaced in both directions from the rest.

3. The six points for code 7 data generally suggest a moderate heat loss effect, since they lie at about the same air-fuel ratio value but tend to lower values at higher heat loss values. Thus, the data points themselves add a little empirical evidence to the theory, suggesting that heat loss has an effect on the heating value of the make gas.

4.7.2 Discussion of Various Statistical Analysis

This point was explored further via statistical analysis. However, due to an inherent correlation in the independent variables, and the consequent possibility of misleading results, a special effort was made to explain different kinds of correlating functions. The following terms were used in conjunction with this statistical analysis:

H = Heating Value, Btu/DSCF

C_o = Constant

C_n = Coefficient expressing relative position of n-th data group.

X_n = "Dummy" variable having a value of unity for the n-th group and zero for all others.

K's = Coefficients of air-fuel ratio and heat loss terms.

Q = Total heat loss, kcal/kg mol O_2 fed as air.

σ = standard error of prediction.

The results are summarized in Table 4.12. The same general system was used in all five cases, but certain terms were dropped to give the different kinds of functions. For example, the summation $\sum C_n X_n$ terms were omitted in cases A, C, and E to treat all of the data as if they belonged to the same population; cases B and D retain these terms so as to admit an influence of operating mode. The value of σ at the bottom of the table is the standard error of prediction that results in each case. Large values, of course, imply a less accurate fit of the data.

TABLE 4.12 SUMMARY OF STATISTICAL ANALYSIS INCLUDING HEAT LOSSES

CASE	A	B	C	D	E
Co	130.6	184.0	184.5	-1357.8	+179.2
C_1	—	-76.1	—	1530.6	—
C_2	—	-71.5	—	1534.6	—
C_3	—	-105.9	—	1512.2	
C_4	—	-69.3	—	1529.9	—
C_5	—	-71.5	—	1531.9	—
C_6	—	-86.0	—	1523.4	—
C_7	—	-55.8	—	1536.1	—
K_1	-1.03	-.61	+.79	-.45	+.49
K_2	—	—	-.0090	+.0010	-.0071
K_3	-.000041	-.000030	-.0021	-.0013	-.0018
K_4	—	—	$+3.8\times10^{-9}$	$+2.3\times10^{-9}$	$+3.3\times10^{-9}$
σ	13.3	5.9	5.9	4.5	4.9

GENERAL EQUATION:

$$H=C_o+K_1A+K_2A^2+K_3Q+K_4Q^2+\sum_{1}^{7} C_nX_n$$

The following conclusions are drawn from Table 4.12:

Case A

Simple linear fits were allowed for the effects of air-fuel ratio and heat loss. This amounts to fitting a single plane through the data points in heating value, air-fuel ratio, heat loss space. In this analysis the various codes were not permitted to "float"; all the data was lumped into one group. The statistical fit was not too good in that it produced a standard deviation of 13.3 Btu/dscf, compared with about half this value in the other four cases.

Case B

In this analysis the simplicity of the previous fit with respect to air-fuel ratio and heat loss was retained, but the various codes were permitted to "float". This produced a much better fit giving a standard deviation of 5.9 Btu/dscf. The constants, C_1 through C_7, are indicative of the relative heating values of the data in the various codes. For codes 1, 2, 4, and 5, the C values are about the same. Code 3 data (all coal to the devolatilizer, Eastern coal) is much lower, indicating that these data points were tending to fall below the correlation. In addition, code 6 also tended to fall a little below, and code 7 data was significantly higher than the others — about 20 Btu/dscf higher.

Case C

Here the "float" of the individual codes was eliminated, but we allowed more complicated functions to represent the effects of air-fuel ratio and heat loss. For this case the same degree of fit is obtained as in Case B, the standard deviation being 5.9 Btu/dscf.

Case D

This was the most complicated case in that the codes were permitted to "float" and the complicated functions were retained to represent the effects of air-fuel ratio and heat loss. This was the best fit as judged by the standard deviation of 4.5 Btu/dscf. Note that C_3, the constant for code 3, is still significantly below the typical values of the other cases; and again the heating values for code 7 data are significantly above the average.

Case E

The "float" was eliminated but the complicated functions were retained to represent the air-fuel ratio and heat loss effect. However, the Code 3 data was eliminated from this case as it always seemed to be lower than all the other data. The standard deviation is 4.9 Btu/dscf, indicating a fairly good fit.

As far as picking the best case is concerned, Case E is our first preference as it is not overly complex yet it fits the data fairly well. Our second choice is Case B because it represents the "other extreme" in that it allows the various codes to "float", yet it is simple with respect to the air-fuel ratio and heat loss effects. This case also produces a good fit of the data.

Figures 4.33 through 4.36 present the two statistical analyses, E and B, in graphical form showing the effects of heat loss and air-fuel ratio. In Figure 4.33 the effect of air-fuel ratio has been subtracted out from the heating value and the result plotted against heat loss. Figure 4.34 shows the same plot with respect to air-fuel ratio and Figures 4.35 and 4.36 show this same study for analysis B. It will be noted that in analysis E the heat loss effect is steep while the air-fuel ratio is flat. Just the opposite trends are present in the B analysis.

4.7.3 Projections for Reduced Heat Loss

The majority of the data was unfortunately obtained under conditions of high heat loss. This is evident from Figure 4.32 wherein most of the data displays heat losses in excess of 25% of the heating value of the fuel. The question we would like to answer is: What would be the heating value if the heat losses were reduced? Figure 4.37 attempts to answer this question. Extrapolation according to the two statistical analyses, B and E, have been superimposed on the plot of code 7 data. For the B analysis, there is very little effect of heat loss, hence only one curve. It will be noted that this correlation predicts a heating value of about 98 Btu/dscf at 50% theoretical air and 100% carbon utilization. In the E analysis, heat loss is a major factor; consequently, three curves are shown for different heat losses. By eliminating the transient heat losses and some of the steady-state losses, the total loss might be brought down to that of the middle curve, 20,000 kcal/kgmol O_2. Note that Case E predicts that, at this reduced loss, a heating value of about 150 Btu/dscf might be possible at 100% carbon utilization, at an air-fuel ratio of 35%. What is possible in actual practice probably lies somewhere between these two cases. Unfortunately, with the present state of knowledge, the extrapolation cannot be made any more precise than this.

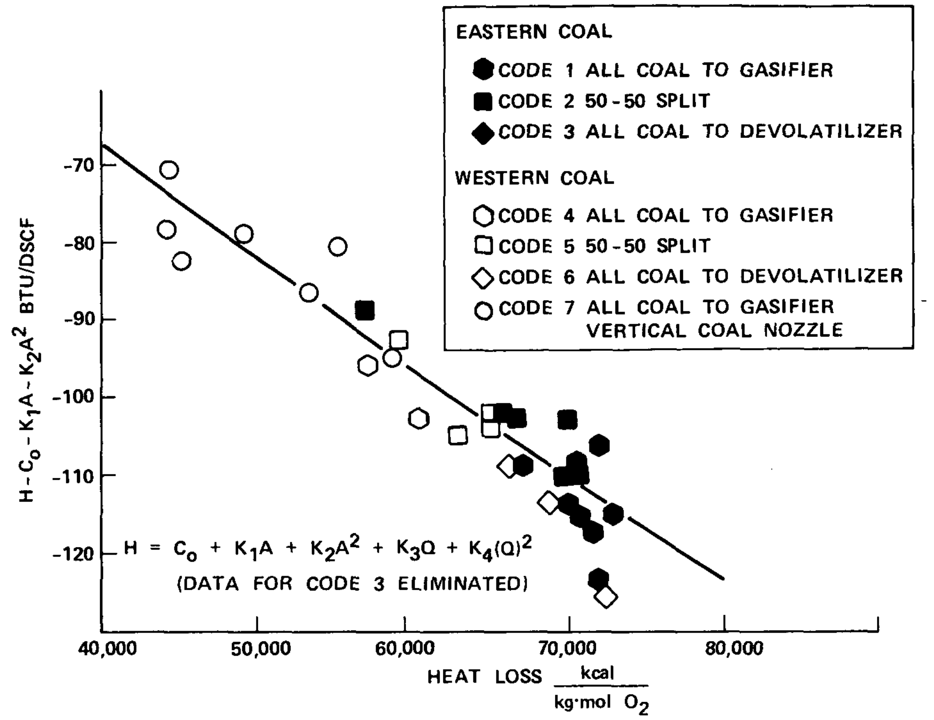


FIGURE 4.33 STATISTICAL ANALYSIS 'E', HEAT LOSS EFFECT

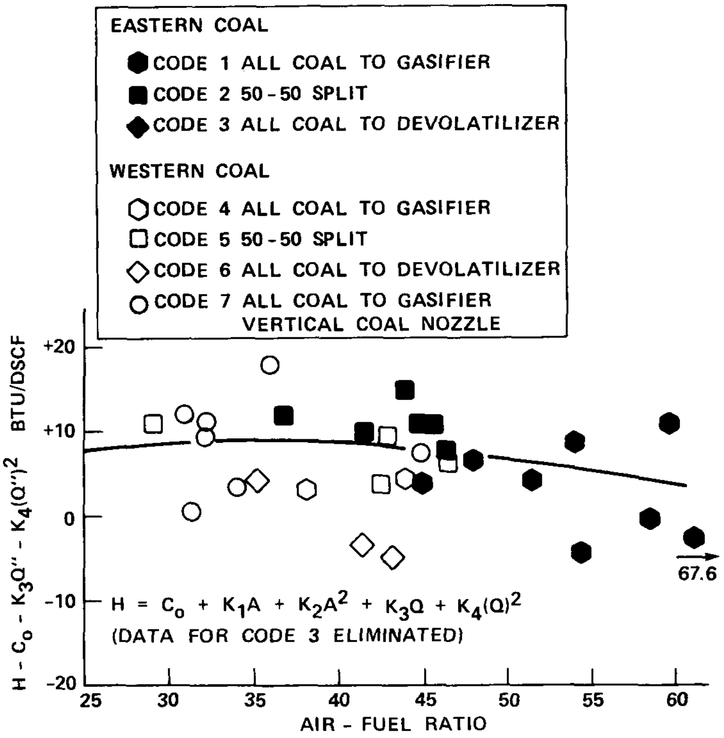


FIGURE 4.34 STATISTICAL ANALYSIS 'E', AIR-FUEL RATIO EFFECT

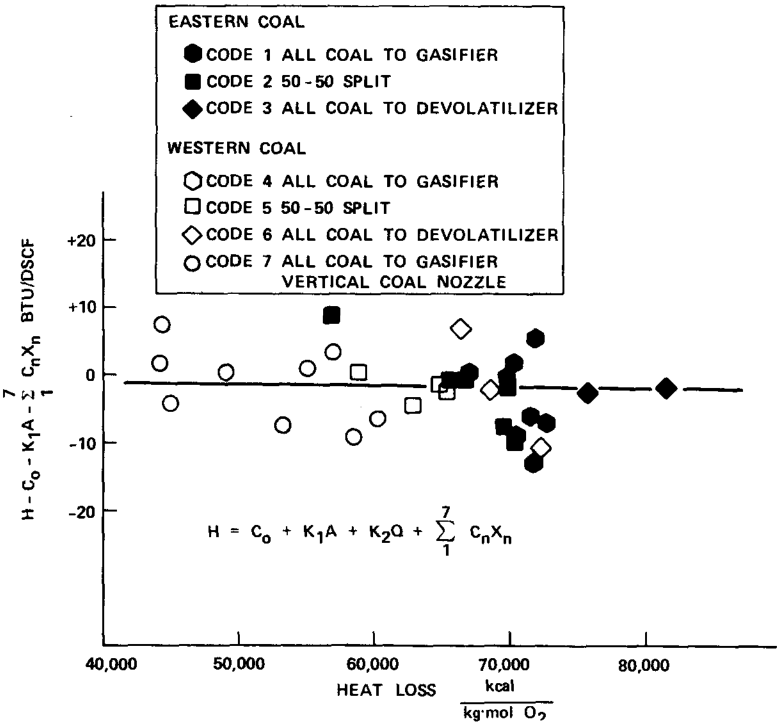


FIGURE 4.35 STATISTICAL ANALYSIS 'B', HEAT LOSS EFFECT

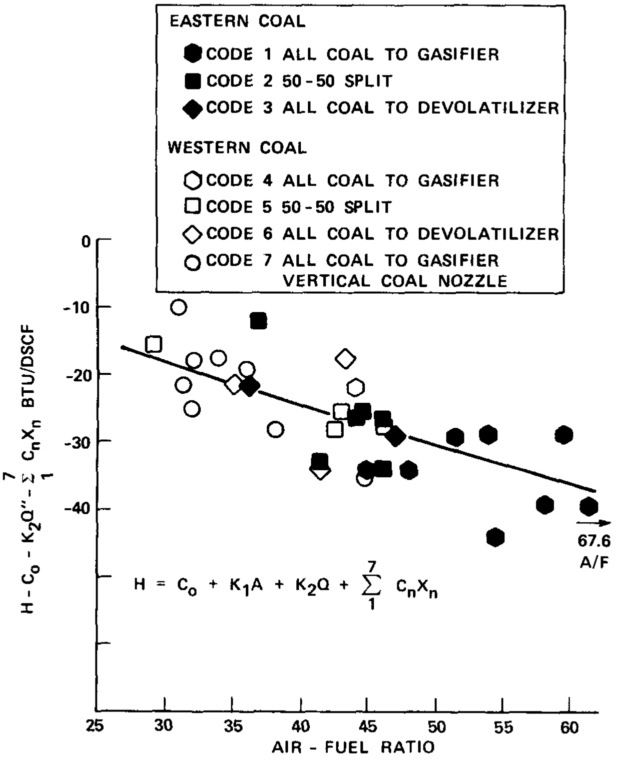


FIGURE 4.36 STATISTICAL ANALYSIS 'B', AIR-FUEL RATIO EFFECT

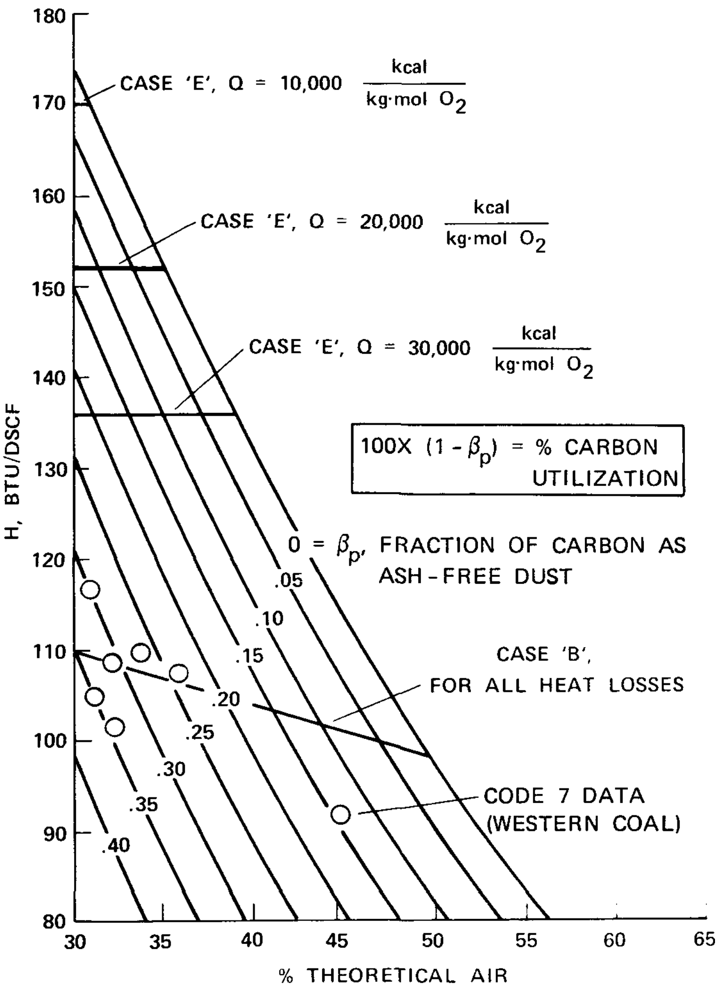


FIGURE 4.37 PROJECTIONS FOR REDUCED HEAT LOSS

Section 5

THERMAL ANALYSIS OF PILOT APPARATUS

Analysis of the data via material and energy balance has shown that unexpectedly large heat losses were encountered. These were due primarily to the transient heating of the large mass of refractory in the gasifier and, presumably, the crossover pipe and devolatilizer as well. Obviously, if the apparatus were run for a long enough period of time under constant operating conditions, transient heat losses could be completely avoided. However, it seems possible that steady-state heat losses might, then, increase to fairly large values. Consequently, it was decided to direct an analytical study toward answering the following questions:

- What heat losses might be achieved at steady-state, and how long might it take to achieve steady-state?
- What changes might be made in the apparatus to shorten thermal equilibrating times or reduce heat losses?

To answer these questions, a thermal model of the pilot apparatus was developed and programmed for a computer. Because of the complex geometry of the apparatus (various thicknesses and types of refractory, various internal dimensions, time varying internal boundary condition due to the gasification reaction), this program was necessarily fairly complex. The purpose of this section is to summarize the thermal model and its use in answering the above two questions.

5.1 DESCRIPTION OF THERMAL ANALYSIS MODELS

5.1.1 Equipment Components for Thermal Analysis

Figure 5.1 shows how the pilot apparatus was broken down into components for the purposes of thermal analysis. The eight major components were:

1. Combustor
2. Bottom of gasifier
3. Top of gasifier

4. Bottom of crossover duct
5. Top of crossover duct
6. Top of devolatilizer
7. Bottom of devolatilizer
8. Cyclone separators

Figures 5.2 through 5.8 show the detail of how each of the components of Figure 5.1 were further broken down into subcomponents for the purpose of thermal analysis. For example, the gasifier (Figure 5.3) was broken down into four axial sections, and each axial section was broken down into 17 radial sections. The radial sections were chosen for convenience in representing the five different kinds of refractory present. Provision was also made for thermal fouling of the inside surface of the carbide liner by char. The outermost steel shell was assumed to have infinite thermal conductivity. As is obvious from Figures 5.3, 5.5, 5.7, and 5.8, the number of radial segments varied from component to component according to the particular construction of each. In such cases as the top of the gasifier, the crossover duct, and the top of the devolatilizer, the geometry adopted for modeling purposes was slightly different from the actual. This was necessary because the actual geometry is three-dimensional and we wished to maintain the simplicity of a two-dimensional model. Consequently, the circular top of the gasifier was ignored, this component being considered to be simply a circular pipe without ends. The radial wall thickness was maintained the same as the actual apparatus; the density of the refractory was adjusted to maintain the same total mass of refractory as in the actual apparatus. The same kind of adjustment was made for the top of the devolatilizer.

In considering the top of the gasifier and devolatilizer to be circular pipes without ends, the lengths of the components were not increased so as to maintain the same internal surface area. Also the heat transfer coefficients on the outside were not adjusted so as to maintain the same product of heat transfer coefficient times outside area as in the actual apparatus. However, the errors introduced by neglecting these adjustments are very minor. Calculations show that the additional heat loss, if the areas and heat transfer coefficients had been properly adjusted, would have accounted for only a 2% increase for each of these components. The effect on the overall heat loss would have been an insignificant 0.1%.

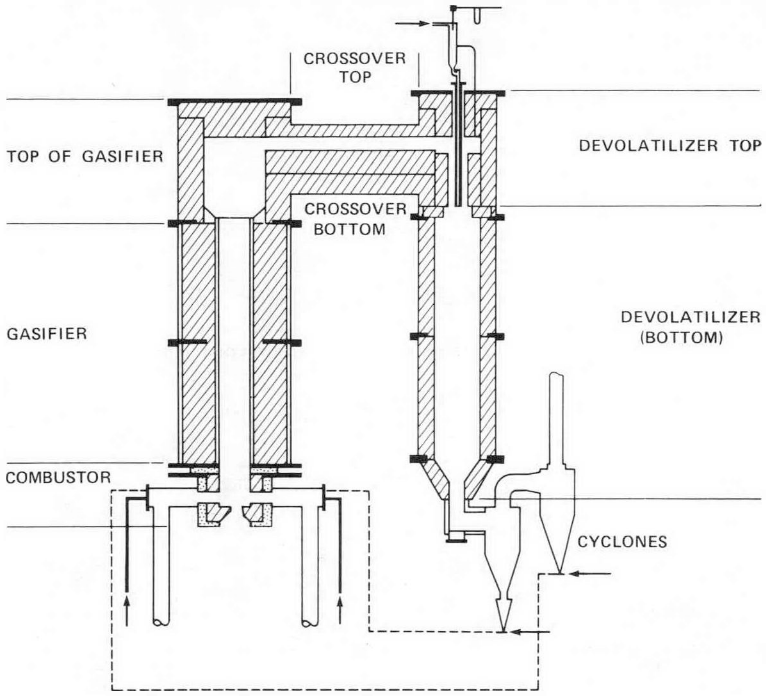
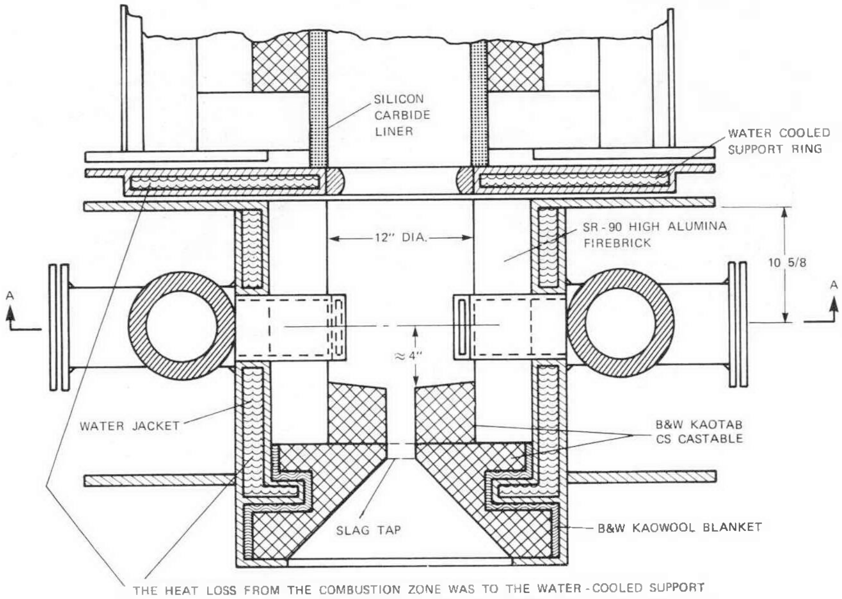


FIGURE 5.1 EQUIPMENT COMPONENTS FOR THERMAL ANALYSIS



THE HEAT LOSS FROM THE COMBUSTION ZONE WAS TO THE WATER-COOLED SUPPORT RING AND THE WATER JACKET. THIS HEAT LOSS WAS CALCULATED USING INLET AND OUTLET WATER TEMPERATURES TOGETHER WITH FLOW RATES.

FIGURE 5.2 COMBUSTOR COMPONENTS FOR THERMAL ANALYSIS

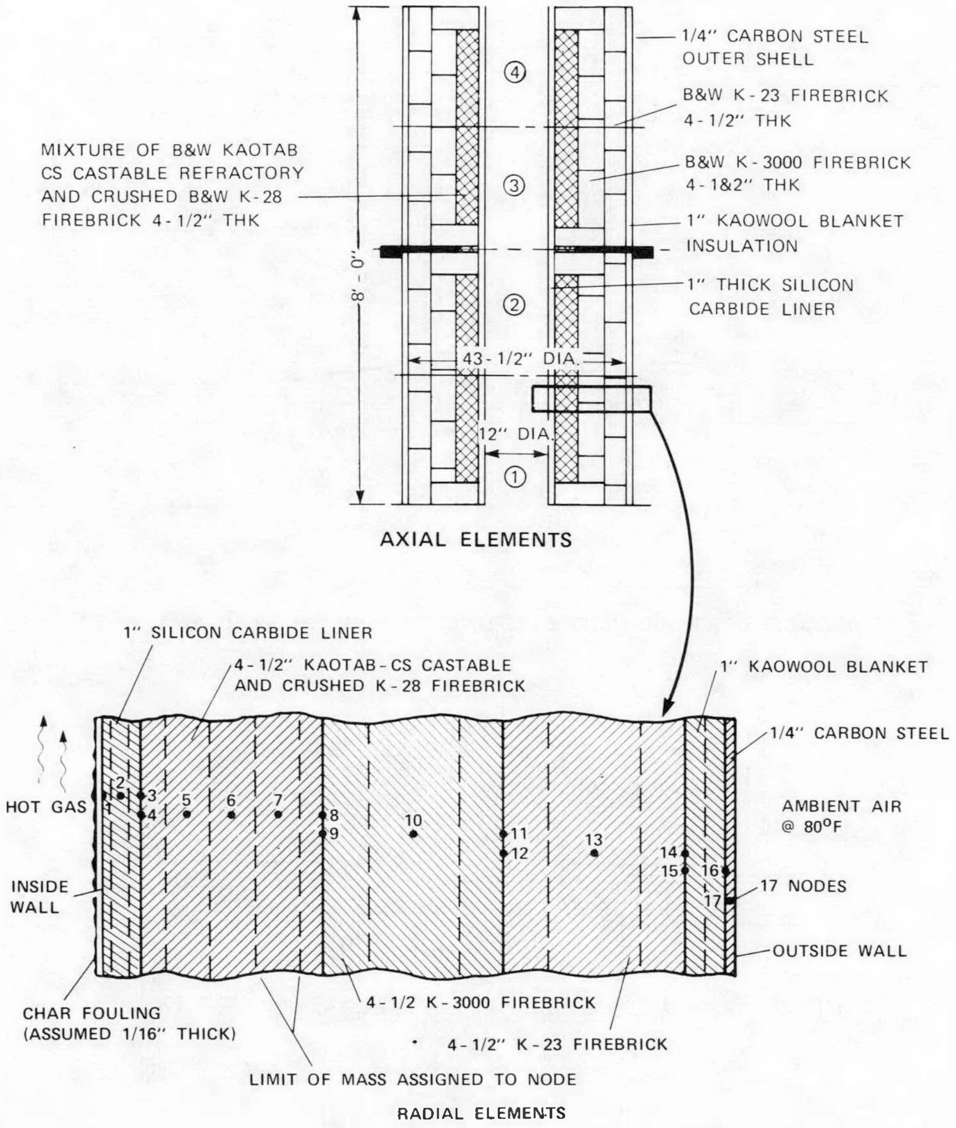


FIGURE 5.3 RADIAL AND AXIAL THERMAL ELEMENTS IN GASIFIER BOTTOM WALL USED IN THERMAL ANALYSIS

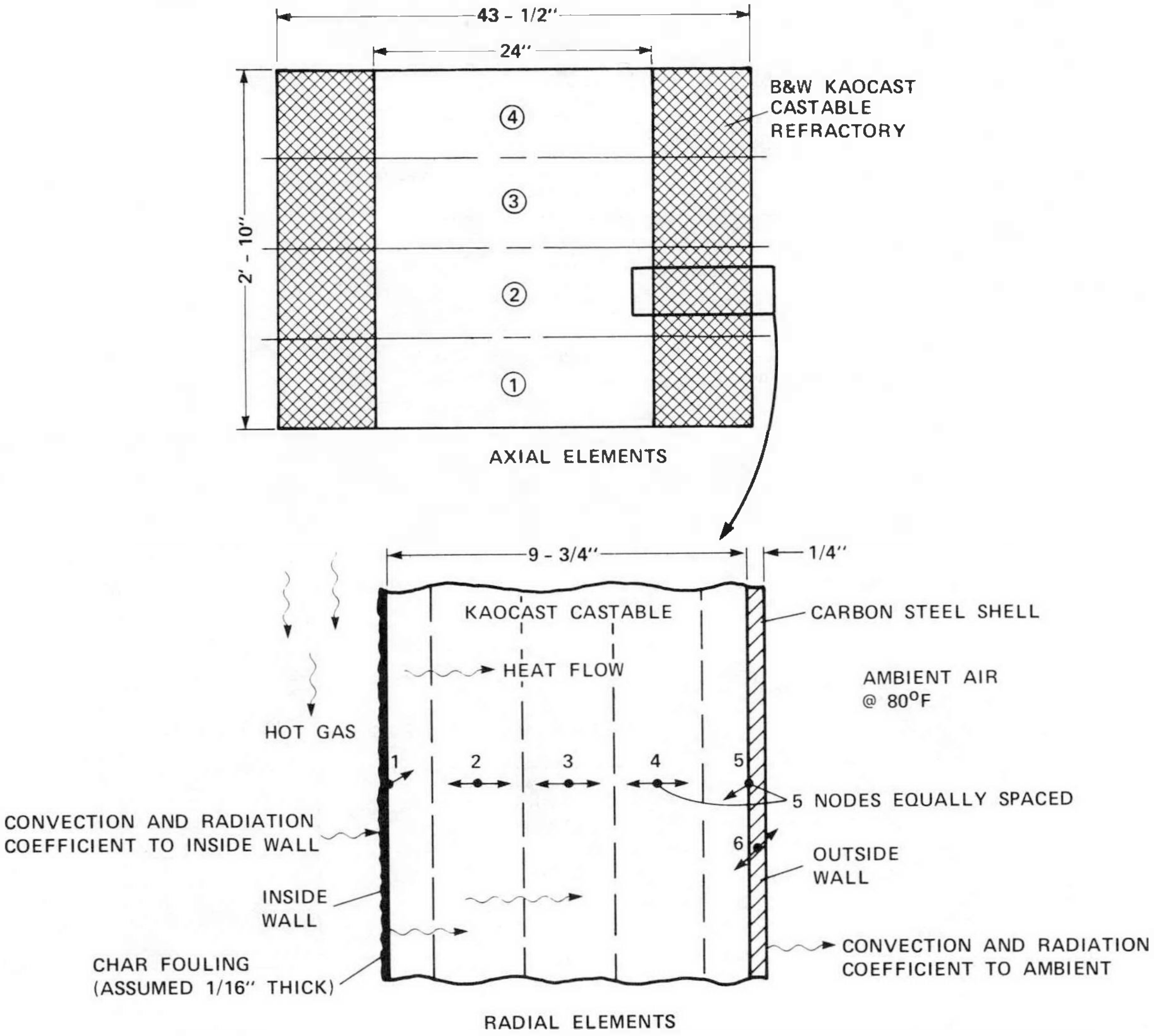


FIGURE 5.4 RADIAL AND AXIAL THERMAL ELEMENTS IN TOP OF GASIFIER USED IN THERMAL ANALYSIS

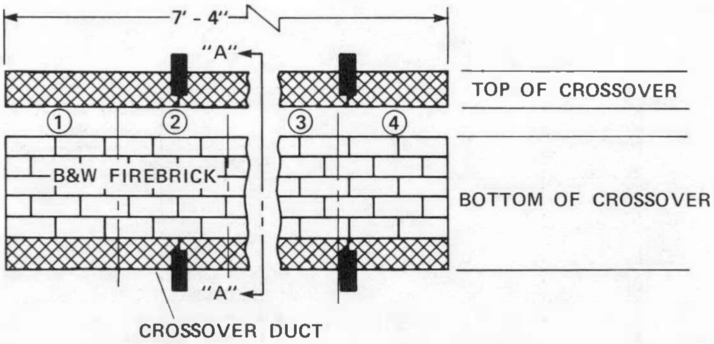
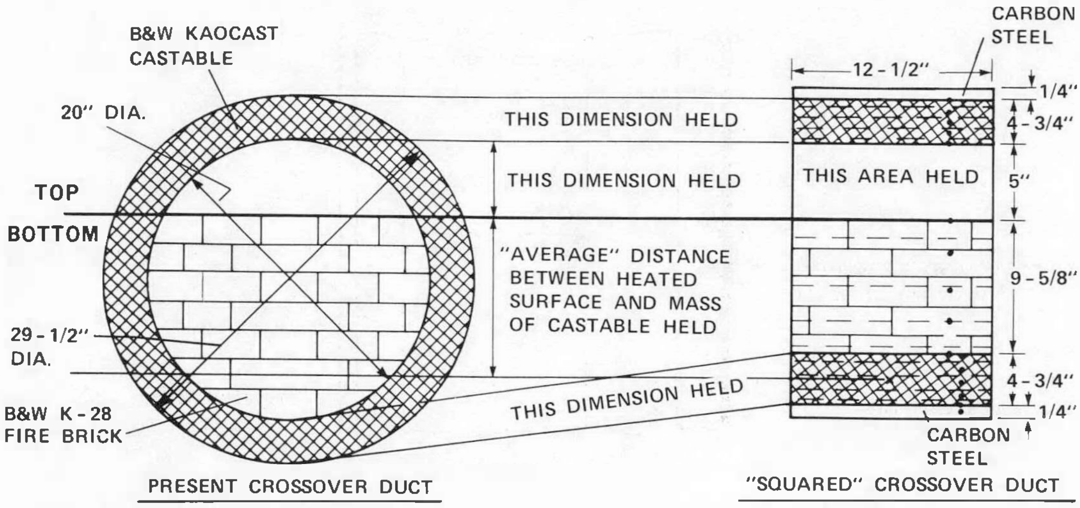


FIGURE 5.5 AXIAL ELEMENTS IN TOP AND BOTTOM OF CROSSOVER DUCT USED IN THERMAL ANALYSIS



NOTE: CERTAIN DIMENSIONS HELD,
ALL CONDUCTIVITIES HELD,
ALL DENSITIES AND HEAT
TRANSFER COEFS. ADJUSTED.

FIGURE 5.6 ILLUSTRATING "SQUARING" OF CROSSOVER DUCT

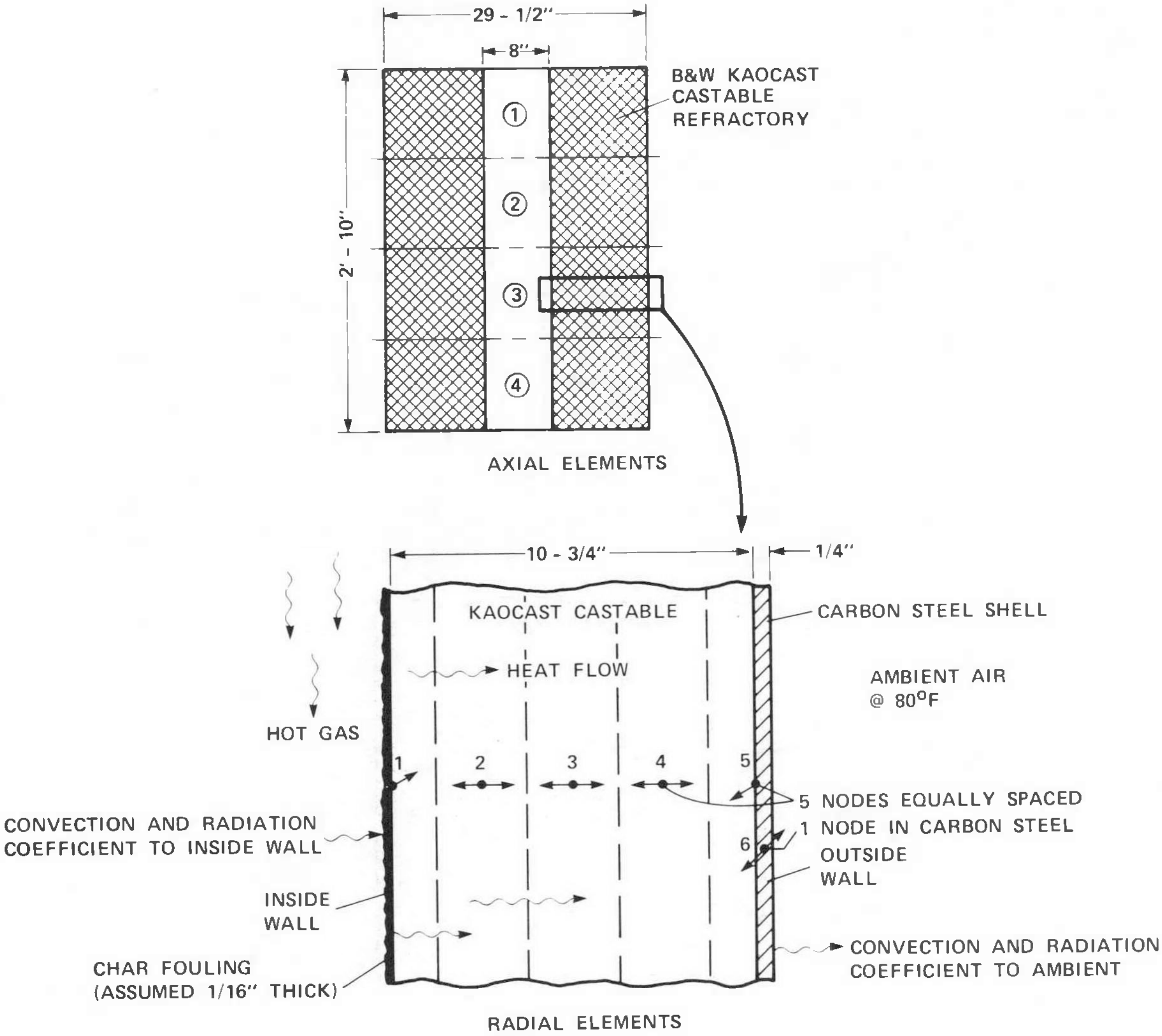


FIGURE 5.7 RADIAL AND AXIAL THERMAL ELEMENTS IN TOP OF DEVOLATILIZER USED IN THERMAL ANALYSIS

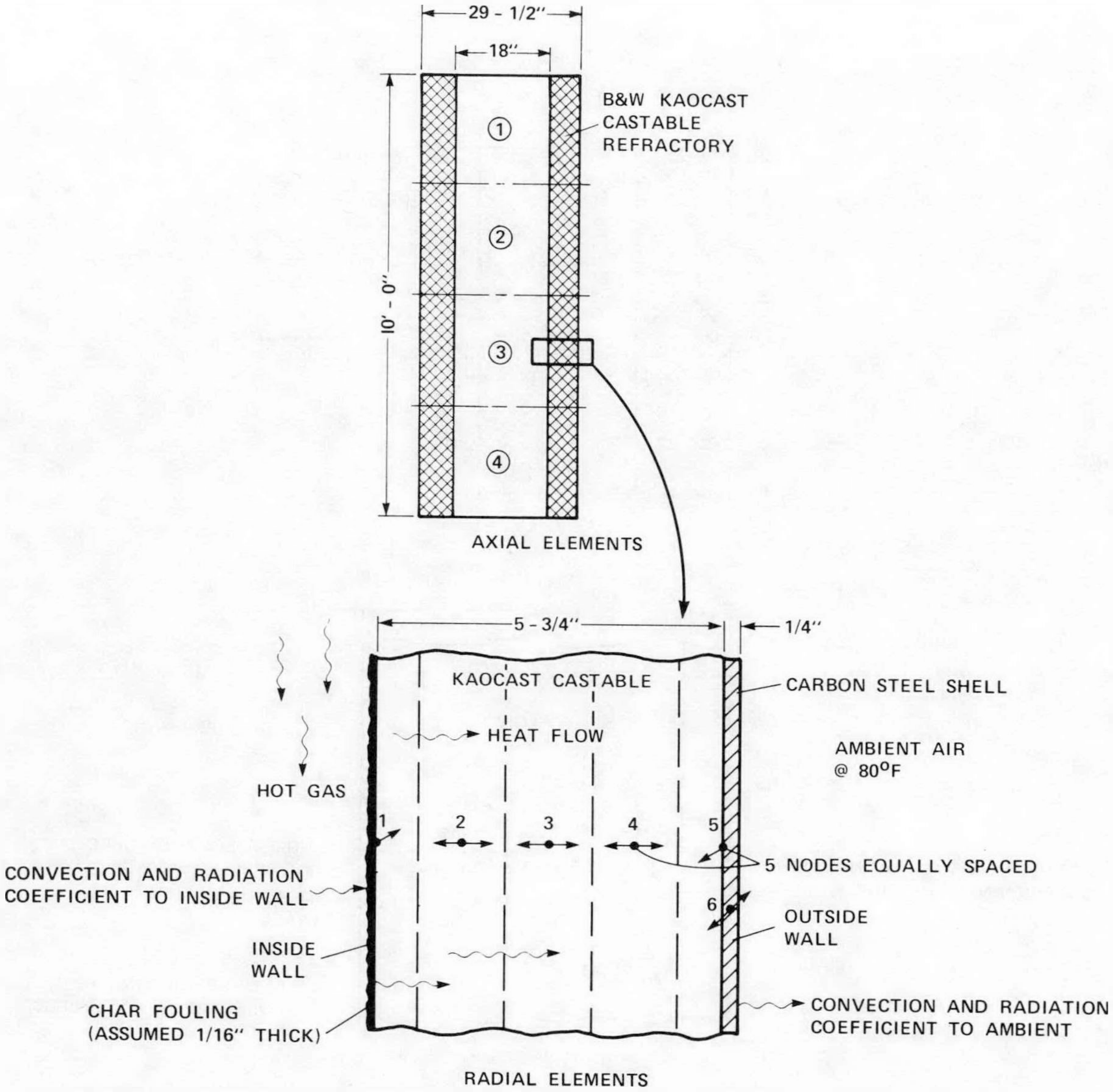


FIGURE 5.8 RADIAL AND AXIAL THERMAL ELEMENTS IN BOTTOM OF DEVOLATILIZER USED IN THERMAL ANALYSIS

For the crossover duct, the adjustment was more difficult because all of the shape is three-dimensional, not just a small fraction of it. Nevertheless, we thought it appropriate not to invoke the complexity of a three-dimensional model (later justified by results) and so made the simplifications as indicated in Figure 5.6. In particular we:

1. Maintained the height of the flow duct (5 inches) and the thickness of the castable refractory (4-3/4 inches) the same in the simplified model as in the actual apparatus.
2. Chose the width of the simplified model (12-1/2 inches) so that the flow area was the same as in the actual apparatus.
3. For the bottom of the duct, estimated the average distance between the heated surface and the mass of refractory, and adjusted the thickness of fire brick in the model to give the same value (9-5/8 inches).
4. Used the same values for thermal conductivities in the model as in the actual apparatus.
5. Adjusted the densities of the various refractory pieces and metal pieces to give the same mass as in the actual apparatus.
6. Adjusted the heat transfer coefficients on the external and internal surfaces so as to give the same coefficient-area product as in the actual apparatus. Used the actual flow and the hydraulic radius of the actual apparatus for computing the internal convection coefficient.
7. Used the actual geometry of the duct in computing the external convection coefficient.

Thus, the main approximation made in "squaring" this round duct was in estimating the mean distance between heated surface and mass of refractory in the bottom of the duct. This was actually done by drawing several vectors to represent approximately the heat flow paths, measuring their length, and averaging the result. We estimated that the error made in choosing this mean length would be less than 20%. The actual material properties used in the computations are listed in Appendix E together with the adjusted values where they apply. Adjustment factors for heat transfer coefficient are shown on the various figures where they apply.

In this fashion, the actual apparatus was transformed into a virtual or "model" apparatus consisting of a combustor of known heat loss, five sections of tubular refractory duct (without ends) comprising the gasifier, crossover duct, and devolatilizer, and the cyclone separators (including the water-cooled elbow at the bottom of the devolatilizer). The transient thermal analysis of the refractory pieces was accomplished by writing the customary difference equations governing transient conduction in cylindrical geometry.

5.1.2 Model Assumptions

The thermal model has five general aspects, and we shall divide the discussion of assumptions accordingly. These aspects are:

1. The state of the internal fluid (temperature and composition) that is transferring heat to the internal walls of the apparatus
2. The description of the heat transfer from the internal fluid to the internal walls
3. The description of a heat transfer within the refractory walls of the equipment
4. The description of the external heat transfer from external surfaces of the apparatus to the ambient atmosphere
5. The process operating conditions

When methane was fired for the purpose of preheating, it was assumed that the excess air was 15%. The heat loss in the combustor was calculated from experimental measurements, and it was assumed that combustion was completed in the combustor. Thereafter, the combustion gas simply cooled as it passed through the apparatus. The temperature was determined by the firing conditions and the heat losses to the walls up to any given point.

To determine the state of the internal fluid when firing coal, we assumed that:

1. In the combustor air and char react according to:

   $$\text{AIR} + \text{CHAR} \rightarrow CO_2 + H_2O + \text{RESIDUAL CHAR}$$

   Coal is then added which immediately devolatilizes to form additional char and gas which equilibrates with CO_2 and H_2O from air combustion, giving a gas containing char, N_2, CO_2, CO, H_2O, H_2 and ash.
2. In the gasifier, some of the char is gasified to form CO and H_2. The total amount of char gasified is determined by material balance using experimental data. Axially, the amount gasified is linearly distributed with respect to gasifier length. The amounts of CO, CO_2, H_2 and H_2O are dependent upon the temperature of the reacting mixture according to the water gas shift equilibrium.
3. No char is gasified in the crossover pipe or devolatilizer.

4. When part of the coal is fed to the devolatilizer, only devolatilization takes place; no gasification reactions occur. The resulting gas equilibrates via water gas shift down to a temperature of 1700°F.
5. Cyclone separator efficiency is 90%.
6. Heat loss from the water-cooled elbow at the bottom of the devolatilizer together with the cyclone heat loss was taken to be 19,606 kcal/kg mol O_2 fed as air, based on previous estimates.
7. Char recycle temperature was taken to be 500°K (440°F). (This requires an additional heat loss that is not otherwise considered in the model.)

Thus, the gas composition was determined from the air-fuel ratio and the temperature, and the temperature, in turn, was determined from heat losses including heat losses to the refractory walls. We have ignored the fact that hydrocarbons would actually be produced upon devolatilization, because the enthalpy change between the hydrocarbons and an equilibrium CO_2, CO, H_2O, H_2 mixture is insignificant. The detail of the energy and material balance calculations based upon these assumptions is given in Appendix E.

The heat transferred to the internal walls of the gasifier, crossover duct, and devolatilizer consists of radiative and convective components. In the case of coal firing, the radiative heat transfer coefficient was computed with the assumption that the gas emissivity is unity. This is justified by the high particulate loading. In the case of gas firing, the gas emissivity was calculated from the CO_2 and H_2O concentrations together with the emissivity correlation presented in Weibelt (see Appendix F). In both cases, the convection coefficient was calculated from a Dittus-Boelter equation modified for entrance effect according to Feild, et al (see Appendix F). In this, mean gas viscosity was calculated at temperature from individual gas viscosities weighted according to the product of mol fraction and the square root of molecular weight according to Janka and Nalhatra. Mean thermal conductivity was calculated from individual conductivities using the product of mol fraction and the cube root of molecular weight as a weighting factor. Specific heat was calculated from individual molar specific heats weighted according to mol fraction. In the case of coal firing, the particulate loading in the gas was ignored in calculating viscosity and thermal conductivity but not in calculating heat capacity and mass flow rate. (Density per se was not used in calculating the Reynolds Number of the flow; mass flow rate was used instead.)

Thus, in effect, the gas density and the gas specific heat included the effect of ash and char particles. This was done in an attempt to allow for the fact that particulate loading tends to increase the heat transfer coefficient as reported by Depew and Kramer (Appendix F).

5.1.3 Determination of Internal Axial Temperature Profile

The basic problem addressed by a thermal model is one of two-dimensional transient conduction in the refractory of the gasifier, crossover duct, and the devolatilizer. Its computer solution is achieved by finite differences in both the space and time variables. As part of the solution, one requires, for each instant of time, a heat flux to the inside of the thick walled refractory cylinders. This, in turn, requires the axial temperature profile for both the inside refractory surface and the fluid. The surface temperature profile was approximated by using that of the previous timed increment. The fluid temperature, however, is a driving force for all other temperature changes, and cannot be approximated in this fashion. Instead, it was calculated for each time increment by energy and material balances as follows:

1. Given the fluid temperature at the entrance to an axial increment, that at the exit was estimated to be 100°K lower, as a starting point.
2. Using the estimated exit temperature, the fluid composition was calculated by energy and material balances (Appendix E). The amount of gasification along the total length of the gasifier, top and bottom, was linearly distributed according to the axial position.
3. The average gas temperature and composition for the increment was calculated by arithmetically averaging the known values at the beginning of the increment and the calculated values at the end of the increment.
4. The heat loss through the wall was calculated from these properties using the wall temperature from the previous increment.
5. From the heat loss to the wall and the known flow rate of the internal fluid and its composition, the fluid temperature at the apex of the increment was calculated. This value was compared with the initial estimate and, if they agreed within 0.01°K, the calculation proceeded to the next increment.
6. If agreement was not achieved, the second estimated temperature was taken 100°K lower than the first and the procedure repeated starting with step 2. For the third and successive trials, the new estimate was found by linear interpolation between the last two.

In this fashion, the internal temperature distribution and the internal heat flux were calculated throughout the axial length of the apparatus for one time increment. This was followed by conduction calculations to determine the change in radial temperature distribution during the time increment.

5.1.4 Determination of Refractory Temperatures

The partial differential equations describing transient heat conduction through the refractories were written in the form of difference equations. A typical equation describing the time rate of temperature change at an internal wall node is:

$$\frac{\Delta T}{\Delta \theta} = \frac{2}{(\rho C_p)_1 \, \Delta r_1^2} \left\{ \frac{q_1 R_1 \Delta r_1 - \left(\frac{k_1 + k_2}{2}\right) (T_1 - T_2) \left(R_1 + \frac{\Delta r_1}{2}\right)}{R_1} \right\}$$

where

k = conductivity

R = radius

Δr = incremental radius

T = temperature

q = heat flux density to wall

C_p = heat capacity of refractory material

ρ = density of refractory material

$\frac{\Delta T}{\Delta \theta}$ = rate of change of temperature

1, 2 = subscripts denote node, as in Figure 5.3

The very simple Euler's Method was used to calculate the temperature of a node at the next time increment. This algorithm is:

$$T_{(\text{Time} + \Delta\theta)} = T_{(\text{Time})} + \frac{dT}{d\theta} \Delta\theta$$

Thus, account was taken of conductive heat transport in a radial direction, but that in the axial direction was ignored. The justification for this is simply that the gradients in the radial direction are much steeper than those in the axial direction, making the additional precision to be gained by considering axial conduction of questionable value compared with the additional complexity.

To avoid stability problems and ensure a reasonable accuracy, the temperature changes for each time increment were computed twice. The first computation served to determine the maximum temperature change anywhere in the apparatus. In the second computation, the length of the time increment was adjusted to:

$$\Delta\theta = \frac{0.005}{\left(\frac{dt}{d\theta}\right)^{.05}_{\max.}}$$

where the dimensions of temperature are degrees Kelvin and time is in hours. This algorithm for setting the time increment was arrived at purely empirically based upon experience.

5.2 VERIFICATION OF COMPUTER PROGRAM

5.2.1 Preliminary Checks

The accuracy of each subroutine was verified by manual computation for at least one set of input parameters. In addition, computer-produced temperature distributions for the bottom of the crossover duct were checked against the Gurney-Lurie chart for a slab as taken from McAdams book on heat transfer.(1) Considering that the Gurney-Lurie chart assumes constant thermal properties, whereas we were calculating using properties that vary with temperature, the results were close enough to convince us of the general accuracy and validity of the program.

The stability of the computer program was checked by reducing the time increments by one-half and then verifying that the calculated temperature at any point was the same or nearly the same as for the full-time increments. The results of this check indicate the calculated temperatures were within 0.1°K, thus veryifying the stability of the computer program.

5.2.2 Verification Against Pilot Plant Data

The computer program was tested by comparing its predicted gasifier outlet, crossover duct outlet, and the devolatilizer outlet temperatures against those produced on the day of tests 33, 34, 35, and 36. It was assumed that all points in the apparatus started at room temperature. The firing conditions used as input to the program were adjusted so as to be identical with those actually used on the day of these tests. The resulting temperatures are compared with experimentally observed temperatures in Figure 5.9. It will be noted that all the predicted temperatures are within 100°K (180°F) for tests 33, 34, and 35. In test 36, differences are as much as 200°K (360°F). For this test, all coal was fired to the devolatilizer. This larger discrepancy might be due to one or both of two factors:

1. The higher outlet temperatures, especially out of the gasifier and crossover duct, may have been missed by the thermocouples due to conduction losses.
2. A cyclone efficiency of 90% was assumed throughout. However, it would not be unreasonable to expect it to be much higher in the case of firing all coal to the devolatilizer. If so, our use of too low a value of cyclone efficiency may account for our overpredicting the temperatures.

TABLE 5.1 HEAT LOSSES CALCULATED BY MATERIAL AND ENERGY BALANCE VERSUS HEAT LOSSES PREDICTED BY COMPUTER MODEL

	EXTERNAL SURFACE HEAT LOSSES				TRANSIENT HEAT LOSS		TOTAL HEAT LOSS				
TEST NO.	COMBUSTOR	GASIFIER	DEVOLATILIZER INCLUDES CROSSOVER	CYCLONES INCLUDES WATER JACKET	GASIFIER	DEVOL.	GASIFIER	DEVOL.	CYCLONES	CHAR RECYCLE LINE	OVERALL HEAT LOSS
33*	9164	0	297	19606	279	12752	9443	13049	19606	5091	47189
33**	9164	0	1036	19606	14262	11206	23426	12242	19606	0	55274
34*	10371	0	734	19606	1412	6351	11783	7085	19606	5549	44023
34**	10371	0	1036	19606	7874	6186	18245	7222	19606	0	45073
35*	8829	80	1484	19606	5191	7819	14100	9303	19606	8760	51769
35**	8829	0	1036	19606	16598	13041	25427	14077	19606	0	59110
36*	9875	635	3041	19606	10129	9051	20640	12093	19606	4951	57291
36**	9875	0	1036	19606	20120	15808	29995	16844	19606	0	66445

*PREDICTED BY THE MODEL
**MATERIAL AND ENERGY BALANCE CALCULATIONS

UNITS: $\frac{\text{kcal}}{\text{kg mol } O_2}$

Table 5.1 compares the heat losses predicted by the model with those calculated by material and energy balance using the experimental data. These apply to the same four runs of Figure 5.9. The difference between the overall heat loss predicted by the model and that calculated by the material energy balance is consistent with the differences in predicted and observed outlet temperatures with one exception. This is the overall loss for test 35, where the two figures should agree quite closely. We have tried to find the explanation for this anomaly; no doubt, it is due to an error in transcription in some data input, but we have been unable to find it. In any event, it seems clear that the overall losses in general agree between computed and calculated. In studying the detail of Table 5.1, the reader will notice the following:

1. Among the "external surface heat losses", the computed and experimental values are either identical or else only very slightly different.
2. The computer model consistently estimates lower heat losses in the gasifier. This is largely compensated by a finite heat loss in the char recycle line compared with zero heat loss in this line according to the "experiments." The reason for this is

that, in analyzing the experimental data, we assumed no heat loss in the char stream recycle line. In the present computer model, on the other hand, we assumed a char recycle temperature (which is probably the more reasonable approach). Thus, the experimentally determined "transient" heat loss should probably have been lower. If it had been, the sums of the transient and devolatilizer heat losses for experimental and model predictions would have been much closer. On the other hand, the distribution between these two pieces of equipment wouldn't have been quite right. In this connection, it should be remembered that the "experimental" transient losses were arbitrarily assigned between devolatilizer and gasifier. Consequently, the model predictions are probably more accurate.

5.2.3 Effect of Cyclone Efficiency on Predicted Temperatures

The cyclone efficiency of 90% assumed and used to calculate the predicted temperatures in Figure 5.9 was arrived at by trial and error. Initially an efficiency of 60% was assumed, resulting in predicted temperatures shown in Figure 5.10, which are much higher than actually observed. This results from the fact that a lower cyclone efficiency causes less cold char to be recycled back to the gasifier thereby allowing temperatures to remain high throughout the system. The cyclone efficiency was then increased in increments up until 90% efficiency, a value which seemed to predict the observed data reasonably well.

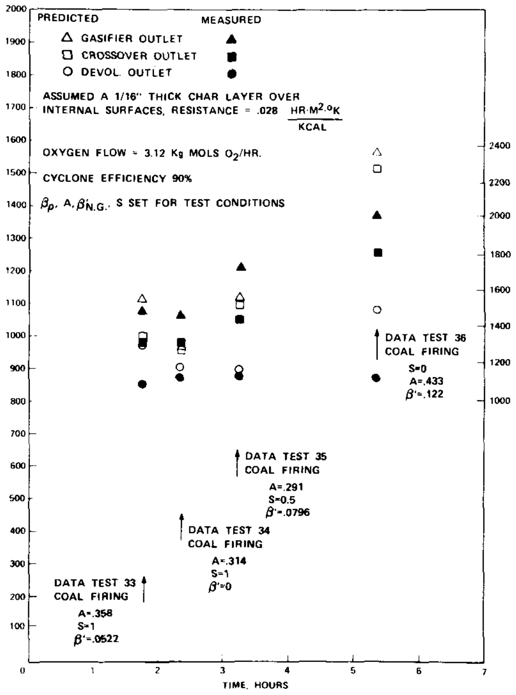


FIGURE 5.9 COMPARISON OF OBSERVED TEMPERATURES VS PREDICTED TEMPERATURES

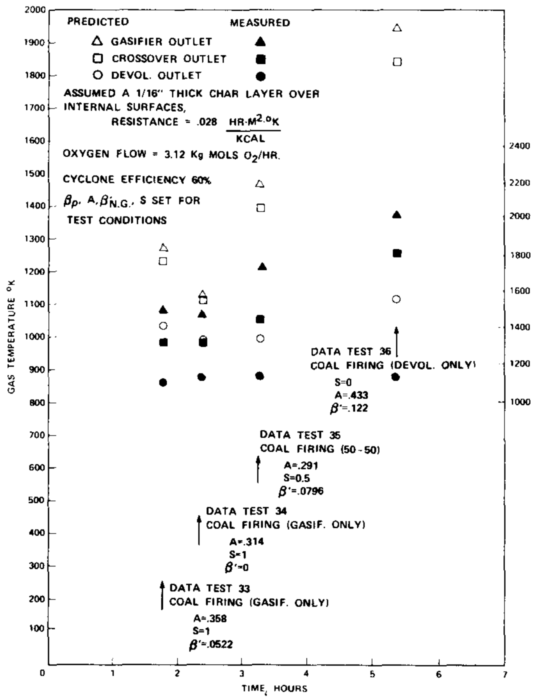


FIGURE 5.10 EFFECT OF LOW CYCLONE EFFICIENCY ON PREDICTED TEMPERATURES

5.3 PREDICTIONS OF THERMAL ANALYSIS MODEL

5.3.1 Achieving Steady-State

As previously stated, the first objective of the present analysis was to determine how long it would take for the pilot apparatus to achieve thermal steady-state and what might be its heat losses under this condition. To accomplish this, we simulated tests 33 and 38 extended to running times of 36 and 30 hours respectively. The results are shown on Figures 5.11 and 5.12.

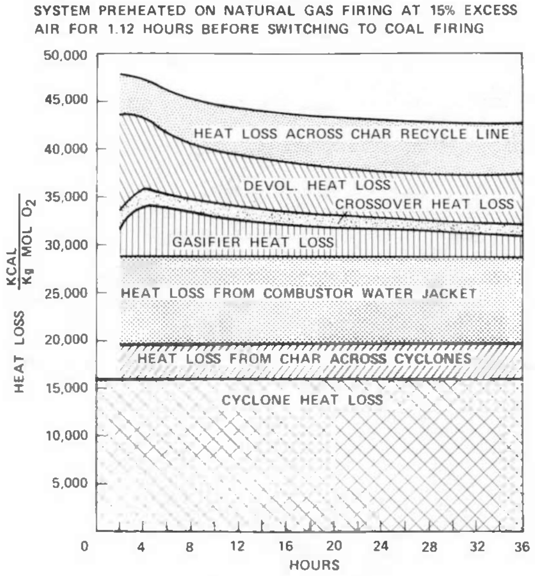


FIGURE 5.11 HEAT LOSSES DURING COAL FIRING AT TEST 33 CONDITIONS CALCULATED VIA MODEL

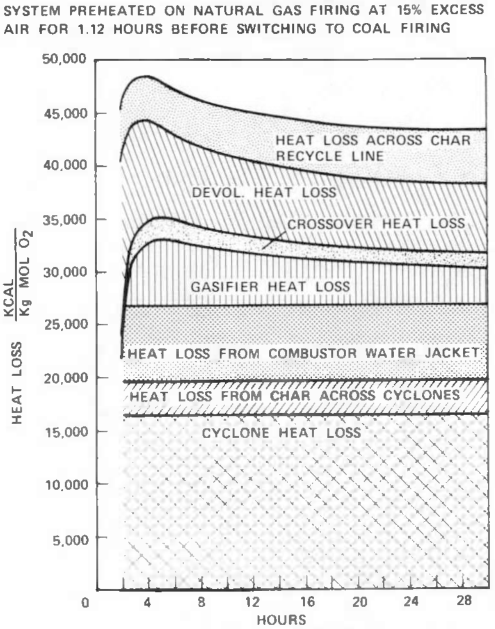


FIGURE 5.12 HEAT LOSSES DURING COAL FIRING AT TEST 38 CONDITIONS CALCULATED VIA MODEL

Before attempting to interpret these results, let us first clarify the meanings of the various heat losses in some detail.

The Cyclone Heat Loss represents the heat loss from the gas only (exclusive of the particulate) as it passes through the cyclone separators. Since this loss occurs after the major volume of the equipment, it is of no significance to the gasification reactions. It represents only cooling of the make gas. The Heat Loss from the Char Across Cyclones represents the heat loss from the char stream as it traverses the water-cooled elbow following the devolatilizer and the cyclone separators. This loss might have some significance for the process were it not for the fact that it is not practical to recycle char that is too hot. Consequently, one must consider this heat loss to be unavoidable in the pilot apparatus as well as in full scale. The Heat Loss Across Char Recycle Line (top of Figure 5.10) is another matter. This represents the heat loss from the char between the point of exiting from the cyclone separators and entering the combustor. Its magnitude is based upon the assumption that the char enters the combustor at 500°K (440°F). In other words, it is the heat loss in the char in the pilot apparatus in cooling from about 1000°F to about 440°F. It would not be present in a full-scale installation, and it could probably be eliminated by redesigning the elbow and cyclone separators in the pilot apparatus. Returning to the middle of Figure 5.11, the Heat Loss from the Combustor Water Jacket is that which is lost in this pilot apparatus to the water jacket and the water-cooled support for the refractory. This loss might possibly be reduced by about a third by going to a much more difficult to design stainless steel air-cooled shell instead of the water-cooled. However, it seems unlikely that it can be reduced below about two-thirds its present magnitude. The problem is that the fluid dynamic agitation and the fluxing action of the slag determine the heat flux density from the combustion zone to a point in the refractory where the slag just solidifies. The thickness of the "refractory", then, adjusts itself to accommodate this heat flux density; if the solid refractory is too thin, more heat flows out through it than is supplied from the combustion, and slag is thus frozen until the thickness builds up to the point where the conduction through the solid equals the input from the fluid; conversely, if the solid is too thick, the slag fluxes the refractory out until the heat flux into and out of the freezing zone balance. On the other hand, this heat loss could probably be at least partially compensated by increasing air preheat. The remaining losses, Gasifier Heat Loss, Crossover Heat Loss, and Devolatilizer Heat Loss are those that are computed in the present mathematical model. They represent transient heating up of the refractory and convective heat losses from the external shells of the various vessels.

Turning now to the interpretation of the results of Figures 5.11 and 5.12, it will be noted that even after substantial steady-state is obtained, the significant heat losses are reduced by only about 10% from their values at the time the data were taken (at a time of about 2 hours on the abscissa of the plots). This is due partly to preheating and, actually, overheating the apparatus a little at the start, and also to the fact that the heat loss across the Char Recycle Line tends to increase as the apparatus equilibrates because the char temperature leaving the cyclone separators tends to increase.

Thus, the answer to the first question is that the pilot apparatus must run for about 24 hours to achieve thermal steady-state, but the significant heat losses are not substantially different at 24 hours than they were at 2 or 3 hours when the data were taken. Inasmuch as significant steady-state heat losses represent about 30% of the heat release capability of the oxygen being put into the system or, very roughly, 40 - 45% of the actual heat release in the process, they are probably very significant from the standpoint of limiting performance. Consequently, we must conclude that this particular pilot apparatus, operated at steady-state under the conditions of the tests performed in this series, is not capable of producing data representative of full scale apparatus.

However, this does not mean that this apparatus, if slightly modified, and operated in a different fashion, might not produce representative data. For example, if the water-cooled elbow beneath the devolatilizer and the stainless steel air-cooled cyclones were replaced by air-cooled ceramic parts, the char recycle temperature could probably be raised from about 440°F to about 1000°F. This would completely eliminate the Heat Loss Across Char Recycle Line. Moreover, although the Heat Loss from Combustor Water Jacket cannot be eliminated, it might be largely compensated by raising the air preheat temperature. For example, raising the air preheat temperature from about 800° or 850° to 1050° or 1100°F would provide an additional heat input equal to about 5000 kcal/kg mol O_2. This compares with 10,000 kcal lost to the combustor water jacket. Thus, raising the air preheat would compensate for all but about 5,000 kcal of water jacket loss, which would bring that loss to about 10% of the potential heat release of the oxygen, or about 7% of the actual heat release in the apparatus. In other words, by increasing the air preheat one could get the heat loss to the combustor water jacket down to a value that should be very comparable with that predicted for commercial practice.

With these modifications to the char recycle system and the air preheat system in mind, there still remains the question of whether or not the heat losses to the refractory in the devolatilizer and gasifier might be reduced to values comparable to that predicted for commercial practice. Inasmuch as the mass of refractory presents a possibility of overpreheating and operating the apparatus in an unsteady-state mode, which could drive these heat losses to zero or even below, we thought it advisable to investigate this question further.

5.3.2 Deliberate Unsteady-State Operations to Minimize Heat Losses Using Present Apparatus

Two series of computer "experiments" were conducted to investigate the possibilities inherent in preheating to internal temperatures above the steady-state temperatures on coal firing. In the first, we maintained the equipment exactly as it is, and in the second, we assumed the modification that would enhance the effect.

Three axial temperature distributions are shown on Figure 5.12. One of them is the computed temperature distribution for test 38 if there were no heat loss to the gasifier, crossover duct, and devolatilizer walls. The other two applied to gas firing at thermal equilibrium, chosen so as to make the refractory inside surface temperature roughly correspond to the adiabatic fluid temperature with coal firing. This was achieved by using an air to fuel ratio of 2.4 in the combustor, and then burning additional gas at the top of the devolatilizer.

Several axial temperature profiles after switching over to coal firing at the conditions of run 38 are shown on Figure 5.13. It will be noticed that just after switching over to coal firing, the gas temperature profile is slightly above the adiabatic profile, implying heat input from the refractory walls rather than loss. Thereafter, the internal temperature profile drops as heat losses pull the refractory temperatures down. Figure 5.14 shows what happens to heat losses during the 2 hour time period immediately after switching over to coal. As noticed in the temperature profiles (Figure 5.13) the heat losses to refractory are initially negative. But within a few minutes after switching over, they become positive and build very quickly to nearly their steady-state values. Thus, unless data could be obtained within 10 minutes or less after switching over to coal, there would be no period of substantially zero heat losses to refractory. Since this is too short a period of time to expect to stabilize flows and get an accurate reading on the coal flow rate, this particular operation would be impractical.

Figure 5.15 shows similar heat losses, but with preheat to somewhat higher temperatures. In fact, the preheat was high enough to produce substantial negative heat losses immediately after switching over to coal. In this case, substantially zero heat loss is obtained for a period from about 12 minutes after switching over to a period of about 24 minutes after switching over (i.e., from 24.2 to 24.4 hours along the abscissa). By stretching one's concept of "zero heat losses" a little bit, this period might be extended from, say, 12 minutes after switching over to 36 minutes after switching over, giving a period of about 24 minutes of substantially zero heat loss to the refractory. These time periods might be adequate to stabilize flows and get an accurate reading of coal flow. However, the "window" within which one can obtain data seems quite small, especially in view of the probable precision of our calculation. Thus, we feel that this would be a difficult way to operate - one that would probably result in one run discarded for every one that is accepted.

COMPUTER SIMULATION OF UNSTEADY - STATE OPERATION

CONDITIONS: AT 140% EXCESS AIR WITH AN ADDITIONAL 7500 $\frac{\text{KCAL*}}{\text{KG MOL } O_2}$ OF HEAT ADDED AT DEVOLATILIZER INLET

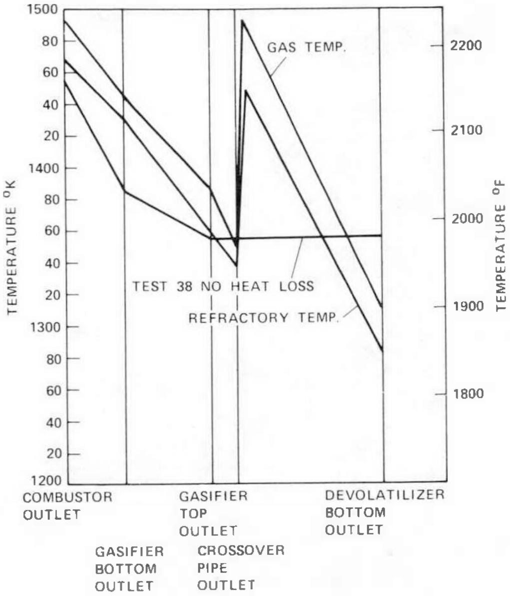


FIGURE 5.13 REFRACTORY AND GAS TEMPERATURES AFTER 24 HOURS ON NATURAL GAS FIRING

SYSTEM PREHEATED FOR 24 HOURS WITH NATURAL GAS FIRING AT 140% EXCESS AIR WITH AN ADDITIONAL 7500 $\frac{\text{KCAL*}}{\text{KG MOL } O_2}$ OF HEAT ADDED AT THE DEVOLATILIZER INLET

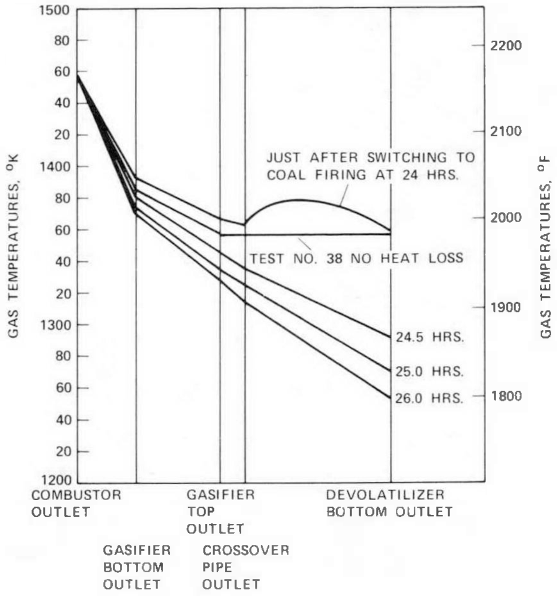


FIGURE 5.14 GAS TEMPERATURES FOR COAL FIRING AT TEST 38 CONDITIONS

SYSTEM PREHEATED ON NATURAL GAS FIRING AT 140% EXCESS AIR FOR 24 HOURS WITH AN ADDITIONAL 7500 $\frac{\text{KCAL*}}{\text{KG MOL } O_2}$ OF HEAT ADDED AT THE DEVOLATILIZER INLET

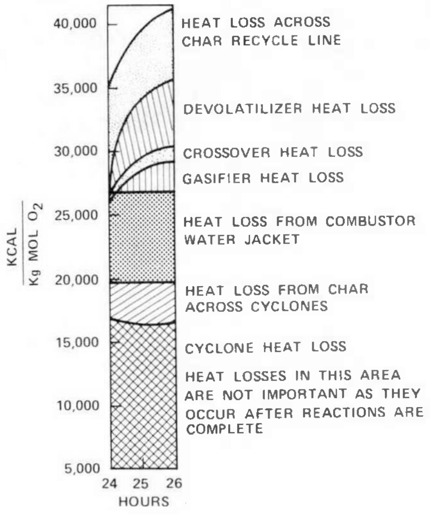


FIGURE 5.15 HEAT LOSSES DURING COAL FIRING AT TEST 38 CONDITIONS

SYSTEM PREHEATED ON NATURAL GAS AT 126% EXCESS AIR WITH AN ADDITIONAL 11500 $\frac{\text{KCAL*}}{\text{KG MOL } O_2}$ HEAT ADDED AT DEVOLATILIZER INLET

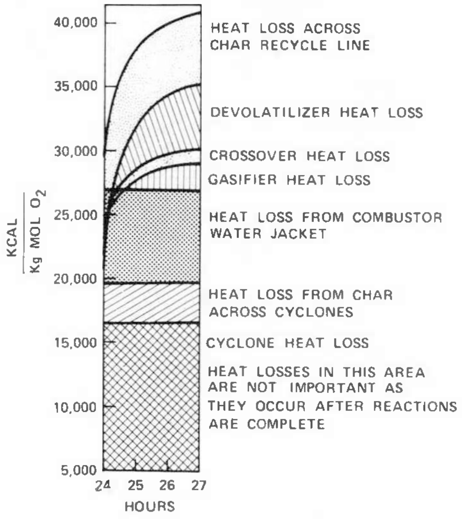


FIGURE 5.16 HEAT LOSSES DURING COAL FIRING AT TEST 38 CONDITIONS

*NOTE: THIS ADDITION OF HEAT WAS SIMULATED IN THE COMPUTER PROGRAM BY ADDING TO THE ENTHALPY OF THE GAS

Inasmuch as the operation implied by Figure 5.15 succeeds to a degree in promising elimination of refractory heat losses, we thought it would be beneficial to redesign the gasifier so as to take full advantage of the technique of over preheating and obtaining transient data. Fortunately, such kinds of changes can be made very readily on a computer model.

5.3.3 Design Change (Figure 5.17)

The light firebrick on the outside of the vessel (the K-3000 and K-23) is exactly the same as in the gasifier bottom in the present apparatus. However, we have replaced the present mixture of castable and broken firebrick with 4-1/2 inches of all castable refractory (no chunks of broken firebrick). This roughly doubles the mass of material in this area. The internal diameter has been retained at 12 inches, the same as the present gasifier bottom. The length is extended to 24 feet so as to maintain the volume of the apparatus the same as the gasifier plus crossover duct plus devolatilizer of the present pilot plant. Figure 5.17 shows a preheat temperature profile assumed using natural gas firing at an initial air/fuel ratio of 2.4. Additional gas added into the middle of the gasifier serves to "flatten" the preheat profile to match the "no heat loss" profile of coal firing. Figure 5.19 shows various axial temperature profiles computed for this equipment. It will be noted that just after switching over to coal (conditions of Test 38) the profile is far above what would be the gas temperature profile in Test 38 if the refractory walls were adiabatic. This implies a substantial negative heat loss at the switchover time. Thereafter, the gas temperature profiles drop until, between 26 and 28 hours (2 and 3 hours after switching over), the gas temperature profile almost exactly matches the adiabatic profile.

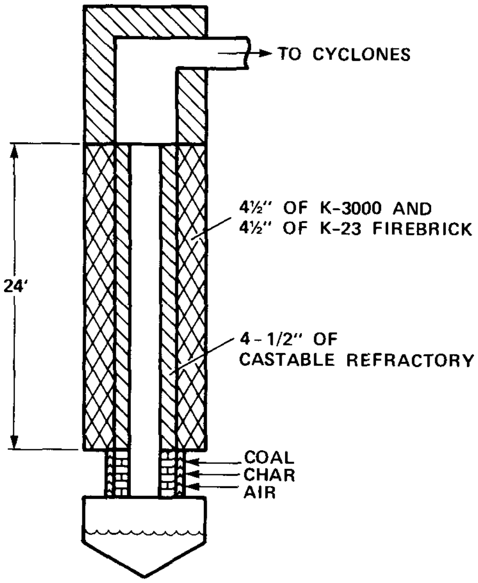
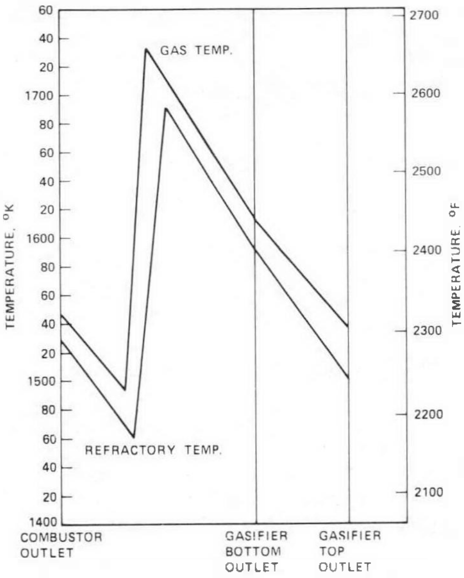


FIGURE 5.17 DESIGN CHANGE

Figure 5.20 shows the heat losses corresponding to Figures 5.18 through 5.19. It will be noted that at 26.4 hours, the refractory heat loss is exactly zero. However, from about 25.3 to about 28.4 hours, the refractory heat loss is within 2000 kcal of being zero. This amounts to about 0.8% of the heating value of the coal fired, or 3% of the actual heat release in the gasifier. Thus, it would be fair to say that this period of 3 hours would amount to essentially adiabatic operation. Thus in this case, the "window" in which data can be taken is quite broad. If data were taken every half hour from hour 25 through 30, one, and probably two, periods could be found wherein thermal balances would show zero heat loss to refractory.

COMPUTER SIMULATION OF UNSTEADY-STATE OPERATION



SYSTEM PREHEATED FOR 24 HOURS ON NATURAL GAS AT 140% EXCESS AIR WITH AN ADDITIONAL 1150 $\frac{\text{KCAL}^*}{\text{KG MOL } O_2}$ OF HEAT ADDED AT MIDPOINT OF GASIFIER

FIGURE 5.18 GAS AND REFRACTORY TEMPERATURES FOR "REDESIGNED" GASIFIER

*NOTE: THIS ADDITION OF HEAT WAS SIMULATED IN THE COMPUTER PROGRAM BY ADDING TO THE ENTHALPY OF THE GAS.

SYSTEM PREHEATED FOR 24 HOURS ON NATURAL GAS

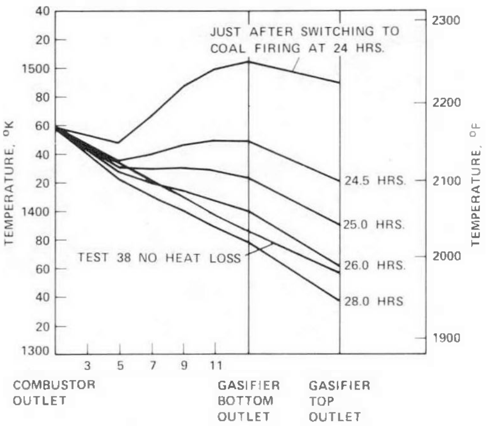


FIGURE 5.19 GAS TEMPERATURES FOR "REDESIGNED" GASIFIER FOR COAL FIRING

SYSTEM PREHEATED ON NATURAL GAS AT 126% EXCESS AIR FOR 24 HOURS WITH AN ADDITIONAL 11500 $\frac{\text{KCAL}^*}{\text{KG MOL } O_2}$ ADDED AT MIDPOINT OF "REDESIGNED" GASIFIER

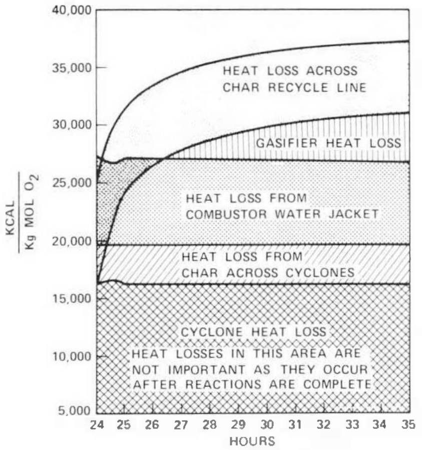


FIGURE 5.20 HEAT LOSSES DURING COAL FIRING FOR "REDESIGNED" GASIFIER AT TEST 38 CONDITIONS

In other words, by rebuilding the gasifier to the same "scale", but with different refractory, and by operating in the "high preheat-transient data" mode, we could completely eliminate heat loss in the refractory. As previously mentioned, the heat loss across the char recycle line could be completely eliminated by eliminating the water cooling and using refractory cyclones. By using more air preheat, the heat loss from the combustor could be compensated to the extent of bringing it into line with that predicted for full scale practice. The remaining heat loss from the char would be unavoidable in commercial practice, and, so, may not be eliminated. Finally, the remaining heat loss from the gas and the cyclone separators need not be compensated because it occurs after the process is complete. Thus, with these equipment modifications and the operation depicted in Figures 5.18 through 5.20, one could achieve in this small pilot scale, the heat losses that would be exactly comparable to those predicted in commercial scale.

5.4 SUMMARY OF CONCLUSIONS FROM THERMAL ANALYSIS OF PILOT APPARATUS

1. A mathematical model has been constructed to simulate the transient thermal behavior of our pilot apparatus. It accurately predicts the axial temperature distribution inside the gasifier according to the thermal history and coal-firing conditions.

2. Using this model, we have shown for the gasifier system as it presently exists that:

    a. Although we have confirmed the presence of transient heat loss in the gasifier, a substantial portion of this heat loss can be attributed to recycling cold char.

    b. There appears to be no way to operate the present apparatus so as to achieve heat losses that will be comparable to those predicted for a full scale installation.

3. By certain equipment modifications and by operating in a "high preheat-transient data" mode, a pilot apparatus of this scale (1000 lb/hr of air) can be made to produce heat losses fully comparable to the low losses expected in large commercial installations. The equipment modifications would include:

    a. Removal of the water-cooled elbow and stainless steel cyclone separators and replacing them with air-cooled ceramic parts so as to produce a recycle char temperature of about 1000°F.

b. Redesigning the char transport system so as to reinject the char at a temperature as close as possible to 1000°F.

c. Adding air preheat up to at least 1050°F so as to compensate for roughly 40% of the combustor heat loss.

d. Rebuilding the reaction volume (gasifier plus crossover duct plus devolatilizer) to employ about 4-1/2 inches of dense castable refractory enclosed in about 9 inches of light fire brick.

The operational mode consists of gas firing with high excess air (about 240% of theoretical) with injection of additional gas at one or more points along the apparatus. This is contrived so as to produce an additional internal refractory surface temperature profile that lies somewhat above the adiabatic gas temperature profile with coal firing. Data are then taken every half hour for 4 hours after changing over to coal firing. Analysis of these data should produce one or more half hour periods wherein the heat loss to the refractory is substantially zero. Under these conditions, the significant heat loss (which is the uncompensated combustor heat loss) should amount to about 2% of the heating value of the coal fired.

Section 6

SUMMARY OF RESULTS AND CONCLUSIONS

Analysis of the data yielded the following results for comparison of operation with all coal fed to the gasifier to all or some coal fed to the devolatilizer, under conditions of the same air-to-fuel ratio:

- The highest heating values were observed when all of the coal was fed to the gasifier.
- Unacceptably large tar quantities were generated when half or all of the coal was fed to the devolatilizer.
- Tar content of the make-gas tended to be negligible or low when all the coal was fed to the gasifier.

However, the data analyses also showed that heat losses were generally high--much higher than had been anticipated at the inception of this program. This was due to a combination of transient heating of the mass of refractory that had been substituted for the unsuccessful annular-fired design of the gasifier, too much heat loss due to recycling cold char, and excessive uncompensated combustor heat loss.

Within the range of substoichiometric air-to-fuel ratios studied utilizing this particular test apparatus, heat losses were related to the air-to-fuel ratio; the higher air-to-fuel ratios tended to produce higher internal temperatures which resulted in higher heat losses. This made it difficult to separate the independent effects of air-to-fuel ratio and heat loss. Consequently, statistical projections to reasonable levels of heat loss assuming virtually 100% carbon utilization could give only a broad range, 100-150 Btu/dscf for Western coal, all fed to the gasifier. However, the upper end of that range, if it would turn out to be actually attainable, would be quite encouraging.

A detailed thermal analysis of the pilot apparatus has shown that with the present design there appears to be no way to operate so as to significantly lower heat losses. However, by certain modifications and a change in operating procedure, a pilot apparatus of this scale can be made to produce heat losses fully comparable to low losses expected in large commercial installations.

Section 7

RECOMMENDATIONS

1. The next step should be a redesign, aided by the thermal model, of the pilot gasifier and adding of an externally fired air heater to the facility in order to reduce heat losses to that representative of a commercial installation.

2. Upon completion of the necessary modifications, additional tests using the gasification scheme only, should be conducted to achieve a definite answer to the question, "Can heat content be increased simply by reducing heat losses?"

3. The development of a mathematical model of suspension gasification based upon rate control by other than gas-phase diffusion (e.g., chemical kinetics) would make a significant contribution to continued development of this type gasification.

Appendix A

TEST DATA

A computer program was written for the purpose of consolidating all the pertinent data on one computer output sheet and also for the calculation of material balances. A brief description of how the various quantities on this output sheet were obtained follows:

INPUTS

COAL RATE, LB/HR	A total coal flow rate was measured via a load cell supporting the coal feed tank. A strip chart recorder was used to record the total weight of the coal feed tank as a function of time; from this a coal rate was obtained. Coal flow split was, for a given tank pressure, a function of transport air flow rate. A calibration was made of the system using the variables of coal feed tank pressure and transport air flow rate. The resulting curve, Figure A.1, was then used to determine the coal feed split.
AIR FLOWS, LB/HR	All the flows listed were measured using machined orifices for which curves were calculated; flow rates taken from these curves were used as input to the computer program. The exception to this was the transport air flow which was measured using a rotameter.
NATURAL GAS FLOW, LB/HR GASIFIER SEC COMB	The natural gas flowing to the gasifier was used to maintain reducing conditions in the event of char recycle interruptions. This flow was measured using an orifice; flow rate obtained from curve was input to computer program.

	The natural gas to the secondary combustion furnace was measured with an orifice and flow rate obtained from a curve.
STEAM FLOW, LB/HR GASIFIER DEVOL	During a few tests team was added to the system through a lance inserted in the horizontal burners to determine its effect on make-gas heating value. For the devolatilizer, steam was added at the coal injection probe. Steam flow was measured using an orifice; flow rate was obtained from a curve.
OXYGEN ADDED, LB/HR	During a few tests oxygen enrichment of the gasifier air was tried in an attempt to increase temperatures. Oxygen addition was made upstream of the gasifier burners. Flow rate measurement was made by an orifice; flow rate was obtained from a curve.
SEC COMB PERCENT TOTAL AIR, %	The oxygen concentration of the flue gas leaving the secondary combustor was measured. The assumption of complete combustion was used to convert it to percent total air. This measurement was used to calculate the carbon balance at point "C", the exit of the secondary combustion furnace.
TEMPERATURES, °F	Temperatures at the gasifier outlet, devolatilizer inlet, devolatilizer mid-point, and devolatilizer outlet were measured using platinum thermocouples. The cyclone separator outlet and the preheated gasifier combustion air temperature were measured with chromel-alumel thermocouples. See Figure 3.6 for locations.
SOLID LOADINGS, LB/HR	This is the flow rate of solids passing a specific point in the system as measured by solids loading apparatus. Note: A value of 0.00 for a solids loading indicated NO MEASUREMENT.

MAKE GAS ANALYSIS, VOLUME %	The analysis was given on a volume percent dry basis, as sampled by our gas sampling apparatus and analyzed on the Beckman GC-4 Gas Chromatograph.

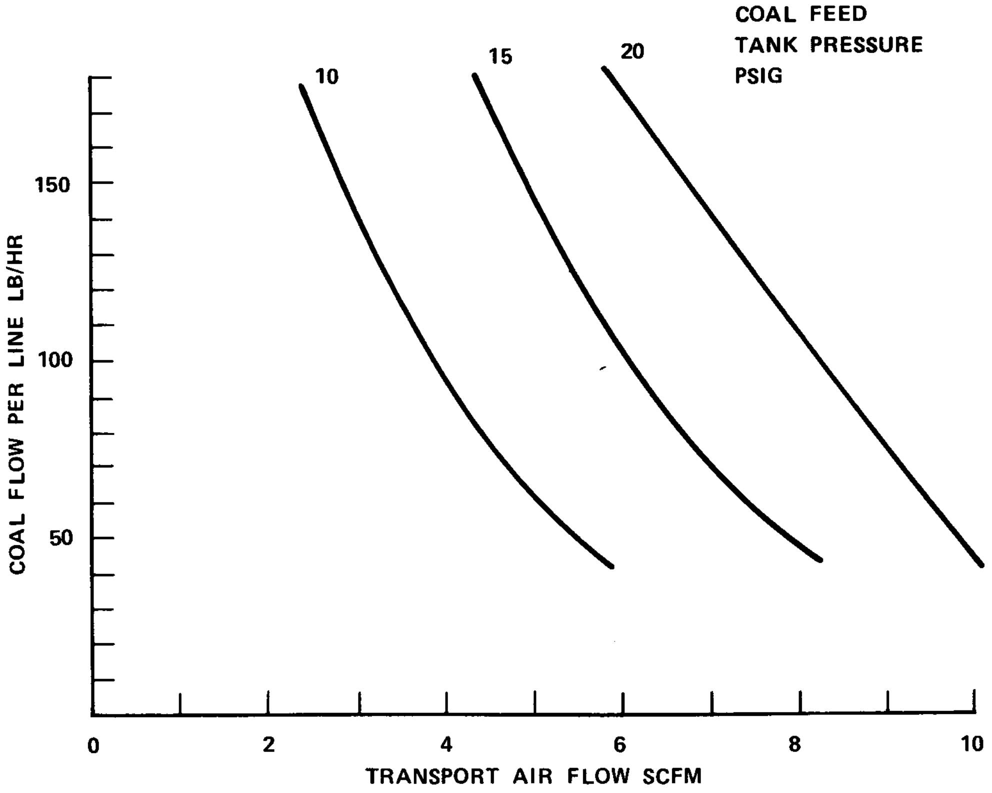


FIGURE A.1 DETERMINATION OF COAL FLOW SPLIT

MATERIAL BALANCE CALCULATIONS

COAL RATE (WET) (DRY), LB/HR	The wet coal rate is measured via load cells, and the dry coal rate is calculated based on an average moisture content determined from moisture measurements.
DRY MAKE GAS RATE, LB/HR	This is calculated using the total flow rate of air and oxygen fed to the gasifier and the make-gas heating value. This calculation assumes that there is a direct relationship between the heating value of the gas and the amount of coal gasified. A plot of $\frac{\text{lbs make gas}}{\text{lbs air}}$ as a function of make-gas heating value was made based on the data, Figure A.2.

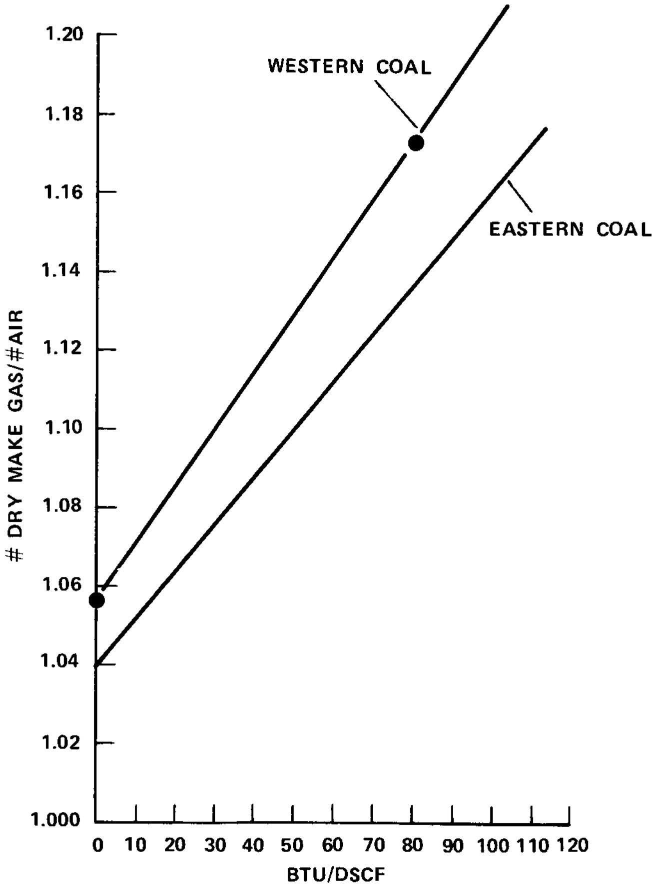


FIGURE A.2 RELATIONSHIP OF DRY MAKE GAS TO HEATING VALUE

WET MAKE GAS RATE, LB/HR	This is calculated as the sum of the DRY MAKE GAS, the TOTAL WATER FED, and WATER FROM REACTION.
TOTAL WATER FED, LB/HR	This is calculated as the sum of the water contained in the coal, the steam fed to the system, and the water content of the gasifier combustion air. Water content of gasifier air was assumed to be one percent.
WATER FROM REACTION, LB/HR	This is based on the difference between the oxygen input as measured and the oxygen accounted for in the dry make gas. The difference was attributed to the formation of water. The oxygen content of solids leaving the system was neglected.
PERCENT THEO AIR, %	This is the total air fed to the system expressed as a percent of the amount of air required to burn all the fuel, both coal and natural gas, completely to CO_2 and H_2O.
HEATING VALUE, BTU/DSCF	This is the heating value of the make gas calculated on the basis of the gas analysis.
MEASURED INPUT, LB/HR	The total carbon input includes the carbon in the coal and carbon in the natural gas. The hydrogen input includes that in the coal and natural gas. The hydrogen in the water is not included. The oxygen input to the system is the sum of oxygen in the coal, air, and any pure oxygen added to enrich the air. The oxygen in the water is not included. The nitrogen input includes that in the coal and air.
OUT AT POINT B, LB/HR CARBON HYDROGEN OXYGEN NITROGEN	The carbon output is based on the amount in the make gas and in the solids. An average carbon content of 82.5% (based on the analysis of a number of samples) was assumed for the solids.

The hydrogen out at this point is calculated on the basis of the hydrogen in the make gas, in the solids, and that hydrogen contained in the water formed by reaction. The average hydrogen content of the solids is assumed to be 2.9%. Other hydrogen in the form of water vapor is not included as the water content of the make gas was not measured.

The quantity of oxygen at this point is based on that found in the make gas as carbon dioxide and carbon monoxide plus the amount contained in the WATER FROM REACTION. Since the WATER FROM REACTION is based on the difference between oxygen IN and OUT, the oxygen balance at this point is forced to be equal to the input.

The amount of nitrogen is that analyzed in the make gas as free nitrogen.

OUT AS POINT C, LB/HR CARBON	The amount of carbon at this point, the exit of the secondary combustion furnace, is calculated based on an oxygen analysis and the assumption of complete combustion.

MISCELLANEOUS CALCULATIONS

TOTAL BTU/HR IN COAL	This value represents the total coal feed rate multiplied by its heating value.
TOTAL BTU/HR IN NAT GAS	This value represents the natural gas feed rate to the gasifier multiplied by its heating value.
TOTAL BTU/HR IN FUEL	The sum of the above two values.
BTU/HR IN MAKE GAS	Product of the make gas flow rate and its heating value.

HYDROGEN IN GAS, LB/HR	This is the amount of hydrogen in the make gas only; solids are not included.
CARBON IN GAS, LB/HR	This represents the quantity of carbon in the make gas as CO, CO_2, CH_4, etc.
MAKE GAS MOL WT	Calculated based on make-gas composition.
COLD-GAS CONV EFF, %	This is equal to the ratio of the BTU/HR IN MAKE GAS to TOTAL BTU/HR IN FUEL.
MAKE GAS ANALYSIS WEIGHT FRACTION	Make gas analysis expressed on a weight basis.

SOLIDS ANALYSIS

This portion presents the results of the analysis that were done on solids samples taken at either the gasifier outlet, char recycle (from bottom of east cyclone), and at the cyclone outlet (solids which were entrained in the gas stream leaving the cyclones). In addition, a screen sizing analysis was occasionally done on the char recycle solids; this is presented here along with the results of the tar determinations.

Abbreviations and terms used are:

Proximate Analysis

- V. M. - Volatile Matter
- F. C. - Fixed Carbon

Ultimate Analysis

- C - Carbon
- H - Hydrogen
- N - Nitrogen
- S - Sulfur
- O - Oxygen

Screen Analysis

% THRU 30 50 100 140 200

The above numbers erfer to the screen mesh number

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               TEST 1
                         10-22-75 0950 HRS ALL COAL TO GASIFIER PITTSBURG 8 COAL
                                      Input                                              Calculations
                                                                                   GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                  TEMPERATURES, F             TOTAL BTU/HR IN COAL 2193510.00
                                                                            TOTAL BTU/HR IN NAT. GAS  259248.00
                    GASIFIER  170.00               GASIFIER OUT 1950.00         TOTAL BTU/HR IN FUEL 2452758.00
                       DEVOL    0.00                   DEVOL IN 1750.00           BTU/HR IN MAKE GAS 1045971.15
                                                      DEVOL MID 1360.00      HYDROGEN IN GAS LB/HR        6.29
                                                      DEVOL OUT 1160.00        CARBON IN GAS LB/HR      102.20
                   AIR FLOWS  LB/HR                 CYC SEP OUT  900.00          MAKE GAS MOL. WT.       25.59
                                                   GASIFIER AIR  790.00        COLD-GAS CONV. EFF.       42.64
                GASIFIER AIR  790.00
               TRANSPORT AIR   60.40               SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
              CHAR EJECT AIR   31.60               GASIFIER OUT    0.00               WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  882.00                CYCLONE OUT    0.00
                SEC COMB AIR 4473.07                                                      HYDROGEN    .006331
                                                         MAKE                      CARBON MONOXIDE    .153197
                 NATURAL GAS  LB/HR             GASIFIER     GAS ANALYSIS    CYCLONE        METHANE  0.000000
                                                  OUTLET  VOL PERCENT DRY    OUTLET          ETHANE  0.000000
                    GASIFIER   11.00                                                       ETHYLENE  0.000000
                    SEC COMB  170.00               -0.00     HYDROGEN          8.10       ACETYLENE  0.000000
                                                   -0.00  CARBON MONOXIDE 14.00    HYDROGEN SULFIDE  0.000000
                                                   -0.00      METHANE          0.00      CARBON DIOXIDE   .135845
                  STEAM FLOW  LB/HR                -0.00      ETHANE           0.00            NITROGEN   .689386
                                                   -0.00     ETHYLENE          0.00       OXYGEN+ARGON    .015242
                    GASIFIER    0.00               -0.00    ACETYLENE          0.00
                       DEVOL    0.00               -0.00 HYDROGEN SULFIDE      0.00
                                                   -0.00 CARBON DIOXIDE        7.90
                                                   -0.00     NITROGEN         63.00
                OXYGEN ADDED  LB/HR                -0.00   OXYGEN+ARGON        1.00
                                0.00
                                                    0.00                      94.00
                    SEC COMB PERCENT
                    TOTAL AIR 117.50                                               MATERIAL BALANCE

                       BASED ON MEASURED                                           CARBON  HYDROGEN   OXYGEN  NITROGEN
                           COAL RATE                             MEASURED INPUT    129.99     11.29   217.18    667.58

        COAL RATE (WET) LB/HR  170.00   (DRY)  167.45            OUT AT POINT B    102.20     10.27   217.18    685.33
           DRY MAKE GAS LB/HR  994.11
           WET MAKE GAS LB/HR 1041.25                            OUT AT POINT C    123.27
        TOTAL WATER FED LB/HR   11.37
 WATER FROM REACTION LB/HR      35.77

            PERCENT THEO. AIR   47.99
      HEATING VALUE BTU/DSCF    71.41

                                    SOLIDS ANALYSIS
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               TEST 2
                         10-28-75 1440 HRS ALL COAL FEED TO GASIFIER PITTSBURG 8 COAL
                                      Input                                            Calculations

                                                                                  GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                 TEMPERATURES, F             TOTAL BTU/HR IN COAL 2322540.00
                                                                           TOTAL BTU/HR IN NAT. GAS  207398.40
                    GASIFIER 180.00               GASIFIER OUT 2200.00         TOTAL BTU/HR IN FUEL 2529938.40
                       DEVOL   0.00                   DEVOL IN 2050.00           BTU/HR IN MAKE GAS  605249.50
                                                     DEVOL MID 1610.00        HYDROGEN IN GAS LB/HR       3.40
                                                     DEVOL OUT 1460.00          CARBON IN GAS LB/HR      89.12
                   AIR FLOWS  LB/HR                CYC SEP OUT 1075.00            MAKE GAS MOL. WT.      28.75
                                                  GASIFIER AIR  800.00          COLD-GAS CONV. EFF.      23.92
                GASIFIER AIR 800.00
               TRANSPORT AIR  56.25              SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
              CHAR EJECT AIR  35.10               GASIFIER OUT    0.00               WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 891.35                CYCLONE OUT    0.00
                SEC COMB AIR 4353.45                                                       HYDROGEN   .003479
                                                         MAKE                   CARBON MONOXIDE   .093512
                 NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE  0.000000
                                              OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                    GASIFIER   8.80                                                        ETHYLENE  0.000000
                    SEC COMB 180.00            -0.00     HYDROGEN      5.00           ACETYLENE  0.000000
                                               -0.00  CARBON MONOXIDE  9.60    HYDROGEN SULFIDE  0.000000
                                               -0.00      METHANE      0.00      CARBON DIOXIDE   .186746
                  STEAM FLOW  LB/HR            -0.00      ETHANE       0.00            NITROGEN   .701339
                                               -0.00     ETHYLENE      0.00        OXYGEN+ARGON   .014924
                    GASIFIER   0.00            -0.00    ACETYLENE      0.00
                       DEVOL   0.00            -0.00 HYDROGEN SULFIDE  0.00
                                               -0.00 CARBON DIOXIDE   12.20
                                               -0.00     NITROGEN     72.00
                OXYGEN ADDED  LB/HR            -0.00   OXYGEN+ARGON    1.10
                               0.00
                                                0.00                  99.90
                    SEC COMB PERCENT
                   TOTAL AIR  124.00                                      MATERIAL BALANCE

                     BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                         COAL RATE                        MEASURED INPUT    135.50     11.24    220.09    674.74

     COAL RATE (WET) LB/HR  180.00   (DRY)  177.30        OUT AT POINT B     89.12      7.73    220.09    686.11
        DRY MAKE GAS LB/HR  978.29
        WET MAKE GAS LB/HR 1028.81                        OUT AT POINT C     87.75
     TOTAL WATER FED LB/HR   11.61
 WATER FROM REACTION LB/HR   38.90

         PERCENT THEO. AIR   47.02
    HEATING VALUE BTU/DSCF   47.16

                                    SOLIDS ANALYSIS
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               TEST 3
                        11-10-75 1545 HRS ALL COAL TO THE GASIFIER PITTSBURG 8 COAL
                                     Input                                           Calculations

                                                                                GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F            TOTAL BTU/HR IN COAL 2283831.00
                                                                         TOTAL BTU/HR IN NAT. GAS  188544.00
                    GASIFIER 177.00             GASIFIER OUT 2240.00         TOTAL BTU/HR IN FUEL 2472375.00
                      DEVOL    0.00                 DEVOL IN 2080.00           BTU/HR IN MAKE GAS 1136738.27
                                                   DEVOL MID 1890.00        HYDROGEN IN GAS LB/HR       5.57
                                                   DEVOL OUT 1730.00          CARBON IN GAS LB/HR     116.83
                  AIR FLOWS  LB/HR                 CYC SEP OUT 1060.00          MAKE GAS MOL. WT.      27.53
                                                GASIFIER AIR  840.00          COLD-GAS CONV. EFF.      45.98
               GASIFIER AIR  850.00
              TRANSPORT AIR   52.40            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
             CHAR EJECT AIR   50.00             GASIFIER OUT   48.78              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 952.40              CYCLONE OUT    5.41
               SEC COMB AIR 4674.30                                                 HYDROGEN   .005158
                                                       MAKE                  CARBON MONOXIDE   .169839
                NATURAL GAS  LB/HR        GASIFIER    GAS ANALYSIS   CYCLONE         METHANE  0.000000
                                            OUTLET  VOL PERCENT DRY  OUTLET           ETHANE  0.000000
                    GASIFIER    8.00                                                ETHYLENE  0.000000
                    SEC COMB  170.00         -0.00     HYDROGEN      7.10          ACETYLENE  0.000000
                                             -0.00  CARBON MONOXIDE 16.70   HYDROGEN SULFIDE  0.000000
                                             -0.00      METHANE      0.00     CARBON DIOXIDE   .129449
                 STEAM FLOW  LB/HR           -0.00      ETHANE       0.00           NITROGEN   .681389
                                             -0.00     ETHYLENE      0.00       OXYGEN+ARGON   .014165
                    GASIFIER    0.00         -0.00    ACETYLENE      0.00
                      DEVOL     0.00         -0.00 HYDROGEN SULFIDE  0.00
                                             -0.00 CARBON DIOXIDE    8.10
                                             -0.00     NITROGEN     67.00
               OXYGEN ADDED  LB/HR           -0.00   OXYGEN+ARGON    1.00
                               0.00
                                              0.00                  99.90
                   SEC COMB PERCENT
                  TOTAL AIR  126.50                                     MATERIAL BALANCE

                    BASED ON MEASURED                                    CARBON  HYDROGEN   OXYGEN   NITROGEN
                        COAL RATE                       MEASURED INPUT   132.75     10.89    234.03     720.81

    COAL RATE (WET) LB/HR  177.00   (DRY) 174.35        OUT AT POINT B   121.30      9.16    234.03     735.76
       DRY MAKE GAS LB/HR 1079.79
       WET MAKE GAS LB/HR 1122.86                       OUT AT POINT C   116.60
    TOTAL WATER FED LB/HR   12.18
WATER FROM REACTION LB/HR   30.90

        PERCENT THEO. AIR   51.41
   HEATING VALUE BTU/DSCF   76.85

                                  SOLIDS ANALYSIS
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              TEST 4
                        11-14-75 1300 HRS ALL COAL FEED TO GASIFIER 8 COAL
                                     Input                                      Calculations
                                                                               GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                TEMPERATURES, F              TOTAL BTU/HR IN COAL 2258025.00
                                                                          TOTAL BTU/HR IN NAT. GAS  188544.00
                   GASIFIER  175.00             GASIFIER OUT 2210.00          TOTAL BTU/HR IN FUEL 2446569.00
                      DEVOL    0.00                 DEVOL IN 2010.00            BTU/HR IN MAKE GAS 1172326.76
                                                   DEVOL MID 1800.00         HYDROGEN IN GAS LB/HR       5.74
                                                   DEVOL OUT 1640.00           CARBON IN GAS LB/HR     120.49
                  AIR FLOWS  LB/HR               CYC SEP OUT  950.00             MAKE GAS MOL. WT.      27.61
                                                GASIFIER AIR  820.00           COLD-GAS CONV. EFF.      47.92
               GASIFIER AIR  870.00
              TRANSPORT AIR   60.00            SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
             CHAR EJECT AIR   55.00             GASIFIER OUT   59.09                WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  985.00              CYCLONE OUT    5.50
               SEC COMB AIR 4798.49                                                   HYDROGEN   .005143
                                                        MAKE                   CARBON MONOXIDE   .169359
                NATURAL GAS  LB/HR         GASIFIER   GAS ANALYSIS   CYCLONE           METHANE  0.000000
                                             OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                   GASIFIER    8.00                                                   ETHYLENE  0.000000
                   SEC COMB  170.00           -0.00     HYDROGEN       7.10          ACETYLENE  0.000000
                                              -0.00  CARBON MONOXIDE 16.70     HYDROGEN SULFIDE  0.000000
                                              -0.00      METHANE       0.00      CARBON DIOXIDE   .129084
                 STEAM FLOW  LB/HR            -0.00      ETHANE        0.00            NITROGEN   .679464
                                              -0.00      ETHYLENE      0.00       OXYGEN+ARGON   .016950
                   GASIFIER    0.00           -0.00     ACETYLENE      0.00
                      DEVOL    0.00           -0.00 HYDROGEN SULFIDE   0.00
                                              -0.00 CARBON DIOXIDE     8.10
                                              -0.00     NITROGEN      67.00
               OXYGEN ADDED  LB/HR            -0.00   OXYGEN+ARGON     1.20
                               0.00
                                               0.00                  100.10
                   SEC COMB PERCENT
                  TOTAL AIR  128.00                                               MATERIAL BALANCE

                   BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                       COAL RATE                        MEASURED INPUT   131.32      10.79   241.45     745.40

    COAL RATE (WET) LB/HR  175.00   (DRY)  172.38      OUT AT POINT B   125.03       9.45   241.45     758.79
       DRY MAKE GAS LB/HR 1116.75
       WET MAKE GAS LB/HR 1161.19                      OUT AT POINT C   121.81
    TOTAL WATER FED LB/HR   12.48
WATER FROM REACTION LB/HR   31.96

        PERCENT THEO. AIR   53.73
  HEATING VALUE BTU/DSCF    76.85

                                   SOLIDS ANALYSIS
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               TEST 5
                         11-19-75 1100 HRS ALL COAL TO GASIFIER PITTSBURG 8 COAL
                                      Input                                                Calculations

                                                                                  GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                 TEMPERATURES, F             TOTAL BTU/HR IN COAL 2116092.00
                                                                           TOTAL BTU/HR IN NAT. GAS  200328.00
                    GASIFIER  164.00              GASIFIER OUT 2300.00         TOTAL BTU/HR IN FUEL 2316420.00
                       DEVOL    0.00                  DEVOL IN 2150.00           BTU/HR IN MAKE GAS 1231607.65
                                                     DEVOL MID 1930.00      HYDROGEN IN GAS LB/HR       6.54
                                                     DEVOL OUT 1800.00        CARBON IN GAS LB/HR     122.49
                   AIR FLOWS  LB/HR                CYC SEP OUT  915.00          MAKE GAS MOL. WT.      27.54
                                                  GASIFIER AIR  840.00        COLD-GAS CONV. EFF.      53.17
                GASIFIER AIR  908.00
               TRANSPORT AIR   58.00             SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
              CHAR EJECT AIR   66.00              GASIFIER OUT    0.00               WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 1032.00               CYCLONE OUT   19.17
                SEC COMB AIR 4237.33                                                     HYDROGEN   .005592
                                                         MAKE                     CARBON MONOXIDE   .163695
                 NATURAL GAS  LB/HR             GASIFIER    GAS ANALYSIS   CYCLONE        METHANE  0.000000
                                                  OUTLET  VOL PERCENT DRY  OUTLET          ETHANE  0.000000
                    GASIFIER    8.50                                                     ETHYLENE  0.000000
                    SEC COMB  168.00               -0.00      HYDROGEN       7.70       ACETYLENE  0.000000
                                                   -0.00  CARBON MONOXIDE   16.10   HYDROGEN SULFIDE  0.000000
                                                   -0.00      METHANE        0.00     CARBON DIOXIDE   .126221
                 STEAM FLOW  LB/HR                 -0.00      ETHANE         0.00           NITROGEN   .683249
                                                   -0.00     ETHYLENE        0.00       OXYGEN+ARGON   .021243
                    GASIFIER    0.00               -0.00     ACETYLENE       0.00
                       DEVOL    0.00               -0.00 HYDROGEN SULFIDE    0.00
                                                   -0.00 CARBON DIOXIDE      7.90
                                                   -0.00      NITROGEN      67.20
               OXYGEN ADDED  LB/HR                 -0.00    OXYGEN+ARGON     1.50
                                0.00
                                                     0.00                  100.40
                   SEC COMB PERCENT
                  TOTAL AIR  115.00                                              MATERIAL BALANCE

                    BASED ON MEASURED                                          CARBON    HYDROGEN    OXYGEN    NITROGEN
                        COAL RATE                           MEASURED INPUT     123.81       10.36    251.54      780.78

    COAL RATE (WET) LB/HR  164.00    (DRY)  161.54          OUT AT POINT B     138.30       11.42    251.54      799.44
       DRY MAKE GAS LB/HR 1170.06
       WET MAKE GAS LB/HR 1221.71                           OUT AT POINT C     128.74
    TOTAL WATER FED LB/HR   12.78
WATER FROM REACTION LB/HR   38.87

        PERCENT THEO. AIR   59.46
   HEATING VALUE BTU/DSCF   76.87

                                   SOLIDS ANALYSIS
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              TEST 6
                        11-19-75 1405 HRS ALL COAL TO GASIFIER PITTSBURG 8 COAL USED
                                     Input                                          Calculations
                                                                               GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                TEMPERATURES, F            TOTAL BTU/HR IN COAL 1832226.00
                                                                        TOTAL BTU/HR IN NAT. GAS  106056.00
                   GASIFIER  142.00             GASIFIER OUT 2300.00        TOTAL BTU/HR IN FUEL 1938282.00
                      DEVOL     0.00                DEVOL IN 2150.00          BTU/HR IN MAKE GAS  979969.24
                                                   DEVOL MID 1930.00       HYDROGEN IN GAS LB/HR       4.32
                                                   DEVOL OUT 1800.00         CARBON IN GAS LB/HR     113.18
                  AIR FLOWS   LB/HR              CYC SEP OUT 1100.00           MAKE GAS MOL. WT.      28.02
                                                GASIFIER AIR  860.00         COLD-GAS CONV. EFF.      50.56

               GASIFIER AIR  850.00
              TRANSPORT AIR   58.50            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
             CHAR EJECT AIR   73.00             GASIFIER OUT    18.80             WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  981.50              CYCLONE OUT    2.72
               SEC COMB AIR 3889.60                                                 HYDROGEN   .003926
                                                       MAKE                  CARBON MONOXIDE   .149898
                NATURAL GAS   LB/HR        GASIFIER   GAS ANALYSIS   CYCLONE         METHANE  0.000000
                                             OUTLET VOL PERCENT DRY  OUTLET           ETHANE  0.000000
                   GASIFIER     4.50                                                ETHYLENE  0.000000
                   SEC COMB  158.00          -0.00     HYDROGEN      5.50          ACETYLENE  0.000000
                                             -0.00  CARBON MONOXIDE 15.00   HYDROGEN SULFIDE  0.000000
                                             -0.00      METHANE      0.00     CARBON DIOXIDE   .141333
                 STEAM FLOW  LB/HR           -0.00      ETHANE       0.00           NITROGEN   .689532
                                             -0.00     ETHYLENE      0.00       OXYGEN+ARGON   .015311
                   GASIFIER    0.00          -0.00    ACETYLENE      0.00
                      DEVOL    0.00          -0.00 HYDROGEN SULFIDE  0.00
                                             -0.00 CARBON DIOXIDE    9.00
                                             -0.00     NITROGEN     69.00
               OXYGEN ADDED  LB/HR           -0.00   OXYGEN+ARGON    1.10
                               0.00

                                              0.00                  99.60
                   SEC COMB PERCENT
                  TOTAL AIR  111.50                                     MATERIAL BALANCE

                    BASED ON MEASURED                                    CARBON   HYDROGEN  OXYGEN   NITROGEN
                        COAL RATE                       MEASURED INPUT    105.06      8.26   238.20    742.43

     COAL RATE (WET) LB/HR  142.00  (DRY)  139.87       OUT AT POINT B    115.42      8.24   238.20    758.49
        DRY MAKE GAS LB/HR 1100.00
        WET MAKE GAS LB/HR 1146.51                      OUT AT POINT C    127.16
     TOTAL WATER FED LB/HR   11.95
 WATER FROM REACTION LB/HR   34.56

         PERCENT THEO. AIR   67.58
    HEATING VALUE BTU/DSCF   66.18

                                   SOLIDS ANALYSIS
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               TEST 7
                         12-10-75 1235 HRS  ALL COAL FEED TO DEVOLATILIZER PITTSBURG B COAL
                                                       NITROGEN TO DEVOLATILIZER 11.3 LB/HR
                                     Input                                                Calculations
                                                                                   GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                 TEMPERATURES, F                 TOTAL BTU/HR IN COAL 1548360.00
                                                                               TOTAL BTU/HR IN NAT. GAS 1178400.00
                    GASIFIER    0.00             GASIFIER OUT 2350.00              TOTAL BTU/HR IN FUEL 2726760.00
                       DEVOL  120.00                 DEVOL IN 1980.00                BTU/HR IN MAKE GAS  661967.85
                                                    DEVOL MID 1450.00             HYDROGEN IN GAS LB/HR       5.25
                                                    DEVOL OUT 1350.00               CARBON IN GAS LB/HR      77.68
                 AIR FLOWS  LB/HR                 CYC SEP OUT 1010.00                 MAKE GAS MOL. WT.      28.23
                                                 GASIFIER AIR  780.00               COLD-GAS CONV. EFF.      24.28
               GASIFIER AIR  880.00
              TRANSPORT AIR    0.00             SOLIDS LOADING LB/HR                   MAKE GAS ANALYSIS
             CHAR EJECT AIR   78.00              GASIFIER OUT    0.00                   WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  958.00               CYCLONE OUT    0.00
               SEC COMB AIR 4395.01                                                       HYDROGEN   .004109
                                                      MAKE                        CARBON MONOXIDE   .065460
             NATURAL GAS  LB/HR          GASIFIER    GAS ANALYSIS   CYCLONE                METHANE   .002267
                                           OUTLET  VOL PERCENT DRY  OUTLET                  ETHANE   .001807
                   GASIFIER   50.00                                                       ETHYLENE  0.000000
                   SEC COMB  150.00           5.30    HYDROGEN        5.80               ACETYLENE  0.000000
                                              6.60  CARBON MONOXIDE   6.60        HYDROGEN SULFIDE  0.000000
                                              0.00      METHANE        .40          CARBON DIOXIDE   .158974
                STEAM FLOW  LB/HR             0.00      ETHANE         .15                NITROGEN   .753781
                                              0.00     ETHYLENE       0.00            OXYGEN+ARGON   .013815
                   GASIFIER    0.00           0.00     ACETYLENE      0.00
                      DEVOL    0.00           0.00 HYDROGEN SULFIDE   0.00
                                             10.20 CARBON DIOXIDE    10.20
                                             76.80     NITROGEN      76.00
              OXYGEN ADDED  LB/HR             1.00   OXYGEN+ARGON     1.00
                                 0.00
                                             99.90                  100.15
                   SEC COMB PERCENT
                  TOTAL AIR  138.00                                              MATERIAL BALANCE

                   BASED ON MEASURED                                            CARBON   HYDROGEN   OXYGEN   NITROGEN
                       COAL RATE                            MEASURED INPUT      123.43      18.53   231.12     724.47

      COAL RATE (WET) LB/HR  120.00   (DRY)  118.20         OUT AT POINT B       77.68      13.99   231.12     792.27
         DRY MAKE GAS LB/HR 1051.07
         WET MAKE GAS LB/HR 1141.11                         OUT AT POINT C       78.90
      TOTAL WATER FED LB/HR   11.38
   WATER FROM REACTION LB/HR   78.67

          PERCENT THEO. AIR   46.89
      HEATING VALUE BTU/DSCF   46.84

                            SOLIDS ANALYSIS

               TEST 7  CHAR RECYCLE-- V.M. 9.1%   F.C. 66.0%   ASH 24.9%
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              TEST 8
                        12-18-75 1350 HRS ALL COAL TO DEVOLATILIZER WITH STEAM TO TOP OF DEVOLAT
                                     Input                PITTSBURG 8 COAL USED         Calculations

                                                                                   GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F                TOTAL BTU/HR IN COAL 2322540.00
                                                                             TOTAL BTU/HR IN NAT. GAS 1201968.00
                   GASIFIER     0.00            GASIFIER OUT 2080.00             TOTAL BTU/HR IN FUEL 3524508.00
                      DEVOL   180.00                DEVOL IN 1800.00               BTU/HR IN MAKE GAS  726858.75
                                                   DEVOL MID   -0.00            HYDROGEN IN GAS LB/HR        6.20
                                                   DEVOL OUT 1080.00              CARBON IN GAS LB/HR       71.33
                  AIR FLOWS  LB/HR               CYC SEP OUT  850.00                MAKE GAS MOL. WT.       29.95
                                                GASIFIER AIR  800.00              COLD-GAS CONV. EFF.       20.62
               GASIFIER AIR  831.00
              TRANSPORT AIR   52.10            SOLIDS LOADING LB/HR                 MAKE GAS ANALYSIS
             CHAR EJECT AIR   72.00             GASIFIER OUT    0.00                 WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  955.10              CYCLONE OUT    0.00
               SEC COMB AIR 4733.85                                                HYDROGEN    .004874
                                                   MAKE                     CARBON MONOXIDE    .063564
              NATURAL GAS  LB/HR        GASIFIER   GAS ANALYSIS   CYCLONE           METHANE    .001602
                                          OUTLET  VOL PERCENT DRY  OUTLET            ETHANE    .003405
                  GASIFIER    51.00                                                ETHYLENE   0.000000
                  SEC COMB   160.00        -0.00     HYDROGEN       7.30          ACETYLENE   0.000000
                                           -0.00  CARBON MONOXIDE   6.80   HYDROGEN SULFIDE   0.000000
                                           -0.00      METHANE        .30     CARBON DIOXIDE    .138078
              STEAM FLOW  LB/HR            -0.00      ETHANE         .30           NITROGEN    .775856
                                           -0.00     ETHYLENE       0.00       OXYGEN+ARGON    .013020
                  GASIFIER     0.00        -0.00     ACETYLENE      0.00
                     DEVOL    33.00        -0.00 HYDROGEN SULFIDE   0.00
                                           -0.00 CARBON DIOXIDE     9.40
                                           -0.00     NITROGEN      83.00
             OXYGEN ADDED  LB/HR           -0.00   OXYGEN+ARGON     1.00
                               0.00
                                            0.00                  108.10
                  SEC COMB PERCENT
                 TOTAL AIR   124.00                                        MATERIAL BALANCE

                 BASED ON MEASURED                                   CARBON    HYDROGEN    OXYGEN    NITROGEN
                     COAL RATE                        MEASURED INPUT  167.15       21.79    234.88      722.87

  COAL RATE (WET) LB/HR  180.00   (DRY)  177.30      OUT AT POINT B   71.33       17.47    234.88      819.51
     DRY MAKE GAS LB/HR 1056.27
     WET MAKE GAS LB/HR 1202.93                      OUT AT POINT C  118.63
  TOTAL WATER FED LB/HR   45.25
WATER FROM REACTION LB/HR 101.41

     PERCENT THEO. AIR    36.17
 HEATING VALUE BTU/DSCF   54.04

                                  SOLIDS ANALYSIS
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TEST 9
          12-23-75 1405  COAL FEED SPLIT TO THE GASIFIER AND THE DEVOLATILIZER
                    Input PITTSBURG 8 COAL USED. ADDITION OF 9 POUNDS PER HOUR N2 TO DEVOLATILIZER
                                                                      Calculations
                                                                  GASIFIER-DEVOLATILIZER
     COAL RATE  LB/HR                TEMPERATURES, F              TOTAL BTU/HR IN COAL 2141898.00
                                                              TOTAL BTU/HR IN NAT. GAS  589200.00
        GASIFIER   83.00            GASIFIER OUT 2120.00          TOTAL BTU/HR IN FUEL 2731098.00
           DEVOL   83.00                DEVOL IN 1900.00            BTU/HR IN MAKE GAS 1234840.61
                                       DEVOL MID 1250.00         HYDROGEN IN GAS LB/HR        7.26
                                       DEVOL OUT 1280.00           CARBON IN GAS LB/HR      108.10
      AIR FLOWS  LB/HR               CYC SEP OUT  930.00             MAKE GAS MOL. WT.       27.68
                                    GASIFIER AIR  840.00           COLD-GAS CONV. EFF.       45.21
    GASIFIER AIR  830.00
   TRANSPORT AIR   30.00           SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
  CHAR EJECT AIR   76.00            GASIFIER OUT    0.00                WEIGHT FRACTION
TOTAL AIR TO GASIFIER  936.00        CYCLONE OUT    0.00
    SEC COMB AIR 4428.12                                                  HYDROGEN   .005275
                                            MAKE                   CARBON MONOXIDE   .141639
     NATURAL GAS  LB/HR          GASIFIER    GAS ANALYSIS   CYCLONE           METHANE   .001734
                                   OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .003686
        GASIFIER   25.00                                                    ETHYLENE   .001518
        SEC COMB  165.00             6.80     HYDROGEN       7.30         ACETYLENE   .002818
                                    14.90  CARBON MONOXIDE 14.00   HYDROGEN SULFIDE  0.000000
                                     0.00      METHANE        .30     CARBON DIOXIDE   .130366
      STEAM FLOW  LB/HR              0.00      ETHANE         .30           NITROGEN   .702125
                                     0.00     ETHYLENE        .15      OXYGEN+ARGON   .011273
        GASIFIER    0.00             0.00    ACETYLENE        .30
           DEVOL    0.00              .25 HYDROGEN SULFIDE  0.00
                                     8.30 CARBON DIOXIDE    8.20
                                    69.60     NITROGEN     69.40
    OXYGEN ADDED  LB/HR               .80   OXYGEN+ARGON     .80
                    0.00
                                   100.65                 100.75
        SEC COMB PERCENT
       TOTAL AIR  115.50                                      MATERIAL BALANCE

         BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
             COAL RATE                       MEASURED INPUT    137.62      14.59   229.42     708.32

 COAL RATE (WET) LB/HR  166.00   (DRY)  163.51   OUT AT POINT B    108.10      12.42   229.42     750.94
    DRY MAKE GAS LB/HR 1069.52
    WET MAKE GAS LB/HR 1127.82               OUT AT POINT C    129.13
  TOTAL WATER FED LB/HR   11.85
WATER FROM REACTION LB/HR   46.45

     PERCENT THEO. AIR   45.74
 HEATING VALUE BTU/DSCF   84.14

                          SOLIDS ANALYSIS

       TEST 9  CHAR RECYCLE-- V.M. 7.7%   F.C. 59.5%   ASH 32.8%
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              TEST 10
                        01-09-76 1130 HRS 50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                                         PITTSBURG 8 COAL
                                    Input                                       Calculations
                                                                             GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F         TOTAL BTU/HR IN COAL 2245122.00
                                                                      TOTAL BTU/HR IN NAT. GAS  589200.00
                   GASIFIER    87.00            GASIFIER OUT 2200.00      TOTAL BTU/HR IN FUEL 2834322.00
                      DEVOL    87.00                DEVOL IN 1960.00        BTU/HR IN MAKE GAS 1286313.21
                                                    DEVOL MID   -0.00    HYDROGEN IN GAS LB/HR        8.32
                                                    DEVOL OUT 1320.00      CARBON IN GAS LB/HR      105.48
                  AIR FLOWS   LB/HR               CYC SEP OUT  990.00        MAKE GAS MOL. WT.       27.06
                                                GASIFIER AIR  785.00       COLD-GAS CONV. EFF.       45.38

               GASIFIER AIR  844.00
              TRANSPORT AIR   32.00            SOLIDS LOADING LB/HR             MAKE GAS ANALYSIS
             CHAR EJECT AIR   72.00            GASIFIER OUT    3.55              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  948.00             CYCLONE OUT   24.82
               SEC COMB AIR 4750.00                                                  HYDROGEN    .006356
                                                     MAKE                    CARBON MONOXIDE    .141749
                NATURAL GAS   LB/HR       GASIFIER    GAS ANALYSIS   CYCLONE          METHANE    .001774
                                           OUTLET  VOL PERCENT DRY   OUTLET            ETHANE    .001885
                   GASIFIER   25.00                                                  ETHYLENE    .003104
                   SEC COMB  166.00            8.20     HYDROGEN       8.60             ACETYLENE    .001441
                                              13.80  CARBON MONOXIDE 13.70      HYDROGEN SULFIDE  0.000000
                                               0.00      METHANE        .30       CARBON DIOXIDE    .118690
                 STEAM FLOW   LB/HR            0.00      ETHANE         .15            NITROGEN    .710812
                                               0.00     ETHYLENE        .30        OXYGEN+ARGON    .014411
                   GASIFIER    9.80            0.00    ACETYLENE        .15
                      DEVOL   22.30            0.00 HYDROGEN SULFIDE   0.00
                                               6.30 CARBON DIOXIDE     7.30
                                              70.70     NITROGEN      68.70
               OXYGEN ADDED   LB/HR            1.10   OXYGEN+ARGON     1.00
                                0.00
                                             100.10                 100.20
                   SEC COMB PERCENT
                  TOTAL AIR  130.00                                         MATERIAL BALANCE

                    BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                        COAL RATE                       MEASURED INPUT    143.35      14.99   232.79     717.45

    COAL RATE (WET) LB/HR  174.00   (DRY)  171.39       OUT AT POINT B    125.96      15.45   232.79     770.58
       DRY MAKE GAS LB/HR 1084.09
       WET MAKE GAS LB/HR 1185.96                       OUT AT POINT C    108.55
    TOTAL WATER FED LB/HR   44.19
 WATER FROM REACTION LB/HR   57.68

        PERCENT THEO. AIR   44.64
   HEATING VALUE BTU/DSCF   84.88

                                    SOLIDS ANALYSIS

                    TEST 10 CHAR RECYCLE-- V.M. 6.7%   F.C. 71.4%   ASH 21.9%
                           CYCLONE OUT-- C 84.1%   H 3.0%   N 1.0%   S 1.5%   ASH 6.7%   O 3.7%
                            TARS 8.39 LB/HR
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               TEST 11
                         01-23-76 1100 HRS 50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                                         PITTSBURG 8 COAL
                                       Input                                            Calculations
                                                                                  GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                  TEMPERATURES, F               TOTAL BTU/HR IN COAL 2064480.00
                                                                             TOTAL BTU/HR IN NAT. GAS  612768.00
                   GASIFIER   80.00              GASIFIER OUT 1950.00            TOTAL BTU/HR IN FUEL 2677248.00
                      DEVOL   80.00                  DEVOL IN 1750.00              BTU/HR IN MAKE GAS 1102701.44
                                                    DEVOL MID   -0.00           HYDROGEN IN GAS LB/HR       7.75
                                                    DEVOL OUT 1200.00             CARBON IN GAS LB/HR      93.69
                  AIR FLOWS  LB/HR                CYC SEP OUT  940.00               MAKE GAS MOL. WT.      27.68
                                                 GASIFIER AIR  800.00             COLD-GAS CONV. EFF.      41.19
               GASIFIER AIR  820.00
              TRANSPORT AIR   32.00             SOLIDS LOADING LB/HR                  MAKE GAS ANALYSIS
             CHAR EJECT AIR   73.00              GASIFIER OUT   18.67                  WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  925.00               CYCLONE OUT   15.88
               SEC COMB AIR 4213.12                                                        HYDROGEN   .005781
                                                        MAKE                          CARBON MONOXIDE   .110268
                NATURAL GAS  LB/HR           GASIFIER    GAS ANALYSIS   CYCLONE               METHANE   .001734
                                               OUTLET  VOL PERCENT DRY  OUTLET                 ETHANE   .003685
                   GASIFIER   26.00                                                          ETHYLENE   .003035
                   SEC COMB  160.00                7.50     HYDROGEN       8.00             ACETYLENE   .001409
                                                  12.10  CARBON MONOXIDE 10.90       HYDROGEN SULFIDE  0.000000
                                                   0.00      METHANE       .30         CARBON DIOXIDE   .136715
                 STEAM FLOW  LB/HR                 0.00      ETHANE        .30               NITROGEN   .722307
                                                   0.00     ETHYLENE       .30           OXYGEN+ARGON   .015500
                   GASIFIER    0.00                0.00    ACETYLENE       .15
                      DEVOL    0.00                0.00 HYDROGEN SULFIDE  0.00
                                                   8.60 CARBON DIOXIDE    8.60
                                                  70.90     NITROGEN     71.40
               OXYGEN ADDED  LB/HR                 1.00   OXYGEN+ARGON    1.10
                               0.00
                                                 100.10                 101.05
                   SEC COMB PERCENT
                  TOTAL AIR  124.00                                                MATERIAL BALANCE

                  BASED ON MEASURED                                           CARBON   HYDROGEN    OXYGEN   NITROGEN
                      COAL RATE                         MEASURED INPUT        134.08      14.54    226.42     699.95

    COAL RATE (WET) LB/HR  160.00   (DRY)  157.60       OUT AT POINT B        106.79      15.20    226.42     757.30
       DRY MAKE GAS LB/HR 1048.45
       WET MAKE GAS LB/HR 1122.97                       OUT AT POINT C         97.72
    TOTAL WATER FED LB/HR   11.65
WATER FROM REACTION LB/HR   62.87

        PERCENT THEO. AIR   46.11
   HEATING VALUE BTU/DSCF   76.60

                                   SOLIDS ANALYSIS

                  TEST 11 CHAR RECYCLE-- V.M. 6.6%   F.C. 58.6%   ASH 34.8%
                    CHAR RECYCLE % THRU  30-96.8%  50-94.3%  100-86.3%  140-77.3%  200-68.3%
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               TEST 12
                         01-23-76 1355   COAL TO GASIFIER AND TO DEVOLATILIZER
                                      Input PITTSBURG 8 COAL                                    Calculations

                                                                                       GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                TEMPERATURES, F                   TOTAL BTU/HR IN COAL 1999965.00
                                                                              TOTAL BTU/HR IN NAT. GAS  612768.00
                    GASIFIER   55.00            GASIFIER OUT 2200.00            TOTAL BTU/HR IN FUEL 2612733.00
                       DEVOL  100.00                DEVOL IN 2000.00              BTU/HR IN MAKE GAS  787437.45
                                                   DEVOL MID 1960.00           HYDROGEN IN GAS LB/HR       6.15
                                                   DEVOL OUT 1430.00             CARBON IN GAS LB/HR      83.63
                   AIR FLOWS  LB/HR              CYC SEP OUT 1060.00               MAKE GAS MOL. WT.      28.01
                                                GASIFIER AIR  840.00             COLD-GAS CONV. EFF.      30.14
                GASIFIER AIR  820.00
               TRANSPORT AIR   34.80           SOLIDS LOADING LB/HR                 MAKE GAS ANALYSIS
              CHAR EJECT AIR   70.00            GASIFIER OUT    14.70                WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  924.80             CYCLONE OUT    14.17
                SEC COMB AIR 4135.11                                                   HYDROGEN   .005142
                                                         MAKE                   CARBON MONOXIDE   .079983
                 NATURAL GAS  LB/HR        GASIFIER   GAS ANALYSIS   CYCLONE              METHANE   .001714
                                             OUTLET  VOL PERCENT DRY  OUTLET               ETHANE  0.000000
                    GASIFIER   26.00                                                     ETHYLENE   .002999
                    SEC COMB  172.00           6.10     HYDROGEN       7.20             ACETYLENE  0.000000
                                              11.30  CARBON MONOXIDE   8.00       HYDROGEN SULFIDE  0.000000
                                               0.00      METHANE        .30         CARBON DIOXIDE   .163394
                  STEAM FLOW  LB/HR            0.00      ETHANE        0.00              NITROGEN   .732843
                                               0.00      ETHYLENE       .30          OXYGEN+ARGON   .013926
                    GASIFIER    0.00           0.00     ACETYLENE      0.00
                       DEVOL    0.00           0.00 HYDROGEN SULFIDE   0.00
                                              10.00 CARBON DIOXIDE    10.40
                                              71.60     NITROGEN      73.30
                OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON     1.00
                                0.00
                                              99.90                  100.50
                    SEC COMB PERCENT
                   TOTAL AIR  112.00                                           MATERIAL BALANCE
                      BASED ON MEASURED
                          COAL RATE                                           CARBON   HYDROGEN   OXYGEN   NITROGEN
                                                              MEASURED INPUT  130.49     14.29    226.00     699.75
     COAL RATE (WET) LB/HR  155.00    (DRY)  152.68
        DRY MAKE GAS LB/HR 1026.15                            OUT AT POINT B   95.31     13.66    226.00     752.01
        WET MAKE GAS LB/HR 1101.65
     TOTAL WATER FED LB/HR   11.57                            OUT AT POINT C  110.67
 WATER FROM REACTION LB/HR   63.93

         PERCENT THEO. AIR   47.24
    HEATING VALUE BTU/DSCF   57.04

                                     SOLIDS ANALYSIS

                    TEST 12 CHAR RECYCLE-- V.M. 6.2%   F.C. 59.9%   ASH 33.9%
                      CHAR RECYCLE % THRU  30-98.4%  50-97.0%  100-90.8%  140-79.2%  200-66.6%
                           CYCLONE OUT-- C 85.9%   H 3.2%   N 0.6%   S 1.6%   ASH 5.8%   O 2.9%
                            TARS 5.67 LB/HR
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              TEST 13
                        01-23-76 1555 HRS 50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                                    Input PITTSBURG 8 COAL                           Calculations
                                                                                 GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F             TOTAL BTU/HR IN COAL 2658018.00
                                                                          TOTAL BTU/HR IN NAT. GAS  612768.00
                   GASIFIER  103.00              GASIFIER OUT 2230.00         TOTAL BTU/HR IN FUEL 3270786.00
                      DEVOL  103.00                  DEVOL IN 2100.00           BTU/HR IN MAKE GAS 1462053.15
                                                    DEVOL MID 2020.00        HYDROGEN IN GAS LB/HR        9.23
                                                    DEVOL OUT 1520.00          CARBON IN GAS LB/HR      112.95
                  AIR FLOWS  LB/HR                CYC SEP OUT 1100.00            MAKE GAS MOL. WT.       26.67
                                                 GASIFIER AIR  870.00          COLD-GAS CONV. EFF.       44.70
               GASIFIER AIR  800.00             SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
              TRANSPORT AIR   29.70              GASIFIER OUT    0.00                WEIGHT FRACTION
             CHAR EJECT AIR   70.00               CYCLONE OUT   21.26
      TOTAL AIR TO GASIFIER  899.70
               SEC COMB AIR 4135.11                                                   HYDROGEN   .007499
                                                        MAKE                   CARBON MONOXIDE   .174272
                NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE   .001800
                                             OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .001912
                   GASIFIER   26.00                                                   ETHYLENE   .003149
                   SEC COMB  157.00            9.50     HYDROGEN     10.00           ACETYLENE   .001462
                                              16.80  CARBON MONOXIDE 16.60    HYDROGEN SULFIDE  0.000000
                                               0.00      METHANE       .30      CARBON DIOXIDE   .107233
                 STEAM FLOW  LB/HR             0.00      ETHANE        .15            NITROGEN   .689738
                                               0.00     ETHYLENE       .30        OXYGEN+ARGON   .013160
                   GASIFIER    0.00            0.00    ACETYLENE       .15
                      DEVOL    0.00            0.00 HYDROGEN SULFIDE  0.00
                                               6.30 CARBON DIOXIDE    6.50
                                              66.50     NITROGEN     65.70
               OXYGEN ADDED  LB/HR             1.00   OXYGEN+ARGON     .90
                               0.00
                                             100.10                 100.60
                   SEC COMB PERCENT
                  TOTAL AIR  113.50                                      MATERIAL BALANCE
                    BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                        COAL RATE                        MEASURED INPUT    167.02     16.85    223.95    681.30

    COAL RATE (WET) LB/HR  206.00   (DRY)  202.91        OUT AT POINT B    130.49     14.66    223.95    720.16
       DRY MAKE GAS LB/HR 1044.10
       WET MAKE GAS LB/HR 1099.50                        OUT AT POINT C    123.06
    TOTAL WATER FED LB/HR   12.09
WATER FROM REACTION LB/HR   43.31

        PERCENT THEO. AIR   36.71
   HEATING VALUE BTU/DSCF   98.77

                                   SOLIDS ANALYSIS

                   TEST 13 CHAR RECYCLE-- V.M. 4.5%   F.C. 63.2%   ASH 32.3%
                     CHAR RECYCLE % THRU  30-99.9%  50-99.8%  100-98.7%  140-95.1%  200-89.1%
                          CYCLONE OUT-- C 88.1%   H 3.3%   N 1.5%   S 1.8%   ASH 2.6%   O 2.7%
                           TARS 4.55 LB/HR
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               TEST 14
                         01-28-76 1150 HRS 50-50 SPLIT ON COAL TO GAS-DEVOL.
                                          GAS COOLING PROBES INSERTED IN CROSSOVER PIPE   PITTSBURG 8 COAL
                                      Input                                            Calculations
                                                                                  GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                 TEMPERATURES. F             TOTAL BTU/HR IN COAL 2258025.00
                                                                           TOTAL BTU/HR IN NAT. GAS  636336.00
                    GASIFIER   87.50              GASIFIER OUT 2080.00         TOTAL BTU/HR IN FUEL 2894361.00
                       DEVOL   87.50                  DEVOL IN 1490.00           BTU/HR IN MAKE GAS 1272189.67
                                                     DEVOL MID   -0.00        HYDROGEN IN GAS LB/HR       7.93
                                                     DEVOL OUT 1150.00          CARBON IN GAS LB/HR     107.03
                   AIR FLOWS  LB/HR                CYC SEP OUT  880.00            MAKE GAS MOL. WT.      27.15
                                                  GASIFIER AIR  875.00          COLD-GAS CONV. EFF.      43.95

                GASIFIER AIR  850.00
               TRANSPORT AIR   31.00             SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
             CHAR EJECT AIR    72.00              GASIFIER OUT  106.79               WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  953.00               CYCLONE OUT   23.80
                SEC COMB AIR 4393.75                                                   HYDROGEN   .006410
                                                         MAKE                   CARBON MONOXIDE   .149567
                 NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE   .000884
                                              OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .001879
                    GASIFIER   27.00                                                   ETHYLENE   .001547
                    SEC COMB  164.00            8.70     HYDROGEN      8.70           ACETYLENE   .001437
                                               14.50  CARBON MONOXIDE 14.50    HYDROGEN SULFIDE  0.000000
                                                0.00      METHANE       .15      CARBON DIOXIDE   .115086
                  STEAM FLOW  LB/HR             0.00      ETHANE        .15            NITROGEN   .707607
                                                0.00     ETHYLENE       .15        OXYGFN+ARGON   .015804
                    GASIFIER    0.00            0.00    ACETYLENE       .15
                       DEVOL    0.00            0.00 HYDROGEN SULFIDE  0.00
                                                7.20 CARBON DIOXIDE    7.10
                                               68.60     NITROGEN     68.60
                OXYGEN ADDED  LB/HR             1.00   OXYGEN+ARGON    1.10
                                0.00
                                              100.00                 100.60
                    SEC COMB PERCENT
                   TOTAL AIR  109.50                                      MATERIAL BALANCE

                     BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                         COAL RATE                        MEASURED INPUT    145.57  15.54       234.02    721.24

     COAL RATE (WET) LB/HR  175.00   (DRY)  172.38        OUT AT POINT B    126.67  14.85       234.02    770.30
        DRY MAKE GAS LB/HR 1088.60
        WET MAKE GAS LB/HR 1156.74                        OUT AT POINT C    147.07
     TOTAL WATER FED LB/HR   12.16
 WATER FROM REACTION LB/HR   55.98

         PERCENT THEO. AIR   43.94
    HEATING VALUE BTU/DSCF   83.84

                                    SOLIDS ANALYSIS

                    TEST 14  GASIFIER OUT-- V.M. 1.4%   F.C. 60.2%   ASH 38.4%
                             CHAR RECYCLE-- V.M. 6.2%   F.C. 59.6%   ASH 34.2%
                            CYCLONE OUT-- C 77.2%   H 2.5%   S 1.8%   N 0.9%   ASH 13.4%   O 4.2%
                             TARS 5.71 LB/HR
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        TEST 15
                 02-09-76 1020 HRS 50-50 SPLIT ON COAL FEED TO GAS-DEVOL.  OXYGEN ADDED TO
                                       GASIFIER
                              Input                                                     Calculations

                                                                              GASIFIER-DEVOLATILIZER
         COAL RATE  LB/HR                  TEMPERATURES, F                 TOTAL BTU/HR IN COAL 2967690.00
                                                                       TOTAL BTU/HR IN NAT. GAS  624552.00
           GASIFIER  115.00              GASIFIER OUT 2010.00              TOTAL BTU/HR IN FUEL 3592242.00
              DEVOL  115.00                  DEVOL IN 1790.00                BTU/HR IN MAKE GAS 1380751.79
                                            DEVOL MID 1440.00             HYDROGEN IN GAS LB/HR       8.49
                                            DEVOL OUT 1280.00               CARBON IN GAS LB/HR     126.45
         AIR FLOWS  LB/HR                 CYC SEP OUT  890.00                 MAKE GAS MOL. WT.      27.00
                                         GASIFIER AIR  830.00               COLD-GAS CONV. EFF.      38.44
       GASIFIER AIR  821.00
      TRANSPORT AIR   27.50              SOLIDS LOADING LB/HR                   MAKE GAS ANALYSIS
     CHAR EJECT AIR   68.00               GASIFIER OUT  119.69                   WEIGHT FRACTION
TOTAL AIR TO GASIFIER 916.50               CYCLONE OUT   21.99
       SEC COMB AIR 4491.38                                                    HYDROGEN   .007333
                                              MAKE                      CARBON MONOXIDE   .172129
        NATURAL GAS  LB/HR           GASIFIER   GAS ANALYSIS   CYCLONE          METHANE  0.000000
                                      OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
           GASIFIER   26.50                                                    ETHYLENE   .003111
           SEC COMB  155.00             9.80      HYDROGEN       9.90         ACETYLENE  0.000000
                                       16.60  CARBON MONOXIDE   16.60  HYDROGEN SULFIDE  0.000000
                                        0.00      METHANE        0.00    CARBON DIOXIDE   .148280
         STEAM FLOW  LB/HR              0.00      ETHANE         0.00          NITROGEN   .653261
                                        0.00      ETHYLENE        .30      OXYGEN+ARGON   .015887
           GASIFIER    0.00             0.00     ACETYLENE       0.00
              DEVOL    0.00             0.00 HYDROGEN SULFIDE    0.00
                                        9.20 CARBON DIOXIDE      9.10
                                       63.40     NITROGEN       63.00
       OXYGEN ADDED  LB/HR              1.00   OXYGEN+ARGON      1.10
                     39.00
                                      100.00                   100.00
           SEC COMB PERCENT
             TOTAL AIR  110.00                                    MATERIAL BALANCE
                   BASED ON MEASURED
                       COAL RATE                                    CARBON   HYDROGEN   OXYGEN   NITROGEN
                                                   MEASURED INPUT   184.58     18.18    268.62     694.22
     COAL RATE (WET) LB/HR  230.00   (DRY)  226.55
        DRY MAKE GAS LB/HR 1093.32                 OUT AT POINT B   144.60     14.51    268.62     714.22
        WET MAKE GAS LB/HR 1154.31
     TOTAL WATER FED LB/HR   12.62                 OUT AT POINT C   172.20
WATER FROM REACTION LB/HR    48.38

       PERCENT THEO. AIR     40.31
    HEATING VALUE BTU/DSCF   90.47

                            SOLIDS ANALYSIS

              TEST 15  CHAR RECYCLE-- V.M. 4.4%   F.C. 61.3%   ASH 34.3%
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        TEST 16
                  02-09-76 1110 HRS  50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                               Input PITTSBURG 8 COAL                       Calculations

                                                                      GASIFIER-DEVOLATILIZER
          COAL RATE  LB/HR                 TEMPERATURES, F            TOTAL BTU/HR IN COAL 2415441.60
                                                                  TOTAL BTU/HR IN NAT. GAS   612768.00
            GASIFIER   93.60             GASIFIER OUT 2010.00         TOTAL BTU/HR IN FUEL 3028209.60
               DEVOL   93.60                 DEVOL IN 1810.00           BTU/HR IN MAKE GAS 1146879.95
                                            DEVOL MID 1500.00       HYDROGEN IN GAS LB/HR        8.19
                                            DEVOL OUT 1340.00         CARBON IN GAS LB/HR       99.27
            AIR FLOWS  LB/HR              CYC SEP OUT  905.00           MAKE GAS MOL. WT.       27.26
                                         GASIFIER AIR  840.00         COLD-GAS CONV. EFF.       37.87

         GASIFIER AIR  840.00            SOLIDS LOADING LB/HR             MAKE GAS ANALYSIS
        TRANSPORT AIR   29.70            GASIFIER OUT   94.33              WEIGHT FRACTION
       CHAR EJECT AIR   68.00             CYCLONE OUT   25.79
  TOTAL AIR TO GASIFIER 937.70                                               HYDROGEN    .006604
         SEC COMB AIR 4442.56                  MAKE                   CARBON MONOXIDE    .121217
                                   GASIFIER    GAS ANALYSIS  CYCLONE          METHANE    .001761
          NATURAL GAS  LB/HR         OUTLET  VOL PERCENT DRY  OUTLET           ETHANE    .001871
                                                                             ETHYLENE    .001541
            GASIFIER   26.00                                               ACETYLENE    .001431
            SEC COMB  145.00           9.30     HYDROGEN       9.00    HYDROGEN SULFIDE  0.000000
                                      13.70  CARBON MONOXIDE 11.80       CARBON DIOXIDE    .138827
                                       0.00     METHANE         .30            NITROGEN    .702645
          STEAM FLOW   LB/HR           0.00     ETHANE          .15        OXYGEN+ARGON    .024324
                                       0.00     ETHYLENE        .15
            GASIFIER    0.00           0.00    ACETYLENE        .15
               DEVOL    0.00           0.00 HYDROGEN SULFIDE  0.00
                                       7.80 CARBON DIOXIDE    8.60
                                      68.30    NITROGEN      68.40
        OXYGEN ADDED  LB/HR            1.00  OXYGEN+ARGON     1.70
                        0.00
                                     100.10                 100.25
            SEC COMB PERCENT
           TOTAL AIR  122.50                                           MATERIAL BALANCE

             BASED ON MEASURED                                          CARBON   HYDROGEN   OXYGEN   NITROGEN
                 COAL RATE                          MEASURED INPUT      153.55      15.90   231.38     709.81

     COAL RATE (WET) LB/HR  187.20   (DRY)  184.39    OUT AT POINT B      120.55      15.19   231.38     747.64
        DRY MAKE GAS LB/HR 1064.03
        WET MAKE GAS LB/HR 1132.49                  OUT AT POINT C      134.56
      TOTAL WATER FED LB/HR   12.19
  WATER FROM REACTION LB/HR   56.28

          PERCENT THEO. AIR   41.33
       HEATING VALUE BTU/DSCF  77.64

                            SOLIDS ANALYSIS

        TEST 16  CHAR RECYCLE-- V.M. 4.6%   F.C. 60.8%   ASH 34.6%
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      TEST 17
                02-09-76 1230 HRS 50-50 COAL FEED SPLIT TO GAS-DEVOL.  OXYGEN ADDITION TO
                                     Input GASIFIER  PITTSBURG 8 COAL                    Calculations

                                                                                GASIFIER-DEVOLATILIZER
         COAL RATE  LB/HR                   TEMPERATURES, F                 TOTAL BTU/HR IN COAL 2916078.00
                                                                        TOTAL BTU/HR IN NAT. GAS  624552.00
           GASIFIER  113.00               GASIFIER OUT 2120.00              TOTAL BTU/HR IN FUEL 3540630.00
              DEVOL  113.00                   DEVOL IN 1870.00               BTU/HR IN MAKE GAS 1295348.07
                                             DEVOL MID 1505.00            HYDROGEN IN GAS LB/HR        8.35
                                             DEVOL OUT 1390.00              CARBON IN GAS LB/HR      121.63
          AIR FLOWS  LB/HR                 CYC SEP OUT 1020.00                MAKF GAS MOL. WT.       27.25
                                          GASIFIER AIR  825.00              COLD-GAS CONV. EFF.       36.59
       GASIFIER AIR  749.00
      TRANSPORT AIR   27.50              SOLIDS LOADING LB/HR                  MAKE GAS ANALYSIS
     CHAR EJECT AIR   70.00               GASIFIER OUT   31.89                  WEIGHT FRACTION
TOTAL AIR TO GASIFIER 846.50                CYCLONE OUT   19.38
       SEC COMB AIR 4311.10                                                       HYDROGEN   .007120
                                              MAKE                        CARBON MONOXIDE   .162361
        NATURAL GAS  LB/HR           GASIFIER    GAS ANALYSIS   CYCLONE           METHANE   .002349
                                      OUTLET  VOL PERCENT DRY   OUTLET             ETHANE  0.000000
           GASIFIER   26.50                                                      FTHYLENE   .003083
           SEC COMP  145.00             8.70      HYDROGEN        9.70          ACETYLENE  0.000000
                                       17.10  CARBON MONOXIDE 15.80      HYDROGEN SULFIDE  0.000000
                                        0.00      METHANE          .40      CARBON DIOXIDE   .167939
         STEAM FLOW  LB/HR              0.00      ETHANE          0.00           NITROGEN   .637111
                                        0.00      ETHYLENE         .30      OXYGEN+ARGON   .020038
           GASIFIER    0.00             0.00     ACETYLENE        0.00
              DEVOL    0.00              .30 HYDROGEN SULFIDE  0.00
                                       10.20 CARBON DIOXIDE   10.40
                                       62.40      NITROGEN       62.00
       OXYGEN ADDED  LB/HR               .90    OXYGEN+ARGON      1.40
                      51.00
                                       99.60                    100.00
         SEC COMB PERCENT
          TOTAL AIR  114.00                                           MATERIAL BALANCE

              BASED ON MEASURED                                       CARBON    HYDROGEN    OXYGEN    NITROGEN
                  COAL RATE                         MEASURED INPUT    181.71      17.98     264.08     641.33

     COAL RATE (WET) LB/HR  226.00   (DRY)  222.61  OUT AT POINT B    137.62      14.34     264.08     653.45
        DRY MAKE GAS LB/HR 1025.64
        WET MAKE GAS LB/HR 1086.35                  OUT AT POINT C    158.42
       TOTAL WATER FED LB/HR   11.86
   WATER FROM REACTION LB/HR   48.85

          PERCENT THEO. AIR    40.21
     HEATING VALUE BTU/DSCF    91.29

                                  SOLIDS ANALYSIS

             TEST 17   CHAR RECYCLE-- V.M. 6.9%   F.C. 56.1%   ASH 37.0%
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              TEST 18
                        02-09-76 1400 HRS 50-50 COAL SPLIT TO GAS-DEVOL.** STEAM AND OXYGEN ADDITION
                                    Input TO GASIFIER**PITTSBURG 8 COAL             Calculations

                                                                               GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                TEMPERATURES, F            TOTAL BTU/HR IN COAL 2838660.00
                                                                        TOTAL BTU/HR IN NAT. GAS  624552.00
                   GASIFIER  110.00             GASIFIER OUT 2240.00        TOTAL BTU/HR IN FUEL 3463212.00
                      DEVOL  110.00                 DEVOL IN 2000.00          BTU/HR IN MAKE GAS 1218178.33
                                                   DEVOL MID 1690.00       HYDROGEN IN GAS LB/HR       8.76
                                                   DEVOL OUT 1540.00         CARBON IN GAS LB/HR     121.65
                  AIR FLOWS  LB/HR               CYC SEP OUT 1110.00           MAKE GAS MOL. WT.      27.33
                                                GASIFIER AIR  790.00         COLD-GAS CONV. EFF.      35.17

               GASIFIER AIR  696.00
              TRANSPORT AIR   27.50            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
             CHAR EJECT AIR   68.00             GASIFIER OUT    7.91              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 791.50              CYCLONE OUT   14.52
               SEC COMB AIR 4347.41                                                 HYDROGEN   .008122
                                                       MAKE                  CARBON MONOXIDE   .148538
                NATURAL GAS  LB/HR        GASIFIER    GAS ANALYSIS  CYCLONE          METHANE   .001756
                                            OUTLET  VOL PERCENT DRY OUTLET            ETHANE  0.000000
                   GASIFIER   26.50                                                 ETHYLENE   .003073
                   SEC COMB  150.00          10.90     HYDROGEN    11.10           ACETYLENE  0.000000
                                             12.90 CARBON MONOXIDE 14.50    HYDROGEN SULFIDE  0.000000
                                              0.00      METHANE      .30      CARBON DIOXIDE   .214100
                 STEAM FLOW  LB/HR            0.00      ETHANE      0.00            NITROGEN   .611568
                                              0.00     ETHYLENE      .30        OXYGEN+ARGON   .012842
                   GASIFIER   84.50           0.00    ACETYLENE     0.00
                      DEVOL    0.00           0.00 HYDROGEN SULFIDE 0.00
                                             13.10 CARBON DIOXIDE  13.30
                                             62.20      NITROGEN   59.70
               OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON    .90
                             64.00

                                            100.00                100.10
                   SEC COMB PERCENT
                  TOTAL AIR  110.00                                    MATERIAL BALANCE

                    BASED ON MEASURED                                   CARBON   HYDROGEN    OXYGEN  NITROGEN
                        COAL RATE                       MEASURED INPUT   177.42     17.68    263.88    599.75

    COAL RATE (WET) LB/HR  220.00   (DRY)  216.70       OUT AT POINT B   133.63     12.81    263.88    596.09
       DRY MAKE GAS LB/HR  974.69
       WET MAKE GAS LB/HR 1103.05                       OUT AT POINT C   167.50
    TOTAL WATER FED LB/HR   95.72
WATER FROM REACTION LB/HR   32.65

        PERCENT THEO. AIR   41.16
   HEATING VALUE BTU/DSCF   90.65

                                  SOLIDS ANALYSIS

                   TEST 18  CHAR RECYCLE-- V.M. 5.2%   F.C. 54.2%   ASH 40.3%
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              TEST 19
                        02-09-76 1450 HRS ALL COAL TO DEVOL.-OXYGEN AND STEAM ADDED TO GASIFIER
                                    Input PITTSBURG 8 COAL                                   Calculations

                                                                                      GASIFIER-DEVOLATILIZER
             COAL RATE  LB/HR                        TEMPERATURES, F               TOTAL BTU/HR IN COAL 1987062.00
                                                                                 TOTAL BTU/HR IN NAT. GAS  636336.00
               GASIFIER    0.00                    GASIFIER OUT 2500.00            TOTAL BTU/HR IN FUEL 2623398.00
                  DEVOL  154.00                        DEVOL IN 2230.00              BTU/HR IN MAKE GAS  506575.80
                                                      DEVOL MID 1900.00          HYDROGEN IN GAS LB/HR       4.49
                                                      DEVOL OUT 1705.00            CARBON IN GAS LB/HR      91.86
              AIR FLOWS  LB/HR                      CYC SEP OUT 1170.00              MAKE GAS MOL. WT.      29.97
                                                   GASIFIER AIR  800.00            COLD-GAS CONV. EFF.      19.31
           GASIFIER AIR  756.00
          TRANSPORT AIR    0.00                   SOLIDS LOADING LB/HR                 MAKE GAS ANALYSIS
         CHAR EJECT AIR   68.00                    GASIFIER OUT      .85                WEIGHT FRACTION
  TOTAL AIR TO GASIFIER  824.00                     CYCLONE OUT    23.11
           SEC COMB AIR 4411.39                                                        HYDROGEN    .003136
                                                         MAKE                   CARBON MONOXIDE    .026156
            NATURAL GAS  LB/HR           GASIFIER    GAS ANALYSIS     CYCLONE           METHANE    .002669
                                          OUTLET  VOL PERCENT DRY     OUTLET             ETHANE   0.000000
               GASIFIER   27.00                                                        ETHYLENE    .004671
               SEC COMB  155.00              0.00       HYDROGEN        4.70          ACETYLENE    .002602
                                             1.30   CARBON MONOXIDE     2.80  HYDROGEN SULFIDE   0.000000
                                             0.00        METHANE         .50     CARBON DIOXIDE    .289184
             STEAM FLOW  LB/HR               0.00        ETHANE         0.00           NITROGEN    .658571
                                             0.00       ETHYLENE         .50      OXYGEN+ARGON    .013011
               GASIFIER   82.00              0.00      ACETYLENE         .30
                  DEVOL    0.00              0.00 HYDROGEN SULFIDE      0.00
                                            21.20 CARBON DIOXIDE       19.70
                                            75.20    NITROGEN          70.50
           OXYGEN ADDED  LB/HR               2.20   OXYGEN+ARGON        1.00
                         64.00
                                            99.90                     100.00
          SEC COMB PERCENT
              TOTAL AIR  125.50                                            MATERIAL BALANCE

                BASED ON MEASURED                                       CARBON   HYDROGEN    OXYGEN    NITROGEN
                    COAL RATE                          MEASURED INPUT   130.53      14.49    266.54      623.64

     COAL RATE (WET) LB/HR  154.00  (DRY)  151.69      OUT AT POINT B   110.92      11.26    266.54      634.27
        DRY MAKE GAS LB/HR  963.10
        WET MAKE GAS LB/HR 1110.63                     OUT AT POINT C   121.78
     TOTAL WATER FED LB/HR   92.55
  WATER FROM REACTION LB/HR  54.98

         PERCENT THEO. AIR   55.98
     HEATING VALUE BTU/DSCF  41.92

                                  SOLIDS ANALYSIS

               TEST 19  CHAR RECYCLE-- V.M. 4.4%   F.C. 62.6%   ASH 33.0%
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        TEST 20
                  02-12-76 1205    HALF OF COAL TO HORIZ. GASIFIER BURNER AND HALF TO TOP OF
                            Input  GASIFIER     PITTSBURG NO.  8  COAL              Calculations

                                                                          GASIFIER-DEVOLATILIZER
           COAL RATE  LB/HR              TEMPERATURES, F                TOTAL BTU/HR IN COAL 1935450.00
                                                                    TOTAL BTU/HR IN NAT. GAS  294600.00
             GASIFIER   75.00          GASIFIER OUT 2100.00             TOTAL BTU/HR IN FUEL 2230050.00
                DEVOL   75.00              DEVOL IN 1870.00               BTU/HR IN MAKE GAS  968527.47
                                          DEVOL MID 1740.00            HYDROGEN IN GAS LB/HR       6.63
                                          DEVOL OUT 1560.00              CARBON IN GAS LB/HR     104.10
            AIR FLOWS  LB/HR            CYC SEP OUT 1050.00                MAKE GAS MOL. WT.      28.28
                                       GASIFIER AIR  815.00              COLD-GAS CONV. EFF.      43.43
         GASIFIER AIR  870.00
        TRANSPORT AIR   32.00         SOLIDS LOADING LB/HR                 MAKE GAS ANALYSIS
       CHAR EJECT AIR   71.00          GASIFIER OUT    0.00                 WEIGHT FRACTION
 TOTAL AIR TO GASIFIER  973.00           CYCLONE OUT   16.87
         SEC COMB AIR 4412.17                                                  HYDROGEN   .005022
                                              MAKE                      CARBON MONOXIDE   .100997
          NATURAL GAS  LB/HR         GASIFIER   GAS ANALYSIS   CYCLONE          METHANE   .001697
                                       OUTLET  VOL PERCENT DRY  OUTLET           ETHANE   .001804
             GASIFIER   12.50                                                  ETHYLENE   .001485
             SEC COMB  150.00            7.40    HYDROGEN       7.10          ACETYLENE   .001379
                                        10.30  CARBON MONOXIDE 10.20   HYDROGEN SULFIDE  0.000000
                                          .30      METHANE       .30     CARBON DIOXIDE   .178938
           STEAM FLOW  LB/HR             0.00      ETHANE        .15           NITROGEN   .695099
                                         0.00     ETHYLENE       .15      OXYGEN+ARGON   .013792
             GASIFIER    0.00            0.00    ACETYLENE       .15
                DEVOL    0.00            0.00 HYDROGEN SULFIDE  0.00
                                        10.00 CARBON DIOXIDE   11.50
                                        70.80    NITROGEN      70.20
         OXYGEN ADDED  LB/HR             1.10  OXYGEN+ARGON     1.00
                         0.00
                                        99.90                 100.75
             SEC COMB PERCENT
            TOTAL AIR  128.00                                        MATERIAL BALANCE

                BASED ON MEASURED                                  CARBON   HYDROGEN   OXYGEN   NITROGEN
                    COAL RATE                      MEASURED INPUT  116.79      10.66   236.82     736.09

    COAL RATE (WET) LB/HR  150.00   (DRY)  147.75   OUT AT POINT B  118.01      11.06   236.82     758.10
       DRY MAKE GAS LB/HR 1090.64
       WET MAKE GAS LB/HR 1138.13                   OUT AT POINT C  121.19
    TOTAL WATER FED LB/HR   11.98
WATER FROM REACTION LB/HR   35.51

      PERCENT THEO. AIR   58.23
   HEATING VALUE BTU/DSCF   66.32

                          SOLIDS ANALYSIS

                TEST 20  CHAR RECYCLE-- V.M. 1.6%   F.C. 60.5%   ASH 37.9%
                         CYCLONE OUT---- V.M. 3.2%   F.C. 87.1%   ASH 9.7%
                         CYCLONE OUT-- C 86.4%   H 0.8%   N 0.8%   S 1.9%   ASH 9.7%   O 0.4%
                          TARS  0.472 LB/HR
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TEST 21
          02-12-76 1240 HRS   HALF OF COAL TO HORIZ. GASIFIER BURNER AND HALF TO TOP OF
                         Input GASIFIER   PITTSBURG NO. 8  COAL              Calculations

                                                                    GASIFIER-DEVOLATILIZER
  COAL RATE  LB/HR                  TEMPERATURES, F              TOTAL BTU/HR IN COAL 2580600.00
                                                              TOTAL BTU/HR IN NAT. GAS  294600.00
    GASIFIER  200.00              GASIFIER OUT 2090.00           TOTAL BTU/HR IN FUEL 2875200.00
       DEVOL    0.00                  DEVOL IN 1890.00             BTU/HR IN MAKE GAS 1056686.25
                                     DEVOL MID 1760.00          HYDROGEN IN GAS LB/HR        7.33
                                     DEVOL OUT 1600.00            CARBON IN GAS LB/HR      106.42
     AIR FLOWS  LB/HR              CYC SEP OUT 1080.00              MAKE GAS MOL. WT.       27.93
                                  GASIFIER AIR  830.00            COLD-GAS CONV. EFF.       36.75
  GASIFIER AIR  865.00
 TRANSPORT AIR   31.00          SOLIDS LOADING LB/HR                  MAKE GAS ANALYSIS
CHAR EJECT AIR   70.00            GASIFIER OUT    0.00                 WEIGHT FRACTION
 TOTAL AIR TO GASIFIER  966.00     CYCLONE OUT   18.20
  SEC COMB AIR 4412.17                                                 HYDROGEN    .005872
                                           MAKE                 CARBON MONOXIDE    .112289
  NATURAL GAS   LB/HR           GASIFIER   GAS ANALYSIS   CYCLONE       METHANE    .000859
                                  OUTLET  VOL PERCENT DRY  OUTLET        ETHANE    .001826
    GASIFIER    12.50                                                  ETHYLENE    .001504
    SEC COMB   150.00                7.00    HYDROGEN       8.20      ACETYLENE    .001396
                                     9.20 CARBON MONOXIDE  11.20  HYDROGEN SULFIDE 0.000000
                                     0.00     METHANE        .15    CARBON DIOXIDE    .171727
   STEAM FLOW   LB/HR                0.00     ETHANE         .15          NITROGEN    .690776
                                     0.00    ETHYLENE        .15     OXYGEN+ARGON    .013964
    GASIFIER     0.00                0.00    ACETYLENE       .15
       DEVOL     0.00                0.00 HYDROGEN SULFIDE  0.00
                                    11.30 CARBON DIOXIDE   10.90
                                    71.60     NITROGEN     68.90
  OXYGEN ADDED  LB/HR                1.00   OXYGEN+ARGON    1.00
                 0.00
                                   100.10                 100.80
    SEC COMB PERCENT
   TOTAL AIR   126.00                                         MATERIAL BALANCE

        BASED ON MEASURED                                        CARBON   HYDROGEN   OXYGEN   NITROGEN
          COAL RATE                         MEASURED INPUT       152.59      13.17   238.89     731.30

    COAL RATE (WET) LB/HR  200.00  (DRY)  197.00   OUT AT POINT B   121.43   11.94   238.89     752.26
       DRY MAKE GAS LB/HR 1089.01
       WET MAKE GAS LB/HR 1138.42                  OUT AT POINT C   125.73
    TOTAL WATER FED LB/HR   12.66
WATER FROM REACTION LB/HR   36.75

      PERCENT THEO. AIR     44.84
  HEATING VALUE BTU/DSCF    71.59

                                SOLIDS ANALYSIS

          TEST 21  CHAR RECYCLE-- V.M. 2.2%   F.C. 60.5%   ASH 37.3%
                   CYCLONE OUT---- V.M. 2.6%   F.C. 85.9%   ASH 11.5%
                    TARS 0.364 LB/HR
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               TEST 22
                         02-12-76 1340 HRS ALL COAL FEED TO GASIFIER
                                     Input PITTSBURG 8 COAL                          Calculations

                                                                                 GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                 TEMPERATURES, F            TOTAL BTU/HR IN COAL 2103189.00
                                                                          TOTAL BTU/HR IN NAT. GAS  294600.00
                    GASIFIER  163.00             GASIFIER OUT 2160.00         TOTAL BTU/HR IN FUEL 2397789.00
                      DEVOL     0.00                 DEVOL IN 1910.00           BTU/HR IN MAKE GAS  901170.11
                                                    DEVOL MID 1800.00        HYDROGEN IN GAS LB/HR       5.04
                                                    DEVOL OUT 1620.00          CARBON IN GAS LB/HR     108.88
                   AIR FLOWS  LB/HR               CYC SEP OUT 1080.00           MAKE GAS MOL. WT.       28.16
                                                 GASIFIER AIR  840.00         COLD-GAS CONV. EFF.       37.58
                GASIFIER AIR  840.00
               TRANSPORT AIR   68.00            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
              CHAR EJECT AIR   70.00             GASIFIER OUT   24.24              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  978.00              CYCLONE OUT    7.74
                SEC COMB AIR 4331.86                                                  HYDROGEN   .004617
                                                        MAKE                   CARBON MONOXIDE   .125289
                 NATURAL GAS  LB/HR        GASIFIER   GAS ANALYSIS   CYCLONE           METHANE  0.000000
                                             OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                    GASIFIER   12.50                                                  ETHYLENE  0.000000
                    SEC COMB  150.00           6.30     HYDROGEN        6.50         ACETYLENE  0.000000
                                              11.40  CARBON MONOXIDE  12.60   HYDROGEN SULFIDE  0.000000
                                               0.00      METHANE        0.00    CARBON DIOXIDE   .168756
                  STEAM FLOW  LB/HR            0.00      ETHANE         0.00          NITROGEN   .686104
                                               0.00     ETHYLENE        0.00      OXYGEN+ARGON   .015235
                    GASIFIER    0.00           0.00     ACETYLENE       0.00
                       DEVOL    0.00           0.00 HYDROGEN SULFIDE    0.00
                                               9.40 CARBON DIOXIDE     10.80
                                              71.20     NITROGEN       69.00
                OXYGEN ADDED  LB/HR            1.60   OXYGEN+ARGON      1.10
                                0.00
                                              99.90                   100.00
                    SEC COMB PERCENT
                   TOTAL AIR  130.00                                         MATERIAL BALANCE

                     BASED ON MEASURED                                         CARBON   HYDROGEN   OXYGEN   NITROGEN
                         COAL RATE                         MEASURED INPUT      126.10      11.31   238.94     740.00

       COAL RATE (WET) LB/HR  163.00   (DRY)  160.56       OUT AT POINT B      115.27       8.59   238.94     748.36
          DRY MAKE GAS LB/HR 1090.73
          WET MAKE GAS LB/HR 1132.97                       OUT AT POINT C      112.11
       TOTAL WATER FED LB/HR   12.23
  WATER FROM REACTION LB/HR   30.01

         PERCENT THEO. AIR    54.43
     HEATING VALUE BTU/DSCF   61.70

                                    SOLIDS ANALYSIS

                    TEST 22  CHAR RECYCLE-- V.M. 17.7%   F.C. 72.8%   ASH 9.5%
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              TEST 23
                         02-12-76 1410 HRS ALL COAL FEED TO GASIFIER  OXYGEN ADDED
                                          PITTSBURG 8 COAL
                                      Input                                            Calculations
                                                                                  GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F              TOTAL BTU/HR IN COAL 2335443.00
                                                                           TOTAL BTU/HR IN NAT. GAS  294600.00
                    GASIFIER  181.00             GASIFIER OUT 2250.00          TOTAL BTU/HR IN FUEL 2630043.00
                      DEVOL     0.00               DEVOL IN 1960.00            BTU/HR IN MAKE GAS 1179942.48
                                                  DEVOL MID 1840.00        HYDROGEN IN GAS LB/HR        6.85
                                                  DEVOL OUT 1690.00          CARBON IN GAS LB/HR      128.18
                  AIR FLOWS  LB/HR                CYC SEP OUT 1115.00            MAKE GAS MOL. WT.       27.63
                                                 GASIFIER AIR  800.00        COLD-GAS CONV. EFF.       44.86
                GASIFIER AIR  784.00
               TRANSPORT AIR   58.00            SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
              CHAR EJECT AIR   70.00             GASIFIER OUT   21.70                WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  912.00              CYCLONE OUT    8.00
                SEC COMB AIR 4139.33                                                  HYDROGEN   .006298
                                                        MAKE                   CARBON MONOXIDE   .161135
                NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE  0.000000
                                             OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                    GASIFIER   12.50                                                  ETHYLENE  0.000000
                    SEC COMB  150.00          -0.00     HYDROGEN      8.70           ACETYLENE  0.000000
                                              -0.00  CARBON MONOXIDE 15.90    HYDROGEN SULFIDE  0.000000
                                              -0.00      METHANE      0.00      CARBON DIOXIDE   .178363
                 STEAM FLOW  LB/HR            -0.00      ETHANE       0.00            NITROGEN   .641500
                                              -0.00     ETHYLENE      0.00        OXYGEN+ARGON   .012704
                    GASIFIER    0.00          -0.00    ACETYLENE      0.00
                      DEVOL     0.00          -0.00 HYDROGEN SULFIDE  0.00
                                              -0.00 CARBON DIOXIDE   11.20
                                              -0.00     NITROGEN     63.30
               OXYGEN ADDED  LB/HR            -0.00   OXYGEN+ARGON     .90
                               51.00
                                               0.00                 100.00
                    SEC COMB PERCENT
                   TOTAL AIR  121.00                                     MATERIAL BALANCE
                    BASED ON MEASURED                                     CARBON   HYDROGEN    OXYGEN   NITROGEN
                        COAL RATE                        MEASURED INPUT    138.99     12.22    275.96    690.34

    COAL RATE (WET) LB/HR  181.00   (DRY)  178.29        OUT AT POINT B    134.78     11.38    275.96    697.89
       DRY MAKE GAS LB/HR 1087.90
       WET MAKE GAS LB/HR 1138.42                        OUT AT POINT C    132.27
    TOTAL WATER FED LB/HR   11.84
WATER FROM REACTION LB/HR   38.68

        PERCENT THEO. AIR   57.46
   HEATING VALUE BTU/DSCF   79.47

                                   SOLIDS ANALYSIS
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                TEST 24
                          02-23-76 1005 HRS 50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                                      Input WESTERN COAL                               Calculations

                                                                                   GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                 TEMPERATURES, F             TOTAL BTU/HR IN COAL 2202154.50
                                                                            TOTAL BTU/HR IN NAT. GAS  612768.00
                     GASIFIER  109.50             GASIFIER OUT 1860.00          TOTAL BTU/HR IN FUEL 2814922.50
                        DEVOL  109.50                 DEVOL IN 1600.00            BTU/HR IN MAKE GAS 1365335.27
                                                     DEVOL MID 1250.00         HYDROGEN IN GAS LB/HR        9.52
                                                     DEVOL OUT 1100.00           CARBON IN GAS LB/HR      110.89
                    AIR FLOWS  LB/HR               CYC SEP OUT  870.00              MAKE GAS MOL. WT.      26.41
                                                  GASIFIER AIR  810.00           COLD-GAS CONV. EFF.      48.50

                 GASIFIER AIR  850.00                                                 MAKE GAS ANALYSIS
                TRANSPORT AIR   58.00            SOLIDS LOADING LB/HR
               CHAR EJECT AIR   70.00             GASIFIER OUT   52.24                 WEIGHT FRACTION
          TOTAL AIR TO GASIFIER 978.00             CYCLONE OUT   18.96
                 SEC COMB AIR 4411.39                                                     HYDROGEN    .008026
                                                             MAKE                  CARBON MONOXIDE    .154772
                  NATURAL GAS  LB/HR          GASIFIER   GAS ANALYSIS   CYCLONE            METHANE    .000909
                                                OUTLET  VOL PERCENT DRY  OUTLET              ETHANE  0.000000
                     GASIFIER   26.00                                                      ETHYLENE  0.000000
                     SEC COMB  140.00             9.90     HYDROGEN      10.60            ACETYLENE  0.000000
                                                 13.30  CARBON MONOXIDE  14.60     HYDROGEN SULFIDE  0.000000
                                                  0.00      METHANE        .15       CARBON DIOXIDE   .106614
                   STEAM FLOW  LB/HR              0.00      ETHANE        0.00             NITROGEN   .713437
                                                  0.00      ETHYLENE      0.00         OXYGEN+ARGON   .016242
                     GASIFIER    0.00             0.00     ACETYLENE      0.00
                        DEVOL    0.00             0.00 HYDROGEN SULFIDE   0.00
                                                  8.40  CARBON DIOXIDE    6.40
                                                 67.50     NITROGEN      67.30
                 OXYGEN ADDED  LB/HR               .90   OXYGEN+ARGON     1.10
                                 0.00
                                                100.00                  100.15
                     SEC COMB PERCENT
                     TOTAL AIR  125.50                                        MATERIAL BALANCE

                       BASED ON MEASURED                                     CARBON  HYDROGEN   OXYGEN   NITROGEN
                           COAL RATE                       MEASURED INPUT    148.69     15.25   258.17     740.07

      COAL RATE (WET) LB/HR  219.00   (DRY)  186.15        OUT AT POINT B    126.53     18.41   258.17     822.51
         DRY MAKE GAS LB/HR 1152.88
         WET MAKE GAS LB/HR 1270.59                        OUT AT POINT C    139.28
      TOTAL WATER FED LB/HR   42.63
  WATER FROM REACTION LB/HR   75.08

          PERCENT THEO. AIR   46.10
     HEATING VALUE BTU/DSCF   82.98
                                        SOLIDS ANALYSIS

                     TEST 24  CHAR RECYCLE-- V.M. 2.9%   F.C. 56.7%   ASH 40.4%
                              CYCLONE OUT---- V.M. 28.4%  F.C. 51.7%   ASH 19.9%
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TEST 25
          02-23-76 1055 HRS  25-75 SPLIT ON COAL FLOW TO GAS-DEVOL.
                          Input WESTERN COAL                                     Calculations

                                                                            GASIFIER-DEVOLATILIZER
     COAL RATE  LB/HR                   TEMPERATURES, F                TOTAL BTU/HR IN COAL 2694874.00
                                                                   TOTAL BTU/HR IN NAT. GAS  612768.00
       GASIFIER   67.00               GASIFIER OUT 1930.00             TOTAL BTU/HR IN FUEL 3307642.00
          DEVOL  201.00                   DEVOL IN 1670.00              BTU/HR IN MAKE GAS 1309452.35
                                         DEVOL MID 1300.00           HYDROGEN IN GAS LB/HR        9.81
                                         DEVOL OUT 1150.00             CARBON IN GAS LB/HR      106.94
      AIR FLOWS  LB/HR                 CYC SEP OUT  850.00               MAKE GAS MOL. WT.       26.50
                                      GASIFIER AIR  865.00             COLD-GAS CONV. EFF.       39.59
     GASIFIER AIR  850.00
    TRANSPORT AIR   58.00              SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
   CHAR EJECT AIR   72.00               GASIFIER OUT   62.97                WEIGHT FRACTION
TOTAL AIR TO GASIFIER  980.00            CYCLONE OUT   21.27
     SEC COMB AIR 4393.75                                                        HYDROGEN   .008075
                                              MAKE                       CARBON MONOXIDE   .138410
     NATURAL GAS  LB/HR           GASIFIER    GAS ANALYSIS   CYCLONE              METHANE   .001811
                                   OUTLET  VOL PERCENT DRY   OUTLET                ETHANE  0.000000
       GASIFIER   26.00                                                         ETHYLENE  0.000000
       SEC COMB  145.00              9.60     HYDROGEN      10.70              ACETYLENE  0.000000
                                    14.20  CARBON MONOXIDE  13.10       HYDROGEN SULFIDE  0.000000
                                     0.00      METHANE        .30         CARBON DIOXIDE   .117882
     STEAM FLOW  LB/HR               0.00      ETHANE        0.00               NITROGEN   .720577
                                     0.00     ETHYLENE       0.00          OXYGEN+ARGON   .013245
       GASIFIER    0.00              0.00    ACETYLENE       0.00
          DEVOL    0.00              0.00 HYDROGEN SULFIDE   0.00
                                    10.60 CARBON DIOXIDE     7.10
                                    64.70     NITROGEN      68.20
     OXYGEN ADDED  LB/HR              .90   OXYGEN+ARGON      .90
                   0.00
                                   100.00                  100.30
       SEC COMB PERCENT
       TOTAL AIR  116.00                                          MATERIAL BALANCE

        BASED ON MEASURED                                         CARBON   HYDROGEN   OXYGEN   NITROGEN
            COAL RATE                          MEASURED INPUT     177.59     17.21    265.63    741.95

   COAL RATE (WET) LB/HR  268.00  (DRY)  227.80   OUT AT POINT B     124.49     19.91    265.63    829.32
      DRY MAKE GAS LB/HR 1150.91
      WET MAKE GAS LB/HR 1286.17                 OUT AT POINT C     159.15
   TOTAL WATER FED LB/HR   50.00
WATER FROM REACTION LB/HR   85.26

       PERCENT THEO. AIR   39.32
  HEATING VALUE BTU/DSCF   80.00

                            SOLIDS ANALYSIS

       TEST 25  CHAR RECYCLE-- V.M. 2.2%    F.C. 57.0%   ASH 40.8%
               CYCLONE OUT---- V.M. 27.2%   F.C. 48.6%   ASH 24.2%
                TARS 6.17 LB/HR
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              TEST 26
                     02-23-76 1145 HRS ALL COAL TO DEVOLATILIZER
                                 Input WESTERN COAL                                  Calculations
                                                                               GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR              TEMPERATURES, F                TOTAL BTU/HR IN COAL 2373098.00
                                                                           TOTAL BTU/HR IN NAT. GAS  636336.00
                     GASIFIER     0.00          GASIFIER OUT 1660.00            TOTAL BTU/HR IN FUEL 3009434.00
                        DEVOL   236.00              DEVOL IN 1600.00              BTU/HR IN MAKE GAS  891149.60
                                                   DEVOL MID 1250.00         HYDROGEN IN GAS LB/HR       5.55
                                                   DEVOL OUT 1100.00           CARBON IN GAS LB/HR     107.45
                    AIR FLOWS  LB/HR             CYC SEP OUT  840.00            MAKE GAS MOL. WT.       28.23
                                                GASIFIER AIR  865.00           COLD-GAS CONV. EFF.      29.61
                 GASIFIER AIR  840.00
                TRANSPORT AIR   26.00          SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
               CHAR EJECT AIR   70.00           GASIFIER OUT   10.75                WEIGHT FRACTION
         TOTAL AIR TO GASIFIER  936.00           CYCLONE OUT   23.30
                 SEC COMB AIR 4393.75                                                   HYDROGEN   .004747
                                                     MAKE                        CARBON MONOXIDE   .112095
                  NATURAL GAS  LB/HR       GASIFIER   GAS ANALYSIS   CYCLONE             METHANE   .000850
                                             OUTLET  VOL PERCENT DRY  OUTLET              ETHANE  0.000000
                     GASIFIER   27.00                                                   ETHYLENE   .001488
                     SEC COMB  140.00          6.20     HYDROGEN        6.70           ACETYLENE  0.000000
                                              10.60  CARBON MONOXIDE 11.30      HYDROGEN SULFIDE  0.000000
                                               0.00     METHANE          .15      CARBON DIOXIDE   .185503
                   STEAM FLOW  LB/HR           0.00     ETHANE          0.00            NITROGEN   .681499
                                               0.00     ETHYLENE         .15     OXYGEN+ARGON    .013817
                     GASIFIER     0.00         0.00     ACETYLENE       0.00
                        DEVOL     0.00         0.00 HYDROGEN SULFIDE    0.00
                                              11.40 CARBON DIOXIDE     11.90
                                              70.60     NITROGEN       68.70
                 OXYGEN ADDED  LB/HR           1.00   OXYGEN+ARGON      1.00
                                  0.00
                                             100.00                    99.90
                     SEC COMB PERCENT
                    TOTAL AIR   117.00                                     MATERIAL BALANCE

                     BASED ON MEASURED                                       CARBON   HYDROGEN   OXYGEN   NITROGEN
                        COAL RATE                       MEASURED INPUT       159.47      16.18   250.85     708.49

       COAL RATE (WET) LB/HR  236.00   (DRY)  200.60    OUT AT POINT B       126.68      10.82   250.85     732.23
          DRY MAKE GAS LB/HR 1074.44
          WET MAKE GAS LB/HR 1160.50                    OUT AT POINT C       159.06
         TOTAL WATER FED LB/HR   44.76
    WATER FROM REACTION LB/HR    41.29

            PERCENT THEO. AIR    41.27
      HEATING VALUE BTU/DSCF     62.10

                                       SOLIDS ANALYSIS

                     TEST 26  GASIFIER OUT-- V.M. 4.4%    F.C. 38.2%   ASH 57.4%
                              CHAR RECYCLE-- V.M. 18.6%   F.C. 56.7%   ASH 24.7%
                              TARS 6.03 LB/HR
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               TEST 27
                         02-23-76 1240 HRS  ALL COAL TO GASIFIER
                                    Input WESTERN COAL                                Calculations

                                                                                  GASIFIER-DEVOLATILIZER
                  COAL RATE  LB/HR                  TEMPERATURES, F            TOTAL BTU/HR IN COAL 2192099.00
                                                                           TOTAL BTU/HR IN NAT. GAS  624552.00
                    GASIFIER  218.00               GASIFIER OUT 1930.00        TOTAL BTU/HR IN FUEL 2816651.00
                       DEVOL    0.00                   DEVOL IN 1730.00          BTU/HR IN MAKE GAS 1424736.83
                                                      DEVOL MID 1600.00      HYDROGEN IN GAS LB/HR       11.12
                                                      DEVOL OUT 1400.00        CARBON IN GAS LB/HR      132.10
                   AIR FLOWS  LB/HR                 CYC SEP OUT 1010.00          MAKE GAS MOL. WT.       26.72
                                                   GASIFIER AIR  890.00        COLD-GAS CONV. EFF.       50.58
                GASIFIER AIR  835.00
               TRANSPORT AIR   25.20              SOLIDS LOADING LB/HR             MAKE GAS ANALYSIS
              CHAR EJECT AIR   71.00               GASIFIER OUT  168.85             WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  931.20                CYCLONE OUT   28.02
                SEC COMB AIR 4296.11                                                   HYDROGEN   .009281
                                                        MAKE                    CARBON MONOXIDE   .148802
                 NATURAL GAS  LB/HR         GASIFIER   GAS ANALYSIS   CYCLONE           METHANE   .002994
                                              OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                    GASIFIER   26.50                                                   ETHYLENE  0.000000
                    SEC COMB  145.00           12.10    HYDROGEN      12.40           ACETYLENE  0.000000
                                               12.60  CARBON MONOXIDE 14.20    HYDROGEN SULFIDE  0.000000
                                                 .30     METHANE        .50      CARBON DIOXIDE   .194311
                  STEAM FLOW  LB/HR             0.00     ETHANE        0.00            NITROGEN   .632934
                                                0.00     ETHYLENE      0.00        OXYGEN+ARGON   .011677
                    GASIFIER    0.00            0.00    ACETYLENE      0.00
                       DEVOL    0.00             .30 HYDROGEN SULFIDE  0.00
                                               10.50 CARBON DIOXIDE   11.80
                                               63.70    NITROGEN      60.40
               OXYGEN ADDED  LB/HR               .70   OXYGEN+ARGON     .80
                                0.00
                                              100.20                 100.10
                    SEC COMB PERCENT
                   TOTAL AIR  114.00                                         MATERIAL BALANCE

                     BASED ON MEASURED                                         CARBON   HYDROGEN    OXYGEN   NITROGEN
                         COAL RATE                        MEASURED INPUT      148.47      15.33    247.17     704.72

        COAL RATE (WET) LB/HR  218.00   (DRY)  185.30     OUT AT POINT B      155.22      11.41    247.17     701.85
           DRY MAKE GAS LB/HR 1108.88
           WET MAKE GAS LB/HR 1146.20                     OUT AT POINT C      155.21
        TOTAL WATER FED LB/HR   42.01
    WATER FROM REACTION LB/HR   -4.70

            PERCENT THEO. AIR   43.87
        HEATING VALUE BTU/DSCF  91.09

                                      SOLIDS ANALYSIS

                     TEST 27  GASIFIER OUT-- V.M. 2.7%    F.C. 63.4%   ASH 33.9%
                              CHAR RECYCLE-- V.M. 3.6%    F.C. 61.3%   ASH 35.1%
                             CYCLONE OUT---- V.M. 10.2%   F.C. 65.1%   ASH 24.7%
                              TARS AT GASIFIER OUTLET  0.0 LB/HR
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              TEST 28
                        02-23-76 1325 HRS   50-50 SPLIT ON COAL FEED TO GAS-DEVOL.
                                    InputWESTERN COAL                               Calculations

                                                                               GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                TEMPERATURES, F            TOTAL BTU/HR IN COAL 2352987.00
                                                                        TOTAL BTU/HR IN NAT. GAS  636336.00
                   GASIFIER  117.00             GASIFIER OUT 1950.00        TOTAL BTU/HR IN FUEL 2989323.00
                      DEVOL  117.00                 DEVOL IN 1720.00          BTU/HR IN MAKE GAS 1280549.64
                                                   DEVOL MID 1420.00       HYDROGEN IN GAS LB/HR       8.68
                                                   DEVOL OUT 1270.00         CARBON IN GAS LB/HR     129.02
                  AIR FLOWS  LB/HR               CYC SEP OUT  905.00           MAKE GAS MOL. WT.      27.25
                                                GASIFIER AIR  895.00         COLD-GAS CONV. EFF.      42.84

               GASIFIER AIR  830.00
              TRANSPORT AIR   56.00            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
             CHAR EJECT AIR   70.00             GASIFIER OUT   67.95              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 956.00              CYCLONE OUT   20.26
               SEC COMB AIR 4296.11                                                     HYDROGEN  .007265
                                                       MAKE                      CARBON MONOXIDE  .149996
                NATURAL GAS  LB/HR        GASIFIER    GAS ANALYSIS   CYCLONE             METHANE  .001761
                                            OUTLET  VOL PERCENT DRY  OUTLET               ETHANE 0.000000
                   GASIFIER   27.00                                                     ETHYLENE 0.000000
                   SEC COMB  150.00           9.70     HYDROGEN        9.90            ACETYLENE 0.000000
                                             13.30  CARBON MONOXIDE 14.60       HYDROGEN SULFIDE 0.000000
                                              0.00      METHANE         .30       CARBON DIOXIDE  .179203
                 STEAM FLOW  LB/HR            0.00      ETHANE         0.00             NITROGEN  .650327
                                              0.00     ETHYLENE        0.00         OXYGEN+ARGON  .011448
                   GASIFIER    0.00           0.00     ACETYLENE       0.00
                      DEVOL    0.00           0.00 HYDROGEN SULFIDE    0.00
                                              8.60 CARBON DIOXIDE     11.10
                                             67.40     NITROGEN       63.30
               OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON       .80
                               0.00
                                             99.90                   100.00
                   SEC COMB PERCENT
                  TOTAL AIR  111.00                                        MATERIAL BALANCE

                  BASED ON MEASURED                                          CARBON   HYDROGEN   OXYGEN   NITROGEN
                      COAL RATE                          MEASURED INPUT      158.29     16.10    255.21     723.57

    COAL RATE (WET) LB/HR  234.00   (DRY)  198.90        OUT AT POINT B      145.73     10.72    255.21     732.19
       DRY MAKE GAS LB/HR 1125.88
       WET MAKE GAS LB/HR 1183.66                        OUT AT POINT C      159.86
    TOTAL WATER FED LB/HR   44.66
WATER FROM REACTION LB/HR   13.12

        PERCENT THEO. AIR   42.44
   HEATING VALUE BTU/DSCF   82.23

                                     SOLIDS ANALYSIS

                 TEST 28  GASIFIER OUT-- V.M. 2.0%    F.C. 56.7%   ASH 41.3%
                          CHAR RECYCLE-- V.M. 6.8%    F.C. 61.2%   ASH 32.0%
                         CYCLONE OUT---- V.M. 21.7%   F.C. 53.6%   ASH 24.7%
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               TEST 29
                         03-01-76 0940 HRS   50-50 SPLIT ON COAL FLOW TO GAS-DEVOL.
                                      Input WESTERN COAL                                  Calculations

                                                                                        GASIFIER-DEVOLATILIZFR
                  COAL RATE  LB/HR                    TEMPERATURES, F              TOTAL BTU/HR IN COAL 2363042.50
                                                                                TOTAL BTU/HR IN NAT. GAS  612768.00
                    GASIFIEP  117.50                 GASIFIER OUT 1810.00          TOTAL BTU/HR IN FUEL 2975810.50
                       DEVOL  117.50                     DEVOL IN 1540.00            BTU/HR IN MAKE GAS 1354758.30
                                                        DEVOL MID 1190.00           HYDROGEN IN GAS LB/HR       9.15
                                                        DEVOL OUT 1090.00             CARBON IN GAS LB/HR     121.13
                   AIR FLOWS  LB/HR                   CYC SEP OUT  800.00               MAKE GAS MOL. WT.      26.76
                                                     GASIFIER AIR  810.00             COLD-GAS CONV. EFF.      45.53
                GASIFIER AIR  860.00
               TRANSPORT AIR   27.50                SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
              CHAR EJECT AIR   72.00                 GASIFIER OUT    0.00                WEIGHT FRACTION
        TOTAL AIR TO GASIFIER  959.50                 CYCLONE OUT   20.42
                SEC COMB AIR 4300.49                                                   HYDROGEN   .007625
                                                            MAKE                CARBON MONOXIDE   .158027
                 NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE   .001794
                                              OUTLET  VOL PERCENT DRY  OUTLET            ETHANE  0.000000
                    GASIFIER   26.00                                                   ETHYLENE  0.000000
                    SEC COMB  145.00           -0.00     HYDROGEN      10.20          ACETYLENE  0.000000
                                               -0.00  CARBON MONOXIDE  15.10   HYDROGEN SULFIDE  0.000000
                                               -0.00      METHANE        .30     CARBON DIOXIDE   .138142
                  STEAM FLOW  LB/HR            -0.00      ETHANE        0.00           NITROGEN   .681293
                                               -0.00     ETHYLENE       0.00       OXYGEN+ARGON   .013119
                    GASIFIER    0.00           -0.00    ACETYLENE       0.00
                       DEVOL    0.00           -0.00 HYDROGEN SULFIDE   0.00
                                               -0.00 CARBON DIOXIDE     8.40
                                               -0.00     NITROGEN      65.10
                OXYGEN ADDED  LB/HR            -0.00   OXYGEN+ARGON      .90
                                0.00
                                                0.00                  100.00
                    SEC COMB PERCENT
                   TOTAL AIR  114.00                                              MATERIAL BALANCE

                     BASED ON MEASURED                                              CARBON   HYDROGEN   OXYGEN   NITROGEN
                         COAL RATE                               MEASURED INPUT     158.13      15.89   256.16     726.22

     COAL RATE (WET) LB/HR  235.00   (DRY)  199.75               OUT AT POINT B     137.98      14.71   256.16     772.36
        DRY MAKE GAS LB/HR 1133.67
        WET MAKE GAS LB/HR 1223.20                               OUT AT POINT C     157.71
      TOTAL WATER FED LB/HR   44.85
 WATER FROM REACTION LB/HR    44.69

         PERCENT THEO. AIR    42.79
    HEATING VALUE BTU/DSCF    84.81

                                    SOLIDS ANALYSIS

                    TEST 29 CYCLONE OUT-- V.M. 25.4%   F.C. 48.4%   ASH 26.2%
                            CYCLONE OUT-- C 68.1%   H 2.3%   N 0.6%   S 1.9%   ASH 26.2%   O 0.9%
                             TARS 5.11 LB/HR
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              TEST 30
                        03-01-76 1035 HRS  50-50 SPLIT ON COAL FLOW TO GAS-DEVOL.
                                    InputWESTERN COAL   OXYGEN ENRICHMENT TO GASIFIER  Calculations
                                                                                GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR                 TEMPERATURES, F            TOTAL RTU/HR IN COAL 2654652.00
                                                                          TOTAL BTU/HR IN NAT. GAS  648120.00
                   GASIFIER  132.00              GASIFIER OUT 1970.00        TOTAL BTU/HR IN FUEL 3302772.00
                      DEVOL  132.00                  DEVOL IN 1690.00          BTU/HR IN MAKE GAS 1565140.92
                                                    DEVOL MID 1290.00        HYDROGEN IN GAS LB/HR      10.11
                                                    DEVOL OUT 1200.00          CARBON IN GAS LB/HR    141.86
                  AIR FLOWS  LB/HR                CYC SEP OUT  865.00            MAKF GAS MOL. WT.     26.67
                                                 GASIFIER AIR  830.00          COLD-GAS CONV. EFF.     47.39
               GASIFIER AIR  800.00
              TRANSPORT AIR   28.10             SOLIDS LOADING LB/HR               MAKF GAS ANALYSIS
             CHAR EJECT AIR   74.00              GASIFIER OUT    0.00               WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  902.10               CYCLONE OUT   29.63
               SEC COMB AIR 4221.64                                                  HYDROGEN   .008473
                                                        MAKE                  CARBON MONOXIDE   .188955
                NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE         METHANE   .001800
                                             OUTLET  VOL PERCENT DRY  OUTLET           ETHANE 0.000000
                   GASIFIER   27.50                                                  ETHYLENE 0.000000
                   SEC COMB  122.00           10.70     HYDROGEN    11.30           ACETYLENE 0.000000
                                              16.70  CARBON MONOXIDE 18.00     HYDROGFN SULFIDE 0.000000
                                               0.00      METHANE      .30        CARBON DIOXIDE   .156713
                 STEAM FLOW  LB/HR             0.00      ETHANE      0.00            NITROGEN   .630900
                                               0.00     ETHYLENE     0.00         OXYGEN+ARGON   .013159
                   GASIFIER    0.00            0.00    ACETYLENE     0.00
                      DEVOL    0.00            0.00 HYDROGEN SULFIDE  0.00
                                              10.10 CARBON DIOXIDE    9.50
                                              61.70    NITROGEN    60.10
               OXYGEN ADDED  LB/HR              .90   OXYGEN+ARGON    .90
                              50.00
                                             100.10                100.10
                   SEC COMB PERCENT
                  TOTAL AIR  114.00                                      MATERIAL BALANCE

                    BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN  NITROGEN
                        COAL RATE                        MEASURED INPUT    176.36     17.42    296.99    683.11

    COAL RATE (WET) LB/HR  264.00   (DRY)  224.40        OUT AT POINT B    166.30     16.63    296.99    714.87
       DRY MAKE GAS LB/HR 1133.09
       WET MAKE GAS LB/HR 1232.70                        OUT AT POINT C    192.06
    TOTAL WATER FED LB/HR   48.62
WATER FROM REACTION LB/HR   50.99

        PERCENT THEO. AIR   44.92
   HEATING VALUE BTU/DSCF   97.72

                                   SOLIDS ANALYSIS

                   TEST 30 CYCLONE OUT- V.M. 19.7%   F.C. 55.2%   ASH 25.1%
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                TEST 31
                          03-01-76 1115 HRS  ALL COAL TO THE DEVOLATILIZER
                                      Input WESTERN COAL                                Calculations

                                                                                   GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                 TEMPERATURES, F                 TOTAL BTU/HR IN COAL 2785373.50
                                                                            TOTAL BTU/HR IN NAT. GAS  659904.00
                     GASIFIER    0.00              GASIFIER OUT 2070.00          TOTAL BTU/HR IN FUEL 3445277.50
                        DEVOL  277.00                  DEVOL IN 1760.00            BTU/HR IN MAKE GAS 1087783.52
                                                      DEVOL MID 1210.00         HYDROGEN IN GAS LB/HR       7.28
                                                      DEVOL OUT 1030.00           CARBON IN GAS LB/HR     105.23
                    AIR FLOWS  LB/HR                CYC SEP OUT  820.00             MAKE GAS MOL. WT.      27.44
                                                   GASIFIER AIR  850.00           COLD-GAS CONV. EFF.      31.57
                 GASIFIER AIR  840.00
                TRANSPORT AIR    0.00             SOLIDS LOADING LB/HR               MAKE GAS ANALYSIS
               CHAR EJECT AIR   72.00              GASIFIER OUT    0.00               WEIGHT FRACTION
        TOTAL AIR TO GASIFIER  912.00               CYCLONE OUT   29.94
                 SEC COMB AIR 4269.07                                                  HYDROGEN   .005977
                                                          MAKE                  CARBON MONOXIDE   .126535
                  NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE         METHANE   .001749
                                               OUTLET  VOL PERCENT DRY  OUTLET           ETHANE  0.000000
                     GASIFIER   28.00                                                  ETHYLENE   .003061
                     SEC COMB  125.00            7.80     HYDROGEN       8.20         ACETYLENE  0.000000
                                                12.50  CARBON MONOXIDE 12.40   HYDROGEN SULFIDE  0.000000
                                                 0.00      METHANE        .30    CARBON DIOXIDE   .153941
                   STEAM FLOW  LB/HR             0.00      ETHANE        0.00          NITROGEN   .695944
                                                 0.00     ETHYLENE        .30      OXYGEN+ARGON   .012792
                     GASIFIER    0.00            0.00    ACETYLENE       0.00
                        DEVOL    0.00             .30 HYDROGEN SULFIDE   0.00
                                                 8.90 CARBON DIOXIDE     9.60
                                                69.40     NITROGEN      68.20
                 OXYGEN ADDED  LB/HR             1.00   OXYGEN+ARGON      .90
                                 0.00
                                                99.90                   99.90
                     SEC COMB PERCENT
                    TOTAL AIR  115.00                                      MATERIAL BALANCE

                      BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                          COAL RATE                        MEASURED INPUT    184.40     18.07   251.14     690.68

     COAL RATE (WET) LB/HR  277.00    (DRY)  235.45        OUT AT POINT B    129.93     15.01   251.14     740.19
        DRY MAKE GAS LB/HR 1063.57
        WET MAKE GAS LB/HR 1176.01                         OUT AT POINT C    174.00
     TOTAL WATER FED LB/HR   50.67
 WATER FROM REACTION LB/HR   61.77

         PERCENT THEO. AIR   35.13
    HEATING VALUE BTU/DSCF   74.46

                                     SOLIDS ANALYSIS

                    TEST 31 CYCLONE OUT-- C 68.8,   H 3.3%   N ---   ASH 19.4%   O 7.2%
                             TARS 9.64 LB/HR
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                TEST 32
                          03-01-76 1315 HRS  ALL COAL TO GASIFIER
                                    Input WESTERN COAL                              Calculations
                                                                                 GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                TEMPERATURES, F            TOTAL BTU/HR IN COAL 2956317.00
                                                                          TOTAL BTU/HR IN NAT. GAS  337022.40
                     GASIFIER  294.00            GASIFIER OUT 2040.00         TOTAL BTU/HR IN FUEL 3293339.40
                        DEVOL    0.00                DEVOL IN 1840.00           BTU/HR IN MAKE GAS 1339260.75
                                                    DEVOL MID 1700.00        HYDROGEN IN GAS LB/HR      10.04
                                                    DEVOL OUT 1560.00          CARBON IN GAS LB/HR     122.35
                  AIR FLOWS  LB/HR                CYC SEP OUT  990.00            MAKE GAS MOL. WT.      26.71
                                                 GASIFIER AIR  830.00          COLD-GAS CONV. EFF.      40.67

                 GASIFIER AIR  850.00            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
                TRANSPORT AIR   23.40            GASIFIER OUT    0.00               WEIGHT FRACTION
               CHAR EJECT AIR   72.00             CYCLONE OUT   44.26
        TOTAL AIR TO GASIFIER  945.40                                                 HYDROGEN   .008761
                 SEC COMB AIR 4269.07                    MAKE                  CARBON MONOXIDE   .147821
                  NATURAL GAS  LB/HR        GASIFIER    GAS ANALYSIS  CYCLONE           METHANE  .000899
                                              OUTLET  VOL PERCENT DRY OUTLET            ETHANE  0.000000
                     GASIFIER   14.30                                                 ETHYLENE  0.000000
                     SEC COMB  125.00          11.20     HYDROGEN    11.70           ACETYLENE  0.000000
                                               13.30  CARBON MONOXIDE 14.10   HYDROGEN SULFIDE  0.000000
                                                 .30      METHANE      .15      CARBON DIOXIDE   .166392
                   STEAM FLOW  LB/HR            0.00      ETHANE      0.00            NITROGEN   .661525
                                                0.00     ETHYLENE     0.00        OXYGEN+ARGON   .014602
                     GASIFIER    0.00           0.00    ACETYLENE     0.00
                        DEVOL    0.00            .30 HYDROGEN SULFIDE  0.00
                                               10.00 CARBON DIOXIDE  10.10
                                               64.10     NITROGEN    63.10
                 OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON   1.00
                                 0.00
                                              100.10                100.15
                     SEC COMB PERCENT
                    TOTAL AIR  118.00                                    MATERIAL BALANCE

                      BASED ON MEASURED                                   CARBON   HYDROGEN  OXYGEN   NITROGEN
                          COAL RATE                       MEASURED INPUT   184.16     15.32   261.32    716.03

       COAL RATE (WET) LB/HR  294.00  (DRY)  249.90       OUT AT POINT B   158.86     15.26   261.32    739.05
         DRY MAKE GAS LB/HR 1117.20
         WET MAKE GAS LB/HR 1206.17                       OUT AT POINT C   174.72
       TOTAL WATER FED LB/HR   53.55
   WATER FROM REACTION LB/HR   35.42

          PERCENT THEO. AIR    38.09
      HEATING VALUE BTU/DSCF   84.95

                                     SOLIDS ANALYSIS

                     TEST 32 CYCLONE OUT-- V.M. 3.8%   F.C. 73.0%   ASH 23.2%
                              TARS 0.35 LB/HR
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                TEST 33
                          03-04-76 0945 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE ONLY
                                      Input WESTERN COAL                                Calculations
                                                                                    GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                 TEMPERATURES, F              TOTAL BTU/HR IN COAL 3177538.00
                                                                             TOTAL BTU/HR IN NAT. GAS  388872.00
                     GASIFIER 316.00               GASIFIER OUT 1480.00          TOTAL BTU/HR IN FUEL 3566410.00
                        DEVOL    0.00                  DEVOL IN 1300.00            BTU/HR IN MAKE GAS 1749270.27
                                                      DEVOL MID 1200.00         HYDROGEN IN GAS LB/HR      12.45
                                                      DEVOL OUT 1090.00           CARBON IN GAS LB/HR     137.77
                    AIR FLOWS  LB/HR                CYC SEP OUT  820.00            MAKE GAS MOL. WT.       27.10
                                                   GASIFIER AIR  830.00           COLD-GAS CONV. EFF.      49.05
                  GASIFIER AIR 865.00
                 TRANSPORT AIR  25.90             SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
                CHAR EJECT AIR  72.00              GASIFIER OUT    0.00                WEIGHT FRACTION
         TOTAL AIR TO GASIFIER 962.90               CYCLONE OUT   37.36
                 SEC COMB AIR 4331.50                                                   HYDROGEN   .007308
                                                          MAKE                   CARBON MONOXIDE   .142609
                  NATURAL GAS  LB/HR         GASIFIER    GAS ANALYSIS   CYCLONE          METHANE   .007086
                                               OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .001882
                     GASIFIER  16.50                                                    ETHYLENE   .007234
                     SEC COMB 127.00            10.00     HYDROGEN      9.90           ACETYLENE   .002879
                                                14.40  CARBON MONOXIDE 13.80    HYDROGEN SULFIDE  0.000000
                                                  .60      METHANE      1.20      CARBON DIOXIDE   .168887
                   STEAM FLOW  LB/HR             0.00      ETHANE        .15            NITROGEN   .647942
                                                  .70     ETHYLENE       .70        OXYGEN+ARGON   .014394
                     GASIFIER    0.00            0.00    ACETYLENE       .30
                        DEVOL    0.00            0.00 HYDROGEN SULFIDE  0.00
                                                 9.80 CARBON DIOXIDE   10.40
                                                63.70     NITROGEN     62.70
                 OXYGEN ADDED  LB/HR              .90   OXYGEN+ARGON    1.00
                                 0.00

                                               100.10                 100.15
                     SEC COMB PERCENT
                    TOTAL AIR  114.50                                      MATERIAL BALANCE

                      BASED ON MEASURED                                     CARBON   HYDROGEN   OXYGEN   NITROGEN
                          COAL RATE                        MEASURED INPUT    198.78     16.75   268.52     729.41

      COAL RATE (WET) LB/HR  316.00   (DRY)  268.60        OUT AT POINT B    168.59     17.19   268.52     757.87
         DRY MAKE GAS LB/HR 1169.66
         WET MAKE GAS LB/HR 1259.58                        OUT AT POINT C    186.89
      TOTAL WATER FED LB/HR   57.03
  WATER FROM REACTION LB/HR   32.89

          PERCENT THEO. AIR   35.83
     HEATING VALUE BTU/DSCF  107.25

                                     SOLIDS ANALYSIS

                     TEST 33  CHAR RECYCLE-- V.M. 7.1%    F.C. 67.4%   ASH 25.5%
                             CYCLONE OUT---- V.M. 19.2%   F.C. 54.6%   ASH 26.2%
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        TEST 34
                  03-04-76 1020 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE ONLY
                             Input NO AUXILIARY NATURAL GAS  WESTERN COAL      Calculations
                                                                        GASIFIER-DEVOLATILIZER
           COAL RATE  LB/HR               TEMPERATURES, F            TOTAL BTU/HR IN COAL 3660202.00
                                                                   TOTAL BTU/HR IN NAT. GAS        0.00
             GASIFIER  364.00            GASIFIER OUT 1440.00        TOTAL BTU/HR IN FUEL 3660202.00
                DEVOL    0.00                DEVOL IN 1300.00          BTU/HR IN MAKE GAS 1513682.15
                                            DEVOL MID 1200.00     HYDROGEN IN GAS LB/HR       10.55
                                            DEVOL OUT 1110.00       CARBON IN GAS LB/HR      130.94
            AIR FLOWS  LB/HR              CYC SEP OUT  840.00         MAKE GAS MOL. WT.       27.53
                                         GASIFIER AIR  855.00       COLD-GAS CONV. EFF.       41.36

         GASIFIER AIR  770.00            SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
        TRANSPORT AIR   25.20            GASIFIER OUT    0.00               WEIGHT FRACTION
       CHAR EJECT AIR   72.00              CYCLONE OUT  49.46
 TOTAL AIR TO GASIFIER  867.20                                                 HYDROGEN   .006901
         SEC COMB AIR 4267.47                                          CARBON MONOXIDE   .142385
                                               MAKE                            METHANE   .006974
          NATURAL GAS  LB/HR     GASIFIER   GAS ANALYSIS   CYCLONE               ETHANE   .001852
                                  OUTLET  VOL PERCENT DRY  OUTLET              ETHYLENE   .006102
             GASIFIER    0.00                                                 ACETYLENE   .002833
             SEC COMB  117.00       9.30     HYDROGEN         9.50      HYDROGEN SULFIDE 0.000000
                                   14.50  CARBON MONOXIDE 14.00          CARBON DIOXIDE   .196578
                                     .90      METHANE         1.20              NITROGEN   .622426
           STEAM FLOW  LB/HR        0.00      ETHANE           .15          OXYGEN+ARGON   .014166
                                     .60      ETHYLENE         .60
             GASIFIER    0.00       0.00     ACETYLENE         .30
                DEVOL    0.00       0.00 HYDROGEN SULFIDE    0.00
                                   11.40 CARBON DIOXIDE     12.30
                                   62.40     NITROGEN       61.20
         OXYGEN ADDED  LB/HR        1.00   OXYGEN+ARGON      1.00
                         0.00
                                  100.10                   100.25
             SEC COMB PERCENT                                          MATERIAL BALANCE
            TOTAL AIR  117.00

              BASED ON MEASURED                                   CARBON   HYDROGEN    OXYGEN   NITROGEN
                  COAL RATE                      MEASURED INPUT   214.72      14.54    253.17     657.52

   COAL RATE (WET) LB/HR  364.00   (DRY)  309.40  OUT AT POINT B   171.75      14.13    253.17     653.86
      DRY MAKE GAS LB/HR 1050.50
      WET MAKE GAS LB/HR 1133.08                  OUT AT POINT C   190.44
   TOTAL WATER FED LB/HR   63.27
 WATER FROM REACTION LB/HR 19.31

      PERCENT THEO. AIR    31.44
  HEATING VALUE BTU/DSCF  104.98

                               SOLIDS ANALYSIS

             TEST 34 CYCLONE OUT-- V.M. 15.4%   F.C. 57.9%   ASH 26.7%
                      TARS 8.46 LB/HR
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                TEST 35
                          03-04-76 1115 HRS  50-50 SPLIT ON COAL FLOW BETWEEN NORTH HORIZ. GASIFIER BURNER
                                       InputAND TOP OF DEVOLATILIZER   WESTERN COAL      Calculations

                                                                                     GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                  TEMPERATURES, F               TOTAL BTU/HR IN COAL 3599869.00
                                                                              TOTAL BTU/HR IN NAT. GAS  671688.00
                     GASIFIER  179.00               GASIFIER OUT 1710.00          TOTAL BTU/HR IN FUEL 4271557.00
                        DEVOL  179.00                   DEVOL IN 1420.00            BTU/HR IN MAKE GAS 1524991.62
                                                       DEVOL MID 1200.00        HYDROGEN IN GAS LB/HR       11.67
                                                       DEVOL OUT 1100.00           CARBON IN GAS LB/HR     127.95
                    AIR FLOWS  LB/HR                 CYC SEP OUT  830.00             MAKE GAS MOL. WT.      26.27
                                                    GASIFIER AIR  830.00           COLD-GAS CONV. EFF.      35.70
                 GASIFIER AIR  840.00
                TRANSPORT AIR   23.40              SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
               CHAR EJECT AIR   72.00               GASIFIER OUT    0.00                WEIGHT FRACTION
         TOTAL AIR TO GASIFIER 935.40                CYCLONE OUT   63.98
                 SEC COMB AIR 4330.19                                                     HYDROGEN   .009669
                                                           MAKE                    CARBON MONOXIDE   .160950
                  NATURAL GAS  LB/HR         GASIFIER     GAS ANALYSIS   CYCLONE           METHANE   .003045
                                                OUTLET  VOL PERCENT DRY  OUTLET             ETHANE 0.000000
                     GASIFIER   28.50                                                     ETHYLENE 0.000000
                     SEC COMB  112.00            -0.00     HYDROGEN     12.70            ACETYLENE 0.000000
                                                 -0.00  CARBON MONOXIDE 15.10     HYDROGEN SULFIDE 0.000000
                                                 -0.00      METHANE       .50       CARBON DIOXIDE   .157448
                   STEAM FLOW  LB/HR             -0.00      ETHANE       0.00             NITROGEN   .655526
                                                 -0.00     ETHYLENE      0.00         OXYGEN+ARGON   .013362
                     GASIFIER    0.00            -0.00    ACETYLENE      0.00
                        DEVOL    0.00            -0.00 HYDROGEN SULFIDE  0.00
                                                 -0.00 CARBON DIOXIDE    9.40
                                                 -0.00     NITROGEN     61.50
                 OXYGEN ADDED  LB/HR             -0.00   OXYGEN+ARGON     .90
                                 0.00

                                                  0.00                 100.10
                     SEC COMB PERCENT
                    TOTAL AIR  117.00                                       MATERIAL BALANCE

                      BASED ON MEASURED                                      CARBON   HYDROGEN    OXYGEN   NITROGEN
                          COAL RATE                         MEASURED INPUT    232.56     21.43     268.14    708.97

     COAL RATE (WET) LB/HR  358.00    (DRY)  304.30         OUT AT POINT B    180.73     18.13     268.14    733.69
        DRY MAKE GAS LB/HR 1119.25
        WET MAKE GAS LB/HR 1223.71                          OUT AT POINT C    190.16
     TOTAL WATER FED LB/HR   63.05
 WATER FROM REACTION LB/HR   41.41

         PERCENT THEO. AIR   29.06
    HEATING VALUE BTU/DSCF   94.96

                                     SOLIDS ANALYSIS

                     TEST 35 CYCLONE OUT-- V.M. 16.4%   F.C. 57.0%   ASH 26.6%
                              TARS 3.97 LB/HR
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              TEST 36
                        03-04-76 1320 HRS  ALL COAL TO DEVOLATILIZER WITH CHAR RECYCLE
                                   Input WESTERN COAL                           Calculations

                                                                            GASIFIER-DEVOLATILIZER
                 COAL RATE  LB/HR               TEMPERATURES, F              TOTAL BTU/HR IN COAL 2192099.00
                                                                        TOTAL BTU/HR IN NAT. GAS  624552.00
                   GASIFIER    0.00           GASIFIER OUT 2000.00           TOTAL BTU/HR IN FUEL 2816651.00
                      DEVOL  218.00               DEVOL IN 1800.00             BTU/HR IN MAKE GAS 1149172.40
                                                 DEVOL MID 1450.00          HYDROGEN IN GAS LB/HR       7.15
                                                 DEVOL OUT 1110.00            CARBON IN GAS LB/HR     113.03
                  AIR FLOWS  LB/HR             CYC SEP OUT  880.00              MAKE GAS MOL. WT.      27.67
                                              GASIFIER AIR  835.00            COLD-GAS CONV. EFF.      40.80
               GASIFIER AIR  845.00
              TRANSPORT AIR    0.00          SOLIDS LOADING LB/HR                  MAKE GAS ANALYSIS
             CHAR EJECT AIR   73.00           GASIFIER OUT    0.00                  WEIGHT FRACTION
      TOTAL AIR TO GASIFIER  918.00            CYCLONE OUT   44.09
               SEC COMB AIR 4219.99                                              HYDROGEN   .005493
                                                  MAKE                    CARBON MONOXIDE   .137622
                NATURAL GAS  LB/HR       GASIFIER   GAS ANALYSIS   CYCLONE        METHANE   .002891
                                          OUTLET  VOL PERCENT DRY  OUTLET          ETHANE  0.000000
                   GASIFIER   26.50                                              ETHYLENE   .003036
                   SEC COMB  143.00        -0.00     HYDROGEN       7.60        ACETYLENE  0.000000
                                           -0.00  CARBON MONOXIDE 13.60  HYDROGEN SULFIDE  0.000000
                                           -0.00      METHANE        .50   CARBON DIOXIDE   .155837
                 STEAM FLOW  LB/HR         -0.00      ETHANE        0.00         NITROGEN   .681026
                                           -0.00     ETHYLENE        .30     OXYGEN+ARGON   .014095
                   GASIFIER    0.00        -0.00     ACETYLENE      0.00
                      DEVOL    0.00        -0.00 HYDROGEN SULFIDE   0.00
                                           -0.00 CARBON DIOXIDE     9.80
                                           -0.00     NITROGEN      67.30
               OXYGEN ADDED  LB/HR         -0.00   OXYGEN+ARGON     1.00
                               0.00
                                            0.00                  100.10
                   SEC COMB PERCENT
                  TOTAL AIR  112.00                                     MATERIAL BALANCE

                   BASED ON MEASURED                                CARBON   HYDROGEN   OXYGEN   NITROGEN
                       COAL RATE                   MEASURED INPUT   148.47     15.33    244.11     694.76

    COAL RATE (WET) LB/HR  218.00   (DRY)  185.30  OUT AT POINT B   149.41     13.09    244.11     732.73
       DRY MAKE GAS LB/HR 1075.92
       WET MAKE GAS LB/HR 1159.78                  OUT AT POINT C   157.96
     TOTAL WATER FED LB/HR   41.88
 WATER FROM REACTION LB/HR   41.97

         PERCENT THEO. AIR   43.25
    HEATING VALUE BTU/DSCF   78.40

                               SOLIDS ANALYSIS

                  TEST 36 CYCLONE OUT-- V.M. 27.6%   F.C. 50.6%   ASH 21.8%
                          TARS 4.34 LB/HR
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                TEST 37
                          03-04-76 1410 HRS ALL COAL TO DEVOLATILIZER   NO CHAR RECYCLE
                                      Input WESTERN COAL   LOW VOLATILE FURNACE OXYGEN VARYING FROM 2.0-5.6 AVG USED
                                                                                     Calculations
                                                                                   GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                TEMPERATURES, F                TOTAL BTU/HR IN COAL 2312765.00
                                                                              TOTAL BTU/HR IN NAT. GAS 1555488.00
                     GASIFIER    0.00            GASIFIER OUT 2100.00             TOTAL BTU/HR IN FUEL 3868253.00
                        DEVOL  230.00                DEVOL IN 1640.00               BTU/HR IN MAKE GAS  881900.66
                                                    DEVOL MID 1340.00            HYDROGEN IN GAS LB/HR       8.45
                                                    DEVOL OUT 1030.00              CARBON IN GAS LB/HR      59.31
                    AIR FLOWS  LB/HR              CYC SEP OUT  790.00                MAKE GAS MOL. WT.      25.91
                                                 GASIFIER AIR  820.00              COLD-GAS CONV. EFF.      22.80
                 GASIFIER AIR  580.00
                TRANSPORT AIR    0.00           SOLIDS LOADING LB/HR                  MAKE GAS ANALYSIS
               CHAR EJECT AIR   73.00            GASIFIER OUT    0.00                  WEIGHT FRACTION
        TOTAL AIR TO GASIFIER  653.00             CYCLONE OUT    9.59
                 SEC COMB AIR 4219.37                                                  HYDROGEN    .009803
                                                         MAKE                   CARBON MONOXIDE    .094014
                  NATURAL GAS  LB/HR       GASIFIER    GAS ANALYSIS   CYCLONE           METHANE    .003087
                                             OUTLET  VOL PERCENT DRY  OUTLET             ETHANE   0.000000
                     GASIFIER   66.00                                                  ETHYLENE    .003242
                     SEC COMB  100.00          -0.00     HYDROGEN      12.70          ACETYLENE   0.000000
                                               -0.00  CARBON MONOXIDE   8.70   HYDROGEN SULFIDE   0.000000
                                               -0.00      METHANE        .50     CARBON DIOXIDE    .122265
                   STEAM FLOW  LB/HR           -0.00      ETHANE        0.00           NITROGEN    .751032
                                               -0.00     ETHYLENE        .30       OXYGEN+ARGON    .016557
                     GASIFIER    0.00          -0.00    ACETYLENE       0.00
                        DEVOL    0.00          -0.00 HYDROGEN SULFIDE   0.00
                                               -0.00 CARBON DIOXIDE     7.20
                                               -0.00     NITROGEN      69.50
                 OXYGEN ADDED  LB/HR           -0.00   OXYGEN+ARGON     1.10
                                 0.00
                                                0.00                  100.00
                     SEC COMB PERCENT
                       TOTAL AIR  121.00                                            MATERIAL BALANCE

                     BASED ON MEASURED                                           CARBON   HYDROGEN    OXYGEN   NITROGEN
                         COAL RATE                           MEASURED INPUT      185.18      25.69    184.34     494.77

      COAL RATE (WET) LB/HR  230.00   (DRY)  195.50          OUT AT POINT B       67.23      18.09    184.34     575.37
         DRY MAKE GAS LB/HR  766.11
         WET MAKE GAS LB/HR  891.41                          OUT AT POINT C      148.45
      TOTAL WATER FED LB/HR   41.03
  WATER FROM REACTION LB/HR   84.27

         PERCENT THEO. AIR    22.40
      HEATING VALUE BTU/DSCF  79.20

                                    SOLIDS ANALYSIS

                    TEST 37 CYCLONE OUT-- V.M. 29.5%   F.C. 57.5%   ASH 13.0%
                     CYCLONE OUT AFTER TOLUENE EXT.  V.M. 20.4%   F.C. 61.0%   ASH 18.6%
                             TARS 0.90 LB/HR
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          TEST 38
                03-11-76 1047 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE
                                  NO NATURAL GAS TO GASIFIER  WESTERN COAL
                                Input                                            Calculations
                                                                          GASIFIER-DEVOLATILIZER
            COAL RATE  LB/HR                TEMPERATURES, F              TOTAL BTU/HR IN COAL 2865817.50
                                                                     TOTAL BTU/HR IN NAT. GAS       0.00
              GASIFIER 285.00             GASIFIER OUT 1820.00           TOTAL BTU/HR IN FUEL 2865817.50
                 DEVOL   0.00                 DEVOL IN 1510.00             BTU/HR IN MAKE GAS 1458487.22
                                             DEVOL MID 1420.00         HYDROGEN IN GAS LB/HR      10.57
                                             DEVOL OUT 1290.00           CARBON IN GAS LB/HR     140.53
              AIR FLOWS  LB/HR             CYC SEP OUT  960.00             MAKE GAS MOL. WT.      27.38
                                          GASIFIER AIR  863.00           COLD-GAS CONV. EFF.      50.89
           GASIFIER AIR  860.00
          TRANSPORT AIR   32.40          SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
         CHAR EJECT AIR   72.00           GASIFIER OUT   75.28                WEIGHT FRACTION
   TOTAL AIR TO GASIFIER 964.40            CYCLONE OUT   13.32
           SEC COMB AIR 4411.39                                                HYDROGEN   .008107
                                                    MAKE                CARBON MONOXIDE   .144177
            NATURAL GAS  LB/HR        GASIFIER    GAS ANALYSIS   CYCLONE         METHANE   .001753
                                        OUTLET  VOL PERCENT DRY  OUTLET           ETHANE   .001862
              GASIFIER   0.00                                                   ETHYLENE   .001534
              SEC COMB 142.00            10.40     HYDROGEN      11.10         ACETYLENE   .001424
                                         13.30  CARBON MONOXIDE 14.10   HYDROGEN SULFIDE  0.000000
                                           .30      METHANE        .30    CARBON DIOXIDE   .208889
            STEAM FLOW  LB/HR             0.00      ETHANE         .15          NITROGEN   .619655
                                           .30     ETHYLENE        .15     OXYGEN+ARGON   .012818
              GASIFIER   0.00             0.00     ACETYLENE       .15
                 DEVOL   0.00             0.00 HYDROGEN SULFIDE  0.00
                                         11.40 CARBON DIOXIDE   13.00
                                         63.30     NITROGEN     60.60
           OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON      .90
                         0.00
                                         99.90                  100.45
              SEC COMB PERCENT
             TOTAL AIR  121.00                                         MATERIAL BALANCE

                  BASED ON MEASURED                                 CARBON    HYDROGEN    OXYGEN   NITROGEN
                      COAL RATE                    MEASURED INPUT   168.12       11.39    264.44     730.30

  COAL RATE (WET) LB/HR  285.00   (DRY)  242.25    OUT AT POINT B   151.52       10.29    264.44     712.32
     DRY MAKE GAS LB/HR 1149.54
     WET MAKE GAS LB/HR 1195.94                    OUT AT POINT C   162.35
    TOTAL WATER FED LB/HR  52.39
WATER FROM REACTION LB/HR  -5.99

        PERCENT THEO. AIR  44.65
     HEATING VALUE BTU/DSCF  91.87

                           SOLIDS ANALYSIS
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               TEST 39
                         03-18-76 1045 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE
                                     Input NO NATURAL GAS TO GASIFIER  WESTERN COAL      Calculations

                                                                                 GASIFIER-DEVOLATILIZFR
                  COAL RATE  LB/HR                 TEMPERATURES, F            TOTAL BTU/HR IN COAL 4052366.50
                                                                          TOTAL BTU/HR IN NAT. GAS       0.00
                    GASIFIER  403.00              GASIFIER OUT 1760.00        TOTAL BTU/HR IN FUEL 4052366.50
                       DEVOL    0.00                  DEVOL IN 1610.00          BTU/HR IN MAKE GAS 1914704.89
                                                     DEVOL MID 1540.00       HYDROGEN IN GAS LB/HR      13.60
                                                     DEVOL OUT 1430.00         CARBON IN GAS LB/HR     163.13
                   AIR FLOWS  LB/HR               CYC SEP OUT  990.00            MAKE GAS MOL. WT.      26.73
                                                  GASIFIER AIR  880.00         COLD-GAS CONV. EFF.      47.25
                GASIFIER AIR  850.00
               TRANSPORT AIR   23.00             SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
              CHAR EJECT AIR   70.00              GASIFIER OUT    0.00              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER  943.00               CYCLONE OUT   33.38
                SEC COMB AIR 4333.83                                                      HYDROGEN   .009504
                                                        MAKE                       CARBON MONOXIDE   .184397
                 NATURAL GAS  LB/HR         GASIFIER   GAS ANALYSIS   CYCLONE                  METHANE   .005388
                                              OUTLET  VOL PERCENT DRY  OUTLET                   ETHANE   .001908
                    GASIFIER    0.00                                                        ETHYLENE   .003143
                    SEC COMB  121.00             12.40    HYDROGEN      12.70              ACETYLENE   .001459
                                                 17.50 CARBON MONOXIDE 17.60        HYDROGEN SULFIDE 0.000000
                                                   .40     METHANE        .90         CARBON DIOXIDE   .200861
                  STEAM FLOW  LB/HR               0.00      ETHANE        .15               NITROGEN   .580430
                                                   .30     ETHYLENE       .30           OXYGEN+ARGON   .013134
                    GASIFIER    0.00               .30    ACETYLENE       .15
                       DEVOL    0.00              0.00 HYDROGEN SULFIDE  0.00
                                                 13.50 CARBON DIOXIDE   12.20
                                                 54.80    NITROGEN      55.40
                OXYGEN ADDED  LB/HR                .80  OXYGEN+ARGON      .90
                                0.00
                                              100.00                  100.30
                    SEC COMB PERCENT
                   TOTAL AIR  112.00                                              MATERIAL BALANCE

                     BASED ON MEASURED                                            CARBON   HYDROGEN   OXYGEN   NITROGEN
                         COAL RATE                        MEASURED INPUT          237.73      16.10   276.32     715.05

     COAL RATE (WET) LB/HR  403.00   (DRY)  342.55        OUT AT POINT B          190.67      12.65   276.32     672.65
        DRY MAKE GAS LB/HR 1158.88
        WET MAKE GAS LB/HR 1211.43                        OUT AT POINT C          210.40
     TOTAL WATER FED LB/HR   69.88
 WATER FROM REACTION LB/HR  -17.33

         PERCENT THEO. AIR   30.88
    HEATING VALUE BTU/DSCF  116.84

                                   SOLIDS ANALYSIS

                    TEST 39 CYCLONE OUT-- C 68.9%   H 1.2%   N 0.4%   S 1.4%   ASH 29.0%   O 0.0%
                             TARS 2.30 LB/HR
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TEST 40
           03-18-76 1130 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE
                       Input NO NATURAL GAS TO GASIFIER  WESTERN COAL  SEC. COMB. OXY VARYING
                                                                            Calculations
                                                                    GASIFIER-DEVOLATILIZER
     COAL RATE  LB/HR               TEMPERATURES, F              TOTAL BTU/HR IN COAL 3921645.00
                                                             TOTAL BTU/HR IN NAT. GAS       0.00
       GASIFIER  390.00           GASIFIER OUT 1700.00           TOTAL BTU/HR IN FUEL 3921645.00
          DEVOL    0.00               DEVOL IN 1570.00             BTU/HR IN MAKE GAS 1584781.68
                                     DEVOL MID 1490.00         HYDROGEN IN GAS LB/HR      11.22
                                     DEVOL OUT 1395.00           CARBON IN GAS LB/HR     156.44
      AIR FLOWS  LB/HR             CYC SEP OUT  970.00              MAKE GAS MOL. WT.      27.58
                                  GASIFIER AIR  865.00           COLD-GAS CONV. EFF.      40.41
     GASIFIER AIR  855.00
    TRANSPORT AIR   23.00        SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
   CHAR EJECT AIR   70.00         GASIFIER OUT    0.00                WEIGHT FRACTION
TOTAL AIR TO GASIFIER  948.00      CYCLONE OUT   50.99
     SEC COMB AIR 4382.30                                                  HYDROGEN   .008631
                                           MAKE                     CARBON MONOXIDE   .154343
     NATURAL GAS  LB/HR          GASIFIER   GAS ANALYSIS   CYCLONE          METHANE   .000870
                                  OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .001850
       GASIFIER    0.00                                                    ETHYLENE   .003046
       SEC COMB  100.00            11.30     HYDROGEN      11.90          ACETYLENE   .002829
                                   16.20  CARBON MONOXIDE  15.20  HYDROGEN SULFIDE   0.000000
                                     .30      METHANE        .15     CARBON DIOXIDE   .244134
     STEAM FLOW  LB/HR              0.00      ETHANE         .15           NITROGEN   .573200
                                     .30      ETHYLENE       .30       OXYGEN+ARGON   .011315
       GASIFIER    0.00             0.00     ACETYLENE       .30
          DEVOL    0.00             0.00 HYDROGEN SULFIDE   0.00
                                   11.80 CARBON DIOXIDE    15.30
                                   59.30     NITROGEN      56.45
     OXYGEN ADDED  LB/HR             .90   OXYGEN+ARGON      .80
                   0.00
                                  100.10                  100.55
       SEC COMB PERCENT
      TOTAL AIR  125.00                                      MATERIAL BALANCE

        BASED ON MEASURED                                    CARBON   HYDROGEN   OXYGEN   NITROGEN
           COAL RATE                          MEASURED INPUT  230.06     15.58   275.63     718.72

  COAL RATE (WET) LB/HR  390.00  (DRY)  331.50   OUT AT POINT B  198.51      9.12   275.63     655.18
     DRY MAKE GAS LB/HR 1143.03
     WET MAKE GAS LB/HR 1178.79                  OUT AT POINT C  202.73
   TOTAL WATER FED LB/HR   67.98
WATER FROM REACTION LB/HR  -32.22

       PERCENT THEO. AIR   32.08
    HEATING VALUE BTU/DSCF  101.17

                            SOLIDS ANALYSIS

              TEST 40   TARS 2.96 LB/HR
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                TEST 41
                          03-18-76 1250 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER COAL NOZZLE
                                      Input NO NAT. GAS TO GASIFIER  WESTERN COAL       Calculations

                                                                                      GASIFIER-DEVOLATILIZER
                   COAL RATE  LB/HR                    TEMPERATURES, F               TOTAL BTU/HR IN COAL 4122755.00
                                                                                 TOTAL BTU/HR IN NAT. GAS       0.00
                     GASIFIER  410.00                GASIFIER OUT 1800.00            TOTAL BTU/HR IN FUEL 4122755.00
                        DEVOL    0.00                    DEVOL IN 1650.00              BTU/HR IN MAKE GAS 1437166.90
                                                        DEVOL MID 1560.00          HYDROGEN IN GAS LB/HR       10.39
                                                        DEVOL OUT 1450.00            CARBON IN GAS LB/HR      136.73
                  AIR FLOWS  LB/HR                    CYC SEP OUT 1000.00              MAKE GAS MOL. WT.       26.93
                                                     GASIFIER AIR  830.00            COLD-GAS CONV. EFF.       34.86
                 GASIFIER AIR  840.00
                TRANSPORT AIR   23.00               SOLIDS LOADING LB/HR                 MAKE GAS ANALYSIS
              CHAR EJECT AIR   72.00                 GASIFIER OUT    0.00                 WEIGHT FRACTION
     TOTAL AIR TO GASIFIER  935.00                    CYCLONE OUT   49.26
                 SEC COMB AIR 4383.39                                                       HYDROGEN   .008874
                                                         MAKE                        CARBON MONOXIDE   .162186
                 NATURAL GAS  LB/HR           GASIFIER    GAS ANALYSIS   CYCLONE             METHANE   .001782
                                                OUTLET  VOL PERCENT DRY  OUTLET               ETHANE  0.000000
                    GASIFIER    0.00                                                        ETHYLENE  0.000000
                    SEC COMB   98.00               11.40      HYDROGEN      11.95            ACETYLENE  0.000000
                                                   15.60  CARBON MONOXIDE 15.60      HYDROGEN SULFIDE  0.000000
                                                    0.00       METHANE        .30       CARBON DIOXIDE   .189514
                  STEAM FLOW  LB/HR                 0.00       ETHANE       0.00            NITROGEN   .621714
                                                    0.00      ETHYLENE      0.00        OXYGEN+ARGON   .015929
                    GASIFIER    0.00                0.00     ACETYLENE      0.00
                       DEVOL    0.00                0.00 HYDROGEN SULFIDE  0.00
                                                   11.60 CARBON DIOXIDE   11.60
                                                   60.60     NITROGEN     59.80
                 OXYGEN ADDED  LB/HR                 .80   OXYGEN+ARGON    1.10
                                0.00
                                                  100.00                 100.35
                    SEC COMB PERCENT
                   TOTAL AIR  129.00                                                MATERIAL BALANCE

                       BASED ON MEASURED                                          CARBON   HYDROGEN   OXYGEN   NITROGEN
                           COAL RATE                          MEASURED INPUT      241.86      16.38   275.47     709.06

        COAL RATE (WET) LB/HR  410.00   (DRY)  348.50         OUT AT POINT B      177.38      14.09   275.47     693.10
           DRY MAKE GAS LB/HR 1114.82
           WET MAKE GAS LB/HR 1206.12                         OUT AT POINT C      194.30
        TOTAL WATER FED LB/HR   70.85
  WATER FROM REACTION LB/HR   20.45

            PERCENT THEO. AIR   30.09
       HEATING VALUE BTU/DSCF   92.11

                                             SOLIDS ANALYSIS

                          TEST 41  TARS 0.99 LB/HR
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               TEST 42
                          03-18-76 1430 HRS  ALL COAL TO VERTICAL BOTTOM GASIFIER NOZZLE
                                         NO NAT. GAS TO GASIFIER  WESTERN COAL
                                    Input                                         Calculations

                                                                                GASIFIER-DEVOLATILIZER
                COAL RATE  LB/HR                   TEMPERATURES, F          TOTAL BTU/HR IN COAL 3710479.50
                                                                         TOTAL BTU/HR IN NAT. GAS          0.00
                  GASIFIER  369.00                GASIFIER OUT 1810.00      TOTAL BTU/HR IN FUEL 3710479.50
                     DEVOL    0.00                    DEVOL IN 1680.00        BTU/HR IN MAKE GAS 1796881.93
                                                     DEVOL MID 1600.00     HYDROGEN IN GAS LB/HR         13.21
                                                     DEVOL OUT 1500.00       CARBON IN GAS LB/HR        156.01
                 AIR FLOWS  LB/HR                  CYC SEP OUT 1125.00         MAKE GAS MOL. WT.         26.58
                                                  GASIFIER AIR  845.00       COLD-GAS CONV. EFF.         48.43
              GASIFIER AIR  854.00
             TRANSPORT AIR   23.00               SOLIDS LOADING LB/HR              MAKE GAS ANALYSIS
            CHAR EJECT AIR   72.00                GASIFIER OUT    0.00              WEIGHT FRACTION
       TOTAL AIR TO GASIFIER 949.00                CYCLONE OUT   34.97
             SEC COMB AIR 4383.39                                                   HYDROGEN   .010309
                                                        MAKE                CARBON MONOXIDE   .178035
               NATURAL GAS  LB/HR            GASIFIER   GAS ANALYSIS   CYCLONE          METHANE   .001806
                                               OUTLET  VOL PERCENT DRY  OUTLET          ETHANE   .001919
                  GASIFIER    0.00                                                  ETHYLENE   .001580
                  SEC COMB  107.00              13.10      HYDROGEN      13.70         ACETYLENE   .001467
                                                17.30  CARBON MONOXIDE  16.90  HYDROGEN SULFIDE  0.000000
                                                  .30       METHANE        .30    CARBON DIOXIDE   .201964
                STEAM FLOW  LB/HR                0.00       ETHANE         .15          NITROGEN   .589939
                                                 0.00       ETHYLENE       .15     OXYGEN+ARGON   .013206
                  GASIFIER    0.00               0.00      ACETYLENE       .15
                     DEVOL    0.00               0.00 HYDROGEN SULFIDE   0.00
                                                11.50 CARBON DIOXIDE    12.20
                                                57.00     NITROGEN      56.00
              OXYGEN ADDED  LB/HR                 .80   OXYGEN+ARGON      .90
                              0.00
                                               100.00                  100.45
                  SEC COMB PERCENT
                 TOTAL AIR  126.00                                               MATERIAL BALANCE

                    BASED ON MEASURED                                        CARBON   HYDROGEN   OXYGEN   NITROGEN
                        COAL RATE                            MEASURED INPUT   217.67     14.74    272.86    719.32

      COAL RATE (WET) LB/HR  369.00    (DRY)  313.65         OUT AT POINT B   184.86     12.38    272.86    681.80
         DRY MAKE GAS LB/HR 1155.71
         WET MAKE GAS LB/HR 1203.89                          OUT AT POINT C   191.18
      TOTAL WATER FED LB/HR   64.84
 WATER FROM REACTION LB/HR  -16.66

         PERCENT THEO. AIR   33.94
    HEATING VALUE BTU/DSCF  109.34

                                         SOLIDS ANALYSIS

                    TEST 42  TARS 0.98 LB/HR
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           TEST 43
                    04-20-76 1305 HRS  ALL COAL TO VERTICAL GASIFIER COAL NOZZLE  NO NATURAL GAS TO
                                  Input GASIFIER  WESTERN COAL                      Calculations

                                                                              GASIFIER-DEVOLATILIZER
              COAL RATE  LB/HR               TEMPERATURES, F              TOTAL BTU/HR IN COAL 3921645.00
                                                                      TOTAL BTU/HR IN NAT. GAS         0.00
                GASIFIER  390.00           GASIFIER OUT 1720.00           TOTAL BTU/HR IN FUEL 3921645.00
                   DEVOL    0.00               DEVOL IN 1600.00             BTU/HR IN MAKE GAS 1768856.79
                                              DEVOL MID 1530.00          HYDROGEN IN GAS LB/HR        13.04
                                              DEVOL OUT 1440.00            CARBON IN GAS LB/HR       148.44
               AIR FLOWS  LB/HR             CYC SEP OUT 1000.00              MAKE GAS MOL. WT.        26.86
                                           GASIFIER AIR  860.00            COLD-GAS CONV. EFF.        45.10
            GASIFIER AIR  853.00
           TRANSPORT AIR   22.50          SOLIDS LOADING LB/HR                MAKE GAS ANALYSIS
          CHAR EJECT AIR   72.00           GASIFIER OUT    0.00                 WEIGHT FRACTION
    TOTAL AIR TO GASIFIER 947.50            CYCLONE OUT   34.06
            SEC COMR AIR 4120.20                                                   HYDROGEN   .008861
                                                 MAKE                      CARBON MONOXIDE   .157415
             NATURAL GAS  LB/HR       GASIFIER   GAS ANALYSIS   CYCLONE           METHANE   .005361
                                        OUTLET  VOL PERCENT DRY  OUTLET            ETHANE   .003798
                GASIFIER    0.00                                                 ETHYLENE   .001564
                SEC COMB  110.00         11.10     HYDROGEN      11.90          ACETYLENE   .002904
                                         15.60  CARBON MONOXIDE  15.10   HYDROGEN SULFIDE  0.000000
                                           .50      METHANE        .90     CARBON DIOXIDE   .196582
              STEAM FLOW  LB/HR            .30      ETHANE         .30           NITROGEN   .610894
                                          0.00     ETHYLENE        .15      OXYGEN+ARGON   .013068
                GASIFIER    0.00           .30     ACETYLENE       .30
                   DEVOL    0.00           .30 HYDROGEN SULFIDE   0.00
                                         11.60 CARBON DIOXIDE    12.00
                                         59.80     NITROGEN      58.60
            OXYGEN ADDED  LB/HR            .90   OXYGEN+ARGON      .90
                            0.00
                                        100.40                  100.15
                SEC COMR PERCENT
               TOTAL AIR  118.00                                           MATERIAL BALANCE

                 BASED ON MEASURED                                   CARBON   HYDROGEN   OXYGEN   NITROGEN
                    COAL RATE                      MEASURED INPUT    230.06      15.58   275.51     718.35

        COAL RATE (WET) LB/HR  390.00   (DRY)  331.50   OUT AT POINT B    176.55      14.86   275.51     704.36
           DRY MAKE GAS LB/HR 1153.00
           WET MAKE GAS LB/HR 1228.40                   OUT AT POINT C    192.17
        TOTAL WATER FED LB/HR   67.98
    WATER FROM REACTION LB/HR    7.42

          PERCENT THEO. AIR   32.06
       HEATING VALUE BTU/DSCF  108.71

                                  SOLIDS ANALYSIS

                  TEST 43 CYCLONE OUT-- V.M. 10.5%   F.C. 62.3%   ASH 27.2%
                          CYCLONE OUT-- C 70.3%   H 1.3%   N 0.6%   S 1.0%   ASH 27.2%   O 0.0%
                           TARS 1.91 LB/HR
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APPENDIX B ENERGY BALANCE DATA

		STEADY STATE HEAT LOSS: $\frac{\text{kg-cal}}{\text{kg. mole of } O_2 \text{ fed}}$			TRANSIENT HEAT LOSS: $\frac{\text{kg-cal}}{\text{kg. mole of } O_2 \text{ fed}}$		TOTAL HEAT LOSS			OVER-ALL HEAT LOSS	AVERAGE HEAT LOSS STEADY STATE	AVERAGE HEAT LOSS TRANSIENT	Calc. T_4 Zero heat Loss °F	Measured T_4 °F
	TEST NO.	Gasifier	Devol.	Cyclones	Gasifier	Devol.	Gasifier	Devol.	Cyclones					
Code 1	1	8928	1036	19,606	24,248	19,052	33,176	20,088	19,606	72,870			3251	900
	2	9553			25,987	20,418	35,540	21,454		76,600			3478	1075
	3	8712			21,371	16,792	30,083	17,827		67,156			3274	1060
	4	7356			23,784	18,687	31,140	19,723		70,468			3303	950
	5	8816			23,842	18,733	32,658	19,769		72,033			3388	915
	6	8909			22,591	17,750	31,500	18,786		69,892			3550	1100
	20	12559			21,499	16,892	34,058	17,928		71,592			3457	1050
	21	9633			22,661	17,805	32,294	18,841		70,741			3285	1080
	22	8712			23,850	18,739	32,562	19,775		71,943			3447	1080
Averages		9242	1036	19,606	23,315	18,319				71,477	29,884	41,634		
Code 2	9	9633			20,416	16,041	30,049	17,077		66,732			3048	930
	10	9633			19,893	15,630	29,526	16,666		65,798			3055	990
	11	9633			22,084	17,351	31,717	18,387		69,710			3143	940
	13	9633			14,870	11,683	24,503	12,719		56,828			2777	1100
	14	9633			22,214	17,454	31,847	18,490		69,943			3070	880
	16	13461			20,458	16,074	33,919	17,110		70,635			3063	905
Averages		10271	1036	19,606	19,989	15,706				66,608	30,913	35,695		
Code 3	7	9635			26,133	20,533	35,768	21,569		76,943			3382	1010
	8	9635			28,795	22,625	38,430	23,661		81,697			3201	850
Averages		9635	1036	19,606	27,464	21,579				79,320	30,277	49,043		
Code 4	27	9890			14,880	11,698	24,778	12,734		57,118			3041	1010
	32	8107			17,734	13,933	25,840	14,969		60,415			2951	990
Averages		8999	1036	19,606	16,307	12,816				58,764	29,641	29,123		
Code 5	24	9218			19,546	15,357	28,764	16,393		64,763			2834	870
	28	9890			18,125	14,241	28,015	15,277		62,848			3040	800
	29	7893			20,475	16,088	28,368	17,124		65,098			3045	905
	35	8829			16,598	13,041	25,427	14,077		59,110			2569	830
Averages		8958	1036	19,606	18,686	14,682				62,968	29,600	33,368		
Code 6	26	9765			23,539	18,495	33,304	19,531		72,441			3110	840
	31	9265			21,756	17,094	31,021	18,130		68,757			2879	820
	36	9875			20,120	15,808	29,995	16,844		66,445			3100	880
Averages		9635	1036	19,606	21,806	17,132				69,215	30,277	38,938		
Code 7	33	9164			14,262	11,206	23,426	12,242		55,274			2755	820
	34	10371			7,874	6,186	18,245	7,222		45,073			2515	840
	38	7224			17,215	13,526	24,439	14,562		58,607			3109	960
	39	8371			8,632	6,782	17,003	7,818		44,427			2563	990
	40	8342			13,677	10,746	22,019	11,782		53,407			2689	970
	42	6141			9,703	7,624	15,844	8,660		44,110			2707	1125
	43	8371			11,324	8,897	19,695	9,933		49,234			2656	1000
Averages		8283	1036	19,606	11,812	9,281				50,016	28,925	21,093		

APPENDIX C MATERIAL BALANCE DATA

		MAXIMUM TEMPERATURE IN GASIFIER T_1, °F			GASIFIER OUTLET TEMPERATURE T_2, °F			DEVOLATIZER OUTLET TEMPERATURE T_3, °F			CYCLONE SEPARATOR OUTLET TEMPERATURE T_4, °F			A [(2)] AIR-FUEL RATIO	ε_p [(3)] by STOICHIOMETRY	S FRACTION of COAL to GASIFIER	Hm MAKE-GAS HEATING VALUE BTU/DSCF
Cyclone Efficiency[(1)]		η_c=.90	η_c=.95		η_c=.90	η_c=.95		η_c=.90	η_c=.95		η_c=.90	η_c=.95					
	TEST NO.	Calculated	Calculated	Measured	Calculated	Calculated	Measured	Calculated	Calculated	Measured	Calculated	Calculated	Measured				
Code 1	1	3350	2646	----	1831	1602	1950	1378	1258	1160	900			.48	.23	1	71.4
	2	3020	2372	----	1882	1640	2200	1476	1354	1460	1075			.47	.38	1	47.2
	3	3814	3144	----	2038	1843	2240	1592	1484	1730	1060			.514	.13	1	76.9
	4	4060	3417	----	2066	1883	2210	1530	1433	1640	950			.537	.08	1	76.9
	5	4810	4481	----	2232	2145	2300	1597	1550	1800	915			.595	-.03	1	76.9
	6	5356	5685	----	2527	2563	2300	1848	1862	1800	1100			.676	-.10	1	66.2
	20	4212	3617	----	2154	1990	2100	1650	1559	1560	1050			.582	.07	1	66.3
	21	3159	2489	----	1866	1643	2090	1496	1375	1600	1080			.448	.31	1	76.1
	22	3737	3737	----	2091	1877	2160	1604	1492	1620	1080			.544	.17	1	61.7
Avg. Diff. between Calc. and Meas.					-96	-262		-22	-86								
Code 2	9	3526	2824	----	2447	1999	2120	1420	1308	1280	930			.457	.19	.5	84.1
	10	3422	2725	----	2337	1984	2200	1455	1341	1320	990			.446	.22	.5	84.9
	11	3379	2679	----	2323	1956	1950	1410	1293	1200	940			.461	.24	.5	76.6
	13	2979	2338	----	2173	1831	2230	1471	1358	1520	1100			.367	.32	.5	98.8
	14	3295	2584	----	2238	1870	2080	1337	1221	1150	880			.439	.25	.5	83.8
	16	3038	2350	----	2124	1754	2010	1316	1198	1340	905			.41[illegible]	.33	.5	77.6
Avg. Diff. between Calc. and Meas.					175	-199		100	-15								
Code 3	7	3147	2467	----	3006	2392	2350	1431	1311	1350	1010			.469	.41	0	46.8
	8	2464	1860	----	2509	1915	2080	1167	1056	1080	850			.362	.60	0	54.0
Avg. Diff. between Calc. and Meas.					542	-62		84	-32								
Code 4	27	3514	2822	----	1746	1692	1930	1467	1364	1400	1010			.439	.19	1	91.1
	32	2876	2225	----	1601	1417	2040	1345	1237	1560	990			.381	.34	1	85.0
Avg. Diff. between Calc. and Meas.					-311	-430		-74	-180								
Code 5	24	3528	2816	----	2213	1894	1860	1347	1243	1100	870			.461	.19	.5	83
	28	3215	2514	----	2100	1771	1950	1329	1220	1270	905			.424	.26	.5	82.2
	29	3296	2572	----	2080	1747	1810	1246	1138	1090	800			.428	.23	.5	84.8
	35	2333	1754	----	1668	1361	1710	1106	1010	1100	830			.291	.47	.5	95.0
Avg. Diff. between Calc. and Meas.					183	-139		117	13								
Code 6	26	2841	2165	----	2512	1950	1860	1216	1103	1100	840			.413	.39	0	62.1
	31	2550	1920	----	2325	1779	2070	1142	1037	1030	820			.351	.45	0	74.5
	36	3177	2473	----	2707	2150	2000	1303	1193	1110	880			.433	.28	0	78.4
Avg. Diff. between Calc. and Meas.					538	-17		140	31								
Code 7	33	3039	2332	----	1439	1274	1480	1209	1105	1090	820			.358	.24	1	107.2
	34	2764	2101	----	1303	1167	1440	1182	1082	1110	840			.314	.26	1	105.0
	38	3604	2902	----	1760	1591	1820	1431	1330	1290	960			.447	.14	1	91.9
	39	2727	2100	----	1426	1290	1760	1305	1260	1430	990			.309	.30	1	116.8
	40	2639	2024	----	1454	1298	1700	1278	1178	1395	970			.321	.35	1	101.2
	42	2945	2311	----	1606	1462	1810	1463	1362	1500	1125			.339	.27	1	109.3
	43	2719	2096	----	1469	1321	1720	1315	1216	1440	1000			.321	.32	1	108.3
Avg. Diff. between Calc. and Meas.					182	-331		-10	-110								

(1) the cyclone separator efficiencies, η_c, give here are assumed values.

(2) ratio of actual air flow to that required to burn the total fuel (coal and natural gas) completely to CO_2, H_2O, and SO_2.

(3) fraction of total input carbon appearing as char in the cyclone separator outlet gas.

Appendix D

DIFFUSION-BASED MATHEMATICAL MODEL OF SUSPENSION GASIFIER

INTRODUCTION AND SUMMARY

To aid in understanding and extrapolating gasification data, it would be extremely valuable to have a mathematical model of its operation. The development of the present model was undertaken in connection with the analysis of data recently obtained on the pilot gasifier at ARC. Time being very limited, the customary preliminary literature review was skipped, and the model was kept as simple as possible.

The main features of the model are:

1. Assumption of reaction rate controlled by gas-phase diffusion of CO_2 and H_2O to the surface of char particles.
2. Recycle of char until each particle is either completely consumed by reaction or else escapes the process by the inefficiency of the separator.
3. Assumption of complete conversion of all O_2 and air to CO_2 and H_2O by reaction with recycled char just prior to coal injection.

The reasons for choosing diffusion rather than chemical kinetic rate control were:

A. It provides a simple model that requires no empirical constants.

B. Since pulverized coal combustion seems to be diffusion controlled, there seems to be reasonable hope that the assumption might be valid.

As it turns out, the diffusion assumption was proven to be wront. Nevertheless, the modeling effort succeeded in achieving some valuable insights, namely:

I. The gasification reaction in suspension gasifiers must be controlled by chemical kinetics. Their performance should, therefore, be strongly dependent upon the temperatures achieved in the gasifier. Thus, heat losses should play an important role in determining make-gas quality with respect to both Btu content and char carryover.

II. The operating characteristics of recycle-gasifier processes — in terms of make-gas heating value versus percent theoretical air — must run across lines of constant carbon utilization. That is, as one strives to obtain higher heating values by firing more coal to a given gasifier with given air flow, he must invariably encounter more char carryover and lower carbon utilization.

III. In suspension gasifiers, the separator efficiency is just as important as the gasifier volume in determining performance. In fact, it might even be more important considering that larger gasifier volumes inherently entail higher heat losses whereas higher separator efficiencies might not.

We conclude that the modeling effort should be continued, but redirected towards chemical kinetic control of the rate. To aid in testing such models in the future, it would be very helpful to have experimental data on the actual separator efficiency.

THE MODEL

Figure D.1 shows the gasification process in schematic form. It consists of a reactor vessel, into which are fed coal, char, and air, and a separator that separates recycled char from the make gas to give a product consisting of make gas plus a small amount of char. The gasifier is considered to consist of three separate zones. Into the very bottom are fed air and char, and the air burns completely to CO_2 and H_2O, consuming in the process a portion of the char. The amount of reactor volume required for this combustion is assumed to be small and is henceforth neglected. Coal is fed at only one place into the system, immediately above the combustion zone. It is assumed that the coal almost immediately devolatilizes, that the volatile immediately equilibrates with the combustion gas, and that all the char particles so produced have the same size. As a matter of fact, the combustion assumption is probably not too important because the combustion section doesn't require much space anyhow. The assumptions about the behavior of the coal immediately upon an injection are, of course, all unrealistic. However, if the char particles make several transits through the apparatus, the error introduced by assuming immediate devolatilization may not be too important. Moreover, whether or not the volatile material equilibrates immediately with the combustion gas, or whether it does so over the whole volume of the reactor affects only in a relatively minor way the concentrations of the diffusing species. Thus, this assumption should at least give a good first approximation. Neglect of the polydispersity of char particle sizes may be more serious; but it is justified for the present by the simplicity that it provides.

As illustrated in Figure D.1, it is further assumed that each char particle makes several passes through the gasifier. (In the illustration, three passes are assumed.) For the sake of simplicity, we assume that the number of passes is an exact integer. That is, we assume that each char particle that does not escape through the separator is completely consumed exactly at the place where coal is introduced. While at first this might seem like an outrageously unrealistic assumption, actually it is not, for we might imagine that the reactor size can be adjusted so as to cause each char particle just to disappear at the coal inlet point. Thus, it amounts to assuming that reactor vessels come in discrete sizes that just allow one, two, three, etc., respectively, char-particle passes. To accommodate an actual reactor size lying between these discrete sizes, we simply interpolate between the results for two discrete sizes.

The foregoing and some additional important assumptions are summarized in Table D.1. Since both CO_2 and H_2O are assumed to react with char, the extent of the water gas shift reaction is not too important, although it still retains some significance since the diffusivity of H_2O is about 1.56 times the value for CO_2. Thus, the concentrations of both CO_2 and H_2O are needed in order to compute the reaction rate at any station, and the H_2O is 1.56 times as important as the CO_2. At first blush, assuming the separator efficiency η_c, to be independent of particle size would seem to be at variance with theory. It is made for two reasons. Firstly, it's the simplest assumption one can reasonably make. Secondly, considering that char particle sizes should be of the order of 50 microns and the cyclone cut size of the order of 10 microns, it may actually be fairly accurate. That is, cyclone efficiencies generally don't reach 100 percent, even for very large particles. In any event, the assumption is correct to a first approximation in that the function of the separator is to let some of the particles through, but not all of them.

Assumption No. 6 of Table D.1 is intended to provide a rational starting point for the gasification calculation. It is based upon the fact that this is the experimentally determined course of the reaction in fixed bed gasifiers. It is also based upon the rational that CO_2 and H_2O are probably the main products of reaction up until the point where most, if not all, of the O_2 is consumed.

Nevertheless, it must be admitted that some CO and H_2 are probably reaction products before all the O_2 is consumed, so that the actual starting point for gasification reactions is probably at somewhat lower CO_2 and H_2O concentrations than given by Assumption No. 6. Still, without getting bogged down in this detail, this should be a good first approximation. Assuming that the rate is diffusion controlled is a good assumption, especially if the gasifier itself is diffusion controlled. Characterizing the diffusion by a constant Sherwood number should be valid for particle sizes up to about 100 microns. The reason is that such particles should experience little relative motion with respect to the gas and, thus, the Sherwood number approaches its asymptotic value of 2.0. The effect of a constant Sherwood number is to make the amount of surface removed from a particle in a given portion of the gasifier independent of the initial size of the particle. (A constant diffusion coefficient would make the amount of radius removed a cost independent of particle size.)

As it turns out, the heat losses assumed in this model, Assumption No. 8 of Table D.1, are completely unrealistic with respect to the pilot gasifier. Thus, the assumption made here amounts to a minimal heat loss assumption. In actual execution, we have assumed that the char stream supplies all of the heat loss, with the make-gas temperature being the same as the separator inlet temperature. The char stream was assumed to lose heat to the surroundings, which are the constant temperature, through a heat transfer coefficient, h_s. Thus, the heat loss parameter becomes one proportional to this heat transfer coefficient and the area of the "separator", normalized to the material-balance basis of the flow sheet, namely, one mol of O_2 as in air.

Tables D.2 and D.3 summarize the model itself based upon these assumptions. Table D.2 gives the equations, and Table D.3 the nomenclature. The first set of equations at the top of Table D.2 determines the value of ε_3, the relative amount of surface to be removed from a particle between the injection point (2) and the gasifier exit (3). This is obtained from a trial and error solution of equation 3. The second set of equations determines the gas composition at points between points (2) and (3). The points are equally spaced in terms of amount of surface removed from a given particle. The water gas shift equilibrium is satisfied by solving the quadratic equation (8). The third set of equations in Table D.2 determines the temperature at these various points within the gasifier. This is done by trial and error solution of the enthalpy balance, Equation 15. The value of T_3 necessary for us to obtain the char temperature is obtained by an initial estimate at the beginning of the calculation, and then subsequently from the previously calculated T_3 value. The fourth set of equations in Table D.2 is the set that determines the required reactor volume for given operating conditions. Actually, the nominal reactor volume, V_R is included in the definition of the constant K_{VR}, so that the summation of Δv_R represents the relative reactor volume required for given conditions. Thus, v_R greater than unity means that the reactor would have to be larger than it actually is in order to satisfy the conditions. The various factors that go into the rate constant, K_{VR}, have to do with the initial surface area of the char particles, the Sherwood number, the actual reactor volume, the diffusivity of carbon dioxide, and the variation of diffusivity with temperature and pressure. It is a variation of diffusivity with temperature (proportional to the three halves power of temperature) that gives the peculiar unity to K_{VR}, $(^{\circ}K)^{-1/2}$.

In actual execution, we have evaluated the model of Table D.2 by first assuming successive values of ν, one, two, three, etc. The relative reactor volume, v_R, was calculated for each successive ν value. As a rule, the initial value of v_R was larger than unity, and it became smaller with increasing ν. The end result of the calculation, as indicated by the equations at the bottom of Table D.2, was an interpolation between results for the ν value that first gave v_R less than unity and the preceding one which, of course, gave v_R greater than unity. When a ν value of unity gave v_R less than unity, we discarded the results, or at least earmarked them as probably incorrect.

CALCULATIONAL PROCEDURE

The model was programmed for the Hewlett-Packard Model 9100A with extended memory. It was arranged in various subroutines so as to minimize programming. Each subroutine was debugged and checked by a manual calculation starting with the lowest order routines. (That is, with those subroutines that, themselves, call no other subroutines.) The debugged subroutines were then used in manual checking and debugging of the higher order subroutines. This process was continued until the whole program had been checked and debugged. A final check included a manual (or semi-manual) verification of every value in memory. The calculations were carried out with the following initial values of the constants:

1. A values between 0.3 and 0.55
2. η_c values between 0.7 and 0.95
3. A value of K_{VR} of 2.5×10^{-5} $(^{\circ}K)^{-1/2}$, which corresponds to an initial char particle diameter of 45 microns (45×10^{-6} meters), a char density of 0.44 grams/cc (440 kg/cubic meter), a diffusivity

of CO_2 at 298°K of 0.157 cm^2/sec (1.57 x 10^{-5} $meter^2$/sec), a Sherwood number of 2.0, a reactor volume of 24.44 cubic ft (0.693 $meters^3$), and an air flow rate of 950 lb/hr (8.67 x 10^{-4} kg mols O_2/sec).

4. A value of β_s of 4.5 kcal/mol O_2°K, which corresponds to an h_s value of 30 Btu/hr ft^2°F. (The value of the heat transfer coefficient was a compromise between the expected value of 3 Btu/hr ft^2°F for transfer from a cyclone to air and as high as 100 Btu/hr ft^2°F for transfer from char to the water-cooled elbow at the bottom of the devolatilizer.)

RESULTS

The most immediate and striking result obtained was that the a priori set of constants mentioned above could in no way predict the experimental results observed from the pilot gasifier. With char making only one pass through the apparatus ($\nu = 1$), calculated reactor volumes were far below the actual reactor volume. Only when the value of K_{VR} parameter was raised nearly four orders of magnitude (corresponding to an initial char particle size of 2.5 mm, rather than a few microns), were we able to "predict" actual experimental results. Since char particles of this size were never found in practice, we must conclude that the diffusion assumption is wrong. The alternative is, of course, rate control by chemical kinetics, probably involving gaseous molecules and the char surface. Since chemical-kinetic rate constants are usually more temperature sensitive than diffusivities, this also implies greater temperature sensitivity than assumed in the present model.

Figures D.2 through D.4 show the model's "predictions" with empirical values of the rate cost, K_{VR}. In Figure D.2, we show the data for code 7, wherein Western coal was fired vertically upward in the gasifier with no coal to the devolatilizer. The effects of variation of separator efficiency are illustrated by the three curves for 85, 90, and 95 percent separator efficiency. Figure D.3 shows the data for code 4, wherein Western coal was fired in the conventional manner all into the gasifier. The same central curve, $K_{VR} = 0.10$, $\eta_c = 90$ percent, fits these data fairly well, as it did for the data of code 7, Figure D.3. The effects of varying the rate constant from 0.05 to 0.2 $(°K)^{-1/2}$ are also shown in Figure D.3. In comparing Figures D.2 and D.3, it will be noticed that the effect of varying the rate constant by a factor of 2 is about the same as the effect of varying the separator "penetration" by a factor of 2. (Penetration is 100 - separator efficiency.) Thus, just as one might suspect, it turns out that the separator efficiency is just as important as the rate constant in determining the overall performance of the gasifier process.

Another effect obvious from Figures D.2 and D.3 is that the operating curve predicted by the model tends to cut across the lines of constant carbon utilization. This, too, is as one might expect since, as one increases the amount of coal fired (decreases percent theoretical air), he puts more char into suspension, achieves more reaction and a higher Btu gas, but also loses more char through the separator.

Figure D.4 shows the model "prediction" for code 1 data, Eastern coal fired all into the gasifier. The curve here, $K_{VR} = 0.1$, $\eta_c = 90$ percent, is the same as the middle curve of Figures D.2 and D.3, except that the coal-composition parameters have been changed to correspond to the Eastern coal. It will be noted that the predicted curve lies some 8 Btu's above the same curve for Western coal, and the agreement with the Eastern-coal data is fairly good. Thus, the model appears to correctly predict trends with coal composition. On the other hand, since the diffusion assumption is obviously erroneous, this kind of agreement with experimental data may be purely fortuitous.

DISCUSSION

In spite of the failure of the diffusion assumption, this simple model still appears to have some virtue. That is, even though the constant K_{VR}, had to be adjusted empirically in order to fit the data, the recycle portion of the model remains valid. Thus, it correctly predicts the trend of data with air fuel ratio, and it demonstrates the importance of separator efficiency. It's also obvious that future efforts to fit a model to experimental data will be facilitated considerably if experimental data are available on separator efficiency. This will, of course, require a method of measuring the particulate flows in at least two of the three streams entering or leaving the separator. (We have a method in mind for measuring char flow.)

The fact that the diffusion assumption failed by so wide a margin, two orders of magnitude in particle size, virtually proves that the actual rate is controlled by chemical kinetics. Consequently, we can be fairly sure that it is temperature sensitive, and therefore, sensitive to heat losses.

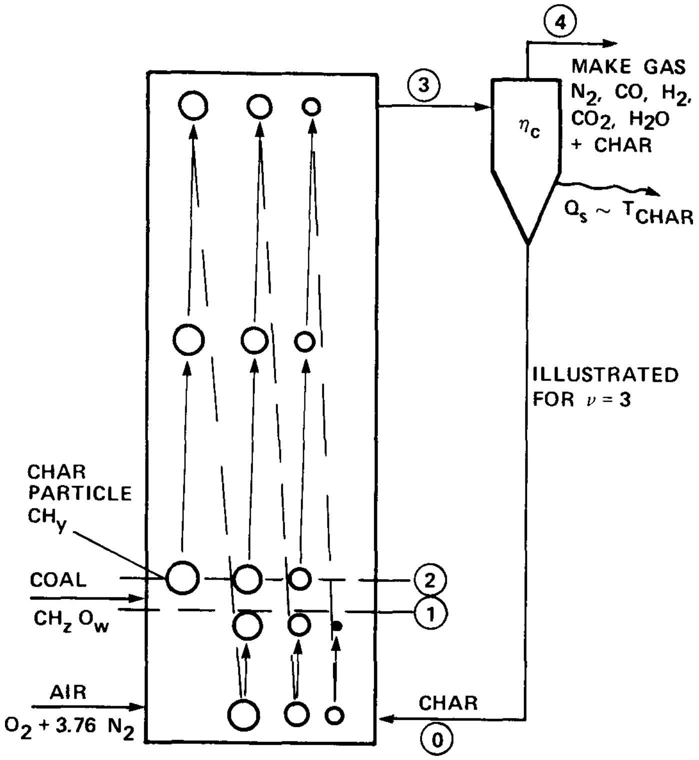


FIGURE D.1 REACTION ENGINEERING MODEL IB

TABLE D.1 REACTION ENGINEERING MODEL I: MAIN ASSUMPTIONS

1. Gasification reactions, between (2) and (3), are:

$$CH_y + CO_2 \rightarrow 2CO + \frac{y}{2} H_2$$

$$CH_y + H_2O \rightarrow CO + (1 + \frac{y}{2}) H_2$$

   and rate is controlled by a diffusion of H_2O and CO_2 to char particle surface.

2. Char particles are formed immediately upon coal injection and are initially uniformly sized.

3. If not lost through the separator, char particles are recycled exactly an integral number of times, ν, until consumed.

4. The separator efficiency is η_c for all particles regardless of size.

5. Within the bulk of the reactor, which lies between points (2) and (3), the gas is at all times in water gas shift equilibrium.

6. All of the air is burned with part of the recycled char to produce a gas containing only CO_2, H_2O, N_2, and CH_y (solid) particles. The rate is diffusion controlled.

7. In both gasifier, (2) — (3), and combustor, (0) — (1), the diffusion rate is characterized by a constant Sherwood number, e.g., $N_{Sh} = 2.0$.

8. There are no heat losses except from the separator and char return line.

TABLE D.2 GASIFIER MODEL IB EQUATIONS

Determining ε_3

$$CH_zO_w \rightarrow Y\ CH_y \text{ (solid)} + (1 - Y)\ CH_{z'}O_{w'} \text{ (gas)} \qquad (1)$$

$$\tau_{O_2} \triangleq A\ (1 + \frac{3}{4} - \frac{w}{2});\ \Delta\omega_{01} \triangleq 4\ \tau_{O_2}/(4 + y)\ Y \qquad (2)$$

$$\Delta\omega_{01} = \eta_c\ [S\ (\nu, \varepsilon_3) - S\ (\nu, 1)];\ S\ (\nu, \varepsilon) \triangleq \sum_{\xi = 0}^{\xi = \nu - 1} \eta_c^{\xi}\ (1 - \frac{\xi}{\nu} - \frac{\varepsilon}{\nu})^{3/2} \qquad (3)$$

Gas Composition at Increments Between (2) and (3)

$$\Delta\varepsilon \triangleq \varepsilon_3/N;\ \varepsilon = \sum \Delta\varepsilon;\ \Delta\omega_{2+} = S\ (\nu, \varepsilon) - S\ (\nu, 0) \qquad (4)$$

$$\alpha_N = 2\ (3.76);\ \alpha_O = 2 + w/\tau_{O_2};\ \alpha_c = \frac{4}{4 + y} + \frac{1 - Y\ (1 + \Delta\omega_{2+})}{\tau_{O_2}} \qquad (5)$$

$$\alpha_H = \frac{4y}{4 + y} + \frac{z - Yy\ (1 + \Delta\omega_{2+})}{\tau_{O_2}};\ \beta \triangleq K_w\ (\frac{1}{2}\ \alpha_H + \alpha_c) - (K_w - 1)\ \alpha_O \qquad (6)$$

$$\alpha \triangleq 4\ \alpha_c\ (\alpha_O - \alpha_C);\ K_w \triangleq p_{CO}\ p_{H_2O}/p_{CO_2}\ p_{H_2} \qquad (7)$$

$$\mu_{CO_2} = [\ - \beta + \sqrt{\beta^2 + (K_w - 1)\ \gamma}\ ]/2\ (K_w - 1),\ K_w \neq 1 \qquad (8)$$

$$= \gamma/4\beta,\ K_w = 1,\ \text{i.e.,}\ |(K_w - 1)\ \gamma\ | < 0.01$$

$$\mu_{CO} = \alpha_c - \mu_{CO_2};\ \mu_{H_2O} = \alpha_O - \alpha_c - \mu_{CO_2} \qquad (9)$$

$$\mu_{H_2} = \frac{1}{2}\ \alpha_H - \mu_{H_2O};\ \mu_{N_2} = \frac{1}{2}\ \alpha_N;\ \lambda \triangleq \sum \mu_i \qquad (10)$$

Determining T

$$\mu_{O\ \text{char}} = Y\eta_c\ \omega_3/\tau_{O_2};\ \omega_3 = S\ (\nu, \varepsilon_3);\ \mu_{\text{char}} = YS\ (\nu, \varepsilon)/\tau_{O_2} \qquad (11)$$

$$B_s' \triangleq h_s A_s/(0.21\ W_A/29);\ \beta_s \triangleq B_s'/(C_p\mu)\ \text{char}; \qquad (12)$$

$$T_{\text{char}} = 298 + (T_3 - 298)\ e^{-\beta_s} \qquad (13)$$

TABLE D.2 CONT'D

$$h_{IN} \triangleq h_{O_2}\ (T_{air}) + 3.76\ h_{N_2}\ (T_{air}) - \mu_{O\ char}\ h_{char}\ (T_{char}) + \frac{h_{coal}(T_{coal})}{\tau_{O_2}} \qquad (14)$$

$$h_T = h_{IN};\ h_T \triangleq \sum_{i=1}^{6} \mu_i h_i\ (T)\ \text{(includes char)} \qquad (15)$$

$$h_i\ (T) \triangleq a_i\ (T - 298) + \frac{b_i}{2}\ (T^2 - 298^2) - c_i\ \left(\frac{1}{T} - \frac{1}{298^2}\right) + h_{fi} \qquad (16)$$

Determining V_R

$$K_{VR} \triangleq \frac{\rho_{CH_y}\ D^2_{po}\ (R_g/P)^2\ (0.21\ W_A/29)(P\ 298^{3/2}/1\ \text{atm})}{4\ (12 + y)\ N_{Sh}\ V_R\ D_{CO_2 298}} \qquad (17)$$

$$\Delta v_R = K_{VR}\ \lambda^2\ T^{1/2}\ \Delta\varepsilon/\nu\ (\mu_{CO_2} + 1.56\ \mu_{H_2O}),\ T \geq T_{KR} \qquad (18)$$

$$= \infty,\ T < T_{KR};\ v_R \triangleq \sum \Delta v_R$$

Interpolation

$\bar{\xi} \triangleq (1 - v_R)\ (\xi' - \xi)/(v_R' - v_R) + \xi$, where $\bar{\xi}$ is an average between

ξ values for the first ν value given, $v_R \leq 1$ and the previous

$$H = (124675\ \bar{\mu}_{CO} + 122891\ \bar{\mu}_{H_2})/387\ (\bar{\lambda} - \bar{\mu}_{H_2O});\ \beta_p = (1 - \eta_i)\ \bar{\omega}_3\ Y \qquad (20)$$

TABLE D.3 GASIFIER MODEL IB EQUATION NOMENCLATURE

English

a_i = constant in empirical heat-capacity equation, kcal/kg mol °K

A = air-to-fuel ratio expressed as a fraction of that theoretically required to burn completely to CO_2 and H_2O with no O_2, nor CO, nor H_2, dimensionless

A_s = heat transfer area of separator, m^2

b_i = constant in empirical heat-capacity equation, kcal/kg mol $(°K)^2$

B_s' = heat loss factor for separator, kcal/sec mol O_2 °K

c_i = constant in empirical heat-capacity equation, kcal °K/kg mol

C_p = $a + bT + c/T^2$ = heat capacity, kcal/kg mol °K

D_{po} = diameter of newly formed char particle, m

$D_{CO_2 298}$ = diffusivity of CO_2 at 298°K, m^2/sec

h_s = heat transfer coefficient from char to surroundings, kcal/sec m^2 °K

h_T = enthalpy of gas-solid mix at temperature, T, referred to elements at 298°K and calculated from heat capacities of components, kcal/kg mol O_2 in air feed

h_{IN} = combined enthalpy of streams that produce gas-solid mix, referred to elements at 298°K, kcal/kg mol O_2 in air feed

h_{fi} = enthalpy of formation at 298°K of i-Th component of gas-solid mix, kcal/kg mol

$h_i(T)$ = enthalpy of i-th component at temperature, T, referred to elements at 298°K, kcal/kg mol

H = heating value of make-gas, Btu/dscf

K_w = equilibrium constant for water-gas shift reaction, dimensionless

K_{VR} = rate constant characteristic of gasifier volume, $(°K)^{-1/2}$

N = number of steps in numerical integrational over gasifier volume, dimensionless

N_{Sh} = Sherwood number $\overset{\Delta}{=} k_g D_p/D$, where k_g is mass transfer coefficient, mols per sec m^2 per (mol/m^3); D_p is particle diameter, m; D is diffusivity m^2/sec; N_{Sh} is dimensionless

TABLE D.3 CONT'D

p = partial pressure atmosphere

P = total pressure, atmosphere

R_g = universal gas constant, atmosphere m^3/kg mol °K

$S(\nu,\varepsilon)$ = relative volume of char, i.e., volume of char for given values of ν and ε, per unit volume of char input from coal, dimensionless

T = temperature, °K

T_{KR} = critical temperature below which chemical kinetic rate is no longer much larger than diffusion rate and reaction rate (for practical purposes) stops, °K

v_R = relative gasifier volume up to point under consideration, i.e. gasifier (reactor) volume divided by total actual gasifier volume, V_R, dimensionless

V_R = gasifier (reactor) volume (exclusive of combustion volume below coal feed point), m^3

w = oxygen in coal, atoms oxygen per atom carbon

w' = oxygen in volatile, atoms oxygen per atom carbon

W_A = air feed rate, kg/sec

y = hydrogen in char, atoms H per atom C

Y = amount of char produced by coal, mols char as CH_y per mol coal as CH_zO_w

z = amount of hydrogen in fuel, atoms H per atom C

z' = amount of hydrogen in volatile, atoms H per atom C

Greek

α = elemental concentration in gas at a given point, kg atoms/kg mol O_2 in air feed

β = a constant appearing in the solution of the water-gas-shift equilibrium, kg atoms/kg mol O_2 in air feed

β_p = char output expressed as atoms carbon per atom carbon input in coal, dimensionless

β_s = a heat-loss parameter appearing in the solution of the char-cooling problem, dimensionless

TABLE D.3 CONT'D

γ = a constant appearing in the solution of the water-gas-shift equilibrium, (kg atoms/kg mol O_2 in air feed)^2

ε = relative amount of char particle area removed between point of first appearance of char particle, point (2), and a given point in the reactor. That is, ε is the amount of area removed divided by the total amount of area removed per pass, where the number of passes is ν. ε is dimensionless.

ε_3 = the value of ε at station (3), dimensionless

$\Delta\varepsilon$ = the change in ε per unit computational increment, dimensionless

η_c = separator efficiency, dimensionless

λ = total gas flow, kg mols/kg mol O_2 in air feed

μ, μ_i = flow of a given component such as CO_2, CO, H_2O, H_2, N_2, char, kg mols/kg mol O_2 in air feed

μ_o = value of μ at station (0), kg mols/kg mol O_2 in air feed

ν = number of passes a char particle makes before it is completely consumed (assuming it does not escape through the separator), dimensionless

ξ = an index variable used in summations or used to stand for several other variables that are manipulated in similar fashions

ξ' = previous value of ξ

$\overline{\xi}$ = linearly interpolated value between current ξ and previous ξ'

ρ_{CH_y} = density of char, kg/m^3

τ_{O_2} = mol ratio of oxygen in air feed to mols of coal feed, dimensionless

ω = relative volume of char flowing, i.e., volume of char flow per unit volume of char input, dimensionless

ω_3 = relative volume of char flowing at station (3), dimensionless

$\Delta\omega_{01}$ = relative volume of char consumed in combustor, dimensionless

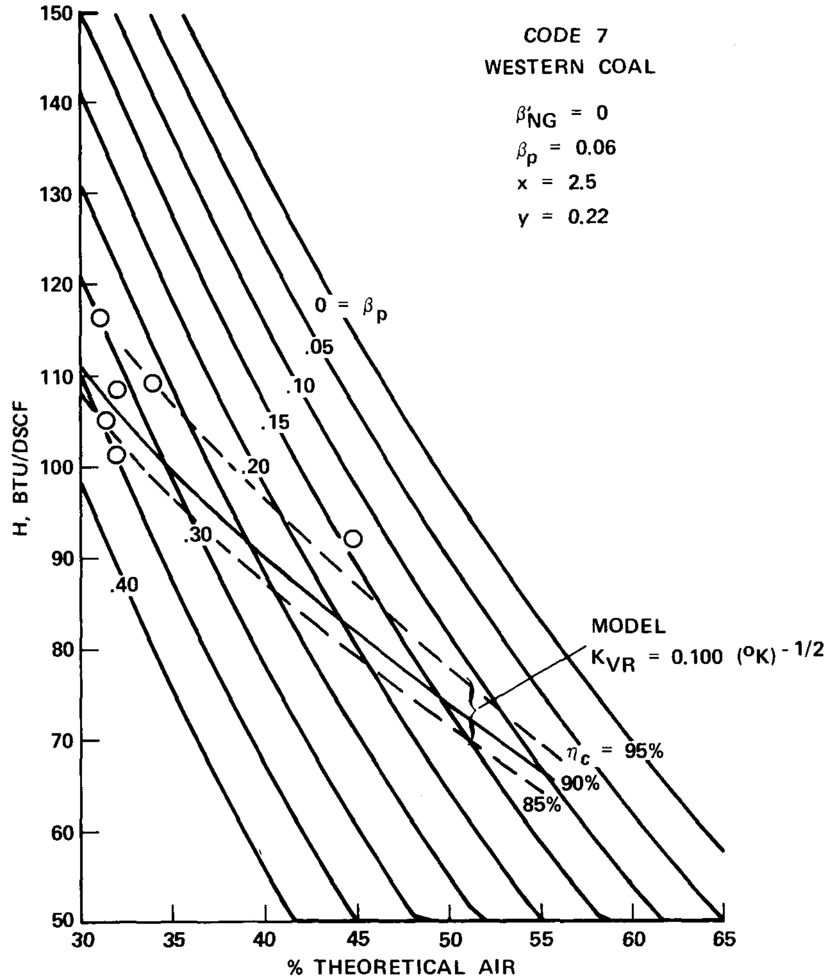
$\Delta\omega_{2+}$ = relative volume of char consumed between point (2) and arbitrary point in reactor between (2) and (3), dimensionless

Subscripts

C, O, H, N = pertaining to carbon, oxygen, hydrogen, and nitrogen

CO_2, CO, H_2O, H_2, N_2, Char, Coal = pertaining to these species

i = an index standing for the first six of the above



β_p = FRACTION OF TOTAL INPUT CARBON APPEARING AS CHAR IN GAS LEAVING CYCLONE SEPARATORS.

β_g = FRACTION OF THE TOTAL INPUT CARBON APPEARING AS HYDROCARBONS, CH_x, IN STREAM LEAVING SYSTEM. THE VALUE OF x IS APPROXIMATELY 2.5.

$\beta'_{N.G.}$ = NATURAL GAS (METHANE) FEED RATE EXPRESSED AS kg OF METHANE PER kg OF AS-FIRED COAL, DIMENSIONLESS.

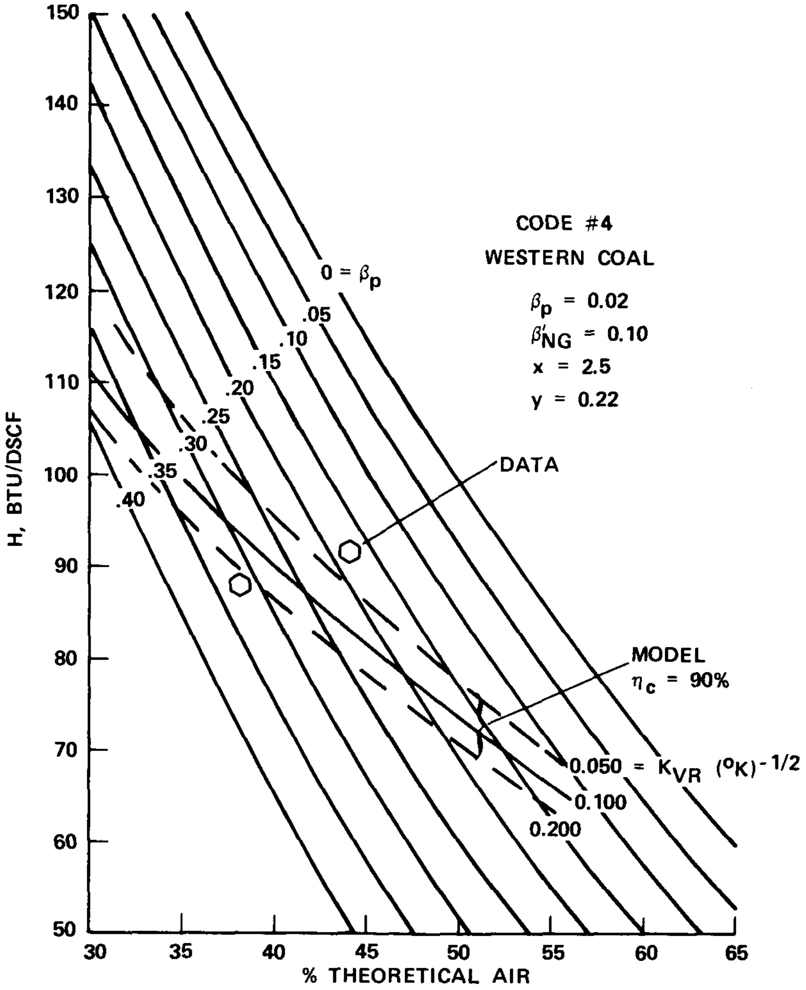
X = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE HYDROCARBON GAS MIXTURE COMPOSED OF CH_4, C_2H_2, C_2H_4, C_2H_6, ETC. IN THE MAKE GAS, DIMENSIONLESS.

Y = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE CHAR, DIMENSIONLESS.

η_c = CYCLONE SEPARATOR EFFICIENCY, DIMENSIONLESS.

K_{VR} = RATE CONSTANT CHARACTERISTIC OF GASIFIER VOLUME, $(^{o}K)^{-1/2}$.

FIGURE D.2 DATA OF CODE 7



β_p = FRACTION OF TOTAL INPUT CARBON APPEARING AS CHAR IN GAS LEAVING CYCLONE SEPARATORS.

β_g = FRACTION OF THE TOTAL INPUT CARBON APPEARING AS HYDROCARBONS, CH_x, IN STREAM LEAVING SYSTEM. THE VALUE OF x IS APPROXIMATELY 2.5.

$\beta'_{N.G.}$ = NATURAL GAS (METHANE) FEED RATE EXPRESSED AS kg OF METHANE PER kg OF AS-FIRED COAL, DIMENSIONLESS.

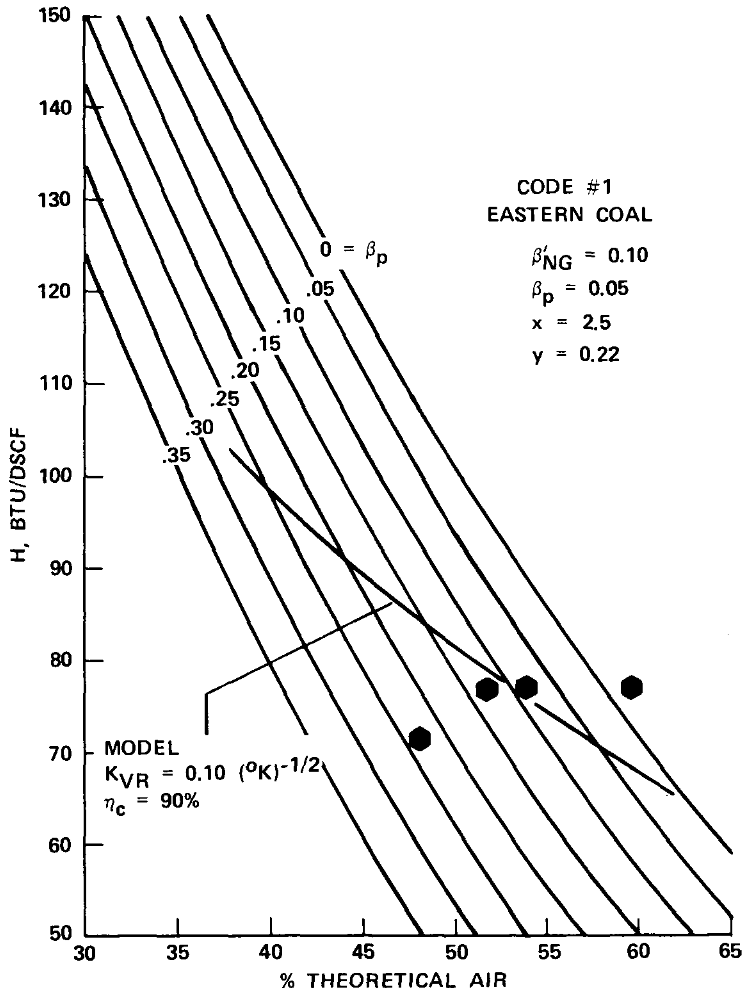
X = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE HYDROCARBON GAS MIXTURE COMPOSED OF CH_4, C_2H_2, C_2H_4, C_2H_6, ETC. IN THE MAKE GAS, DIMENSIONLESS.

Y = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE CHAR, DIMENSIONLESS.

η_c = CYCLONE SEPARATOR EFFICIENCY, DIMENSIONLESS.

K_{VR} = RATE CONSTANT CHARACTERISTIC OF GASIFIER VOLUME, $(^oK)^{-1/2}$.

FIGURE D.3 DATA OF CODE 4



β_p = FRACTION OF TOTAL INPUT CARBON APPEARING AS CHAR IN GAS LEAVING CYCLONE SEPARATORS.

β_g = FRACTION OF THE TOTAL INPUT CARBON APPEARING AS HYDROCARBONS, CH_x, IN STREAM LEAVING SYSTEM. THE VALUE OF x IS APPROXIMATELY 2.5.

$\beta'_{N.G.}$ = NATURAL GAS (METHANE) FEED RATE EXPRESSED AS kg OF METHANE PER kg OF AS-FIRED COAL, DIMENSIONLESS.

X = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE HYDROCARBON GAS MIXTURE COMPOSED OF CH_4, C_2H_2, C_2H_4, C_2H_6, ETC. IN THE MAKE GAS, DIMENSIONLESS.

Y = RATIO OF ATOMS OF HYDROGEN PER ATOM OF CARBON IN THE CHAR, DIMENSIONLESS.

η_c = CYCLONE SEPARATOR EFFICIENCY, DIMENSIONLESS.

K_{VR} = RATE CONSTANT CHARACTERISTIC OF GASIFIER VOLUME, $(^oK)^{-1/2}$.

FIGURE D.4 DATA OF CODE 1

APPENDIX E

SUMMARY OF MATERIAL AND ENERGY BALANCES FOR DETERMINING THE TEMPERATURE AND COMPOSITION OF THE INTERNAL FLUID IN THE THERMAL MODEL

Note: The figures and tables of this appendix assume the apparatus consists of the six components: combustor, gasifier, crossover duct, second combuster devolatilizer, and cyclones. The fact that the complete model contains two additional components, gasifier top and devolatilizer top, required that the equations be modified slightly in translation from the present algebraic form to the FORTRAN program. However, the sense of the present equations was preserved as described in the body of the report.

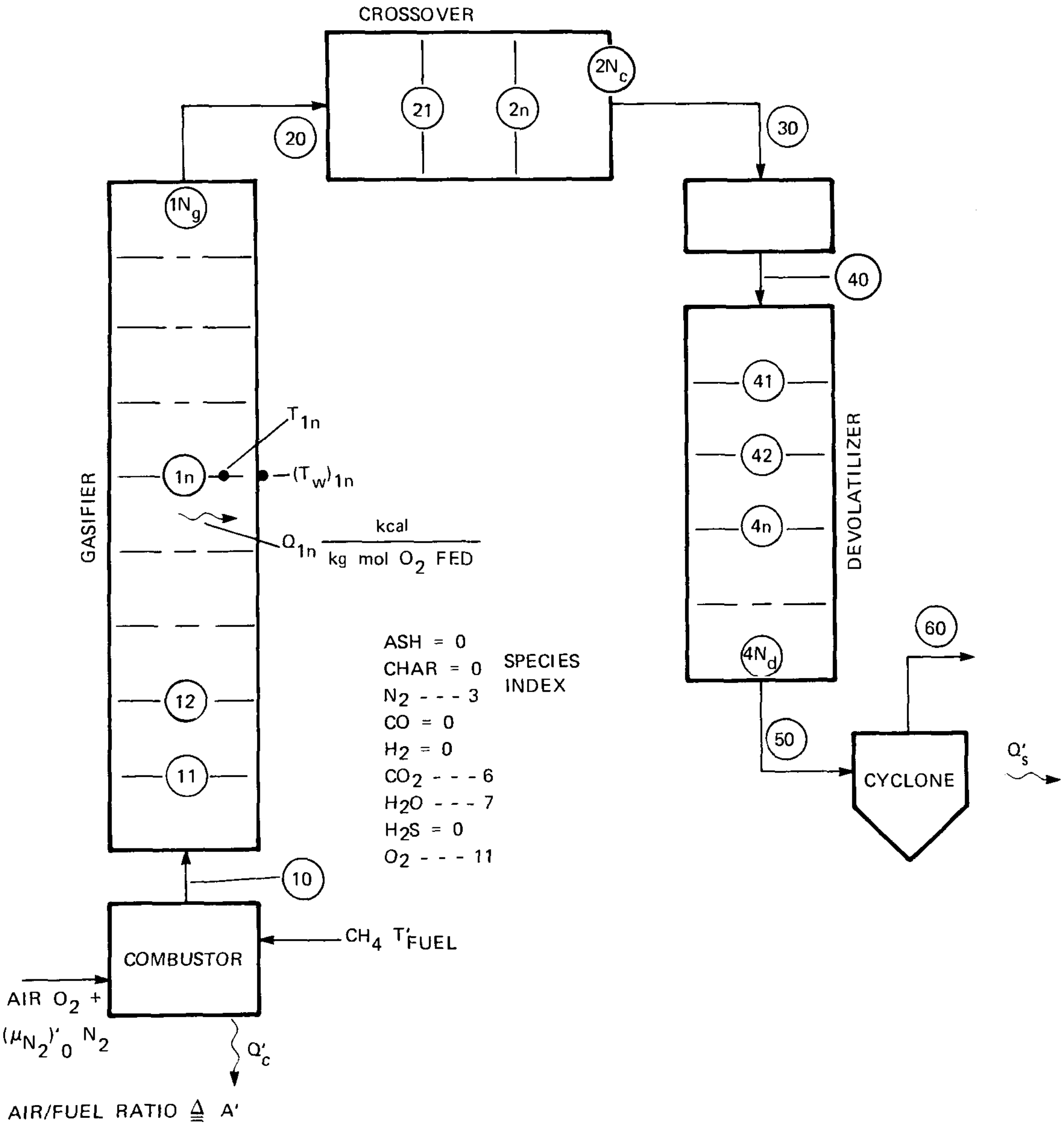


FIGURE E.1 GAS FLOW DIAGRAM AND NOMENCLATURE – NATURAL GAS FIRING

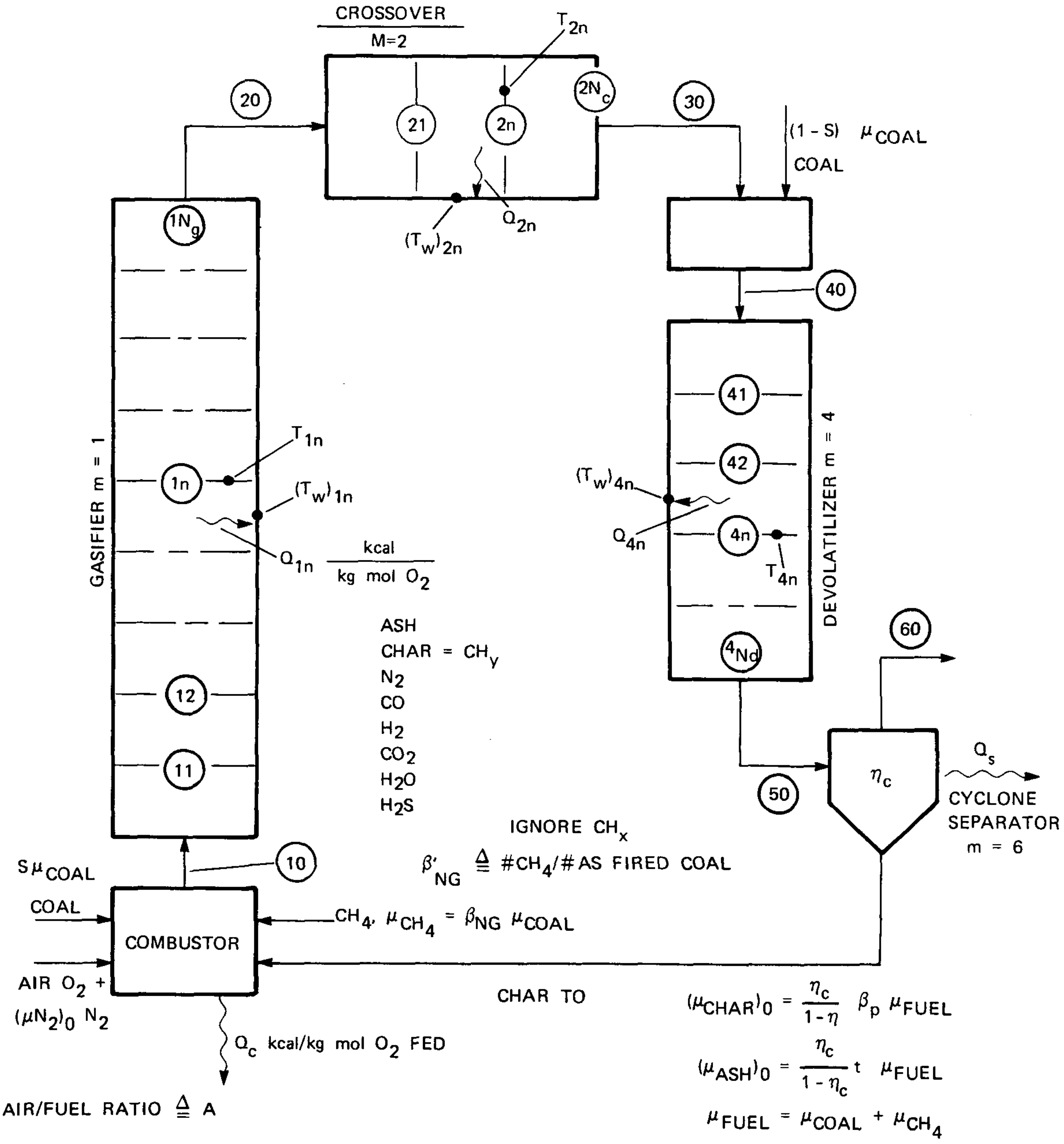


FIGURE E.2 GAS FLOW DIAGRAM AND NOMENCLATURE – COAL FIRING

TABLE E.1 BASIC EQUATIONS FOR NATURAL GAS FIRING

Preliminary Calculations

$$(\mu_{N_2})_{10} = (\mu_{N_2})_0' \; ; \; (\mu_{CO_2})_{10} = \frac{1}{2A'} \qquad (1)$$

$$(\mu_{H_2O})_{10} = \frac{1}{A'} \; ; \; (\mu_{O_2})_{10} = (1 - \frac{1}{A'}) \qquad (2)$$

10

$$g_{10} = h_{O_2}(T'_{air}) + (\mu_{N_2})_0 \, h_{N_2}(T'_{air}) + \frac{1}{2A'} \, h_{CH_4}(T'_{fuel}) - Q_c \qquad (3)$$

$f'(T_{mn})$

$$f'(T_{mn}) \triangleq (\mu_{N_2}) \, h_{N_2}(T_{mn}) + (\mu_{CO_2}) \, h_{CO_2}(T_{mn}) + (\mu_{H_2O}) \, h_{H_2O}(T_{mn})$$

$$+ (\mu_{O_2}) \, h_{O_2}(T_{mn}) - g_{mn} \qquad (4)$$

g's

$$g_{1n} = g_{1,n-1} - Q_{1,n} \qquad (5)$$

$$g_{20} = g_{1N_g} \; ; \; g_{2n} = g_{2,n-1} - Q_{2n} \qquad (6)$$

$$g_{40} = g_{2N_c} \; ; \; g_{4n} - g_{4,n-1} - Q_{4n} \qquad (7)$$

$$g_{50} = g_{4,N_d} \qquad (8)$$

$$g_{60} = g_{50} - Q_s$$

All Stations

$$(\mu_{N_2}) = (\mu_{N_2})'_o \; ; \; (\mu_{CO_2}) = (\mu_{CO_2})_{10} \; ; \; (\mu_{H_2O}) = (\mu_{H_2O})_{10} \qquad (10)$$

$$(\mu_{O_2}) = (\mu_{O_2})_{10} \qquad (11)$$

TABLE E.2 BASIC EQUATIONS FOR COAL FIRING

Preliminary Calculations

$$\text{Coal:}\quad \overset{\text{coal (as fired)}}{CH_{z'}O_{w'}S_{v'}N_{u'}\,(Ash)_{t'}} \rightarrow \overset{\text{char}}{Y'CH_y} + \text{Gas} + t'\,(Ash) \qquad (1)$$

$$\text{Fuel:}\quad CH_{z'}O_{w'}S_{v'}N_{u'}\,(Ash)_{t'} + \beta_{NG}\,CH_4 \rightarrow (1 + \beta_{NG})\,CH_zO_wS_vN_u\,(Ash)_t \qquad (2)$$

$$CH_zO_wS_vN_u\,(Ash)_t \rightarrow Y\,CH_y + t(Ash) + \text{Gas} \qquad (3)$$

$$\beta_{NG} = \beta'_{NG}\;\frac{(12.01 + 1.008z' + 16w' + 32.06v' + 14.01u' + t')}{16.042} \qquad (4)$$

$$t \overset{\Delta}{=} t'/(1 + \beta_{NG}) \; ; \; \mu \overset{\Delta}{=} u'/(1 + \beta_{NG}) \; ; \; v \overset{\Delta}{=} v'/(1 + \beta_{NG}) \; ; \qquad (5)$$

$$w \overset{\Delta}{=} w'/(1 + \beta_{NG}) \; ; \; z \overset{\Delta}{=} (z' + 4\,\beta_{NG})/(1 + \beta_{NG}) \; ; \; y \overset{\Delta}{=} y'/(1 + \beta_{NG}) \qquad (6)$$

$$\tau_{O_2} \overset{\Delta}{=} A\,\left(1 + \frac{z}{4} + v - \frac{w}{2}\right) \; ; \; \mu_{coal} = \frac{1}{\tau_{O_2}\,(1 + \beta_{NG})} \; ; \; \mu_{CH_4} = \frac{\beta_{NG}}{\tau_{O_2}\,(1 + \beta_{NG})} \qquad (7)$$

$$(\mu_{char})_0 = \frac{\eta_c}{(1 - \eta_c)}\;\frac{\beta_p}{\tau_{O_2}} \; ; \; (\mu_{ash})_0 = \frac{\eta_c t}{(1 - \eta_c)\;\tau_{O_2}} \qquad (8)$$

$$\Delta_{12} = -\,\mu_{coal}\left[Y' - \beta_p(1 + \beta_{NG})\right] + 4/(4 + y) \qquad (9)$$

f(T)

$$h_i(T) \overset{\Delta}{=} a_i\,(T - 298) + \frac{b_i}{2}\,(T^2 - 298^2) - c_i\,\left(\frac{1}{T} - \frac{1}{298}\right) + h_{f_i} \qquad (10)$$

$$f(T) \overset{\Delta}{=} \left[\sum_{i=1}^{8} \mu_i\,h_i(T)\right] - g, \; i = \text{ash, char, } N_2,\ CO,\ H_2,\ CO_2,\ H_2O,\ H_2S \qquad (11)$$

At 10

$$g_{10} = -Q_c + h_{O_2}(T_{air}) + (\mu_{N_2})_0 \, h_{N_2}(T_{air}) + S \, \mu_{coal} \, h_{coal}(T_{fuel})$$

$$+ \mu_{CH_4} \, h_{CH_4}(T_{fuel}) + (\mu_{char})_0 \, h_{char}(T_c) + (\mu_{ash})_0 \, h_{ash}(T_0) \qquad (12)$$

$$(\mu_{ash})_{10} = (\mu_{ash})_0 + S \, \mu_{coal} \, t' \; ; \; (\mu_{char})_{10} = (\mu_{char})_0 + S \, \mu_{coal}$$

$$Y' - \frac{4}{4 + y} \qquad (13)$$

$$(\alpha'_c)_{10} = \frac{4}{4 + y} + S \, \mu_{coal} \, (1 - y') + \mu_{CH_4} \; ; \; (\alpha_0)_{10} = 2 + S \, \mu_{coal} \, w' \qquad (14)$$

$$(\alpha'_H)_{10} = \frac{4y}{4 + y} + S \, \mu_{coal} \, (z' - Y'y) - 2(\alpha_S)_{10} + 4\mu_{CH_4} ; \; (\alpha_S)_{10} = S \, \mu_{coal} \, v' \qquad (15)$$

$$(\alpha'_N)_{10} = 2(\mu_{N_2})_0 + S \, \mu_{coal} \, u' \qquad (16)$$

1n

$$g_{1n} = g_{1,n-1} - Q_{1n} ; \; (\alpha'_H)_{1n} = (\alpha'_H)_{10} - ny \, \Delta_{12}/N_g ; \; (\alpha'_C)_{1n} = (\alpha'_C)_{10} - \frac{n\Delta_{12}}{N_g} \qquad (17)$$

$$(\alpha_N)_{1n} = (\alpha_N)_{10} ; \; (\alpha_S)_{1n} = (\alpha_S)_{10} ; \; (\alpha_0)_{1n} = (\alpha_0)_{10} \qquad (18)$$

$$(\mu_{ash})_{1n} = (\mu_{ash})_{10} ; \; (\mu_{char})_{1n} = (\mu_{char})_{10} + n \, \Delta_{12}/N_g \qquad (19)$$

$$n = 1, 2, \ldots n \ldots N_g \qquad (20)$$

WATER GAS SHIFT

$$\beta \overset{\Delta}{=} K_w \, (\tfrac{1}{2} \, \alpha'_H + a'_C) - (K_w - 1) \, \alpha_0 ; \; \gamma \overset{\Delta}{=} 4\alpha'_C \, (\alpha_0 - \alpha'_C)$$

$$(K_w \overset{\Delta}{=} p_{CO} \, p_{H_2O}/p_{CO_2} \, p_{H_2}) \qquad (21)$$

$$\mu_{CO_2} = -\beta + \left[\sqrt{\beta^2 + (K_w - 1)\,\gamma}\right] / 2(K_w - 1); \; K_w \neq 1 \tag{22}$$

$$= \gamma/4\beta, \; K_w = 1, \text{ i.e. } |K_w - 1| < 0.01 \tag{23}$$

$$\mu_{CO} = \alpha'_C - \mu_{CO_2}; \; \mu_{H_2O} = \alpha_O - a'_C - \mu_{CO_2}; \; \mu_{N_2} = \tfrac{1}{2}\alpha_N \tag{24}$$

$$\mu_{H_2} = \tfrac{1}{2}\alpha'_H - \mu_{H_2O}; \; \mu_{H_2S} = \alpha_S \tag{25}$$

<u>2n</u>

$$T_{20} = T_{1N_g}; \; g_{20} = g_{1N_g}; \; (\mu_i)_{20} = (\mu_i)_{1N_g}; \; i = 1 \; . \; . \; . \; 8 \tag{26}$$

$$(\alpha'_C)_{2n} = (\alpha'_C)_{1N_g}; \; (\alpha'_H)_{2n} = (\alpha'_H)_{1N_g}; \; (\alpha_O)_{2n} = (\alpha_O)_{1N_g} \tag{27}$$

$$(\alpha_N)_{2n} = (\alpha_N)_{1N_g}; \; (\alpha_S)_{2n} = (\alpha_S)_{1N_g} \tag{28}$$

$$g_{2n} = g_{2,n-1} - Q_{2n}; \quad n = 1, 2 \; . \; . \; . \; N_c \tag{29}$$

<u>40</u>

$$(\alpha_C)_{40} = (1 + \beta_{NG})\, \mu_{coal}\, (1 - \beta_p); \; (\alpha_O)_{40} = 2 + \mu_{coal}\, w' \tag{30}$$

$$(\alpha'_H)_{40} = \mu_{coal} \left[z' - 2v' + 4\beta_{NG} - (1 + \beta_{NG})\, y\beta_p\right] \tag{31}$$

$$(\alpha_N)_{40} = 2(\mu_{N_2})_0 + \mu_{coal}\, u'; \; (\alpha_S)_{40} = \mu_{coal}\, v' \tag{32}$$

$$(\mu_{char})_{40} = \beta_p/(1 - n_c)\, \tau_{O_2}; \; (\mu_{ash})_{40} = \mu_{coal}\, t'/(1 - \eta_c) \tag{33}$$

$$g_{40} = g_{2N_c} + (1 - S)\, \mu_{coal}\, h_{coal}(T_{fuel}) \tag{34}$$

4n

$$(\alpha'_c)_{4n} = (\alpha'_c)_{40} \; ; \; (\alpha'_H)_{4n} = (\alpha'_H)_{40} \; ; \; (\alpha_N)_{4n} = (\alpha_N)_{40} \tag{35}$$

$$(\alpha_S)_{4n} = (\alpha_S)_{40} \; ; \; (\alpha_O)_{4n} = (\alpha_O)_{40} \; ; \; (\mu_{char})_{4n} - (\mu_{char})_{40} \tag{36}$$

$$(\mu_{ash})_{4n} = (\mu_{ash})_{40} \; ; \; g_{4n} - g_{4,n-1} - Q_{4n} \tag{37}$$

$$n = 1, 2 \; . \; . \; . \; N_d \tag{38}$$

60

$$(\mu_i)_{60} = (\mu_i)_{4N_d}, \; i = 1 \; . \; . \; . \; 8 \; ; \; g_{60} = g_{4N_d} - Q_s \tag{39}$$

NOMENCLATURE

English

A = ratio of actual air flow to that required to burn the total fuel (including CH_4, if any) to CO_2 (g), H_2O (l), SO_2 (g), N_2 (g), and ash with no O_2 (g) or CO (g) in the mixture, dimensionless

a = constant in heat capacity equation, kcal/kg mol °K

b = constant in heat capacity equation, kcal/kg mol $(°K)^2$

c = constant in heat capacity equation, $C_p = a + bT + c/T^2$, kcal °K/kg mol

$f(T)$ = enthalpy error between enthalpy out in a given stream and enthalpy in by all other streams, kcal

h = molal enthalpy referred to the elements in their normal state as 298°K, kcal/kg mol

h_f = heat of formation, kcal/kg mol

K_w = equilibrium constant for water gas shift reaction, dimensionless

Q = heat loss, kcal/mol O_2 fed in air

S = fraction of coal fed to gasifier, dimensionless

T = stream temperature, °K

t = ratio, kilograms of ash to kilogram atoms of carbon in "fuel" ("fuel" is coal plus methane, if any), kg/kg atom

t' = ratio, kilograms of ash to kg atoms of carbon in coal, kg/kg atom

u = ratio, atoms of nitrogen in "fuel" to atoms of carbon in fuel, dimensionless

u' = ratio, atoms of nitrogen in coal to atoms of carbon in coal, dimensionless

v,w,z = ratios similar to u, but for sulfur, oxygen, and hydrogen, respectively, dimensionless

v',w',z' = ratios similar to u', but for sulfur, oxygen, and hydrogen, respectively, dimensionless

x = ratio, atoms of hydrogen per atom of carbon in the hydrocarbon gas mixture composed of CH_4, C_2H_2, C_2H_4, C_2H_6, etc. in the make gas, dimensionless

y = ratio of atoms of hydrogen per atom of carbon in the char, dimensionless

Y = mols of char formed per mol of "fuel" (A mol of fuel is $CH_zO_wS_vN_uAsh_t$), dimensionless

Y' = mols of char formed per mol of coal (A mol of coal is $CH_{z'}$,$O_{w'}$, $S_{v'}$,$N_{u'}$,$Ash_{t'}$,), dimensionless

Greek

α = amount of atoms of a given kind in a given stream, kg atoms/kg O_2 fed as air

α'_c = amount of carbon atoms in a given stream exclusive of those in char (measured by β_p) and hydrocarbons (measured by β_g), kg atoms/kg mols O_2 fed as air

α'_H = amount of hydrocarbon atoms in a given stream exclusive of those in char, hydrocarbons, and H_2S, kg atoms/kg mol O_2 fed as air

β_p = fraction of total input carbon appearing as char in stream (6), dimensionless

β_{NG} = methane feed rate expressed as mols of methane per mol of coal, dimensionless

β'_{NG} = methane feed rate expressed as kg of methane per kg as-fired coal, dimensionless

γ = a constant defined in equation 21

η_c = overall efficiency of particulate collector (both cyclones in series taken together as a single device), dimensionless

λ = dry gas flow rate, mols dry gas per mol O_2 fed as air

μ = molecular flow rates of individual species, kg mols/kg mol O_2 fed as air

μ_{coal} = total input rate of as-fired coal, mols/mol O_2 fed as air

μ_{CH_4} = input rate of CH_4, mols/mol O_2 fed in as air

$(\mu_{N_2})_o$ = input rate of atmospheric nitrogen, mols/mol O_2 in as air. $(\mu_{N_2})_o = 3.76$ in ordinary air

τ_{O_2} = oxygen requirement to completely burn one mol of "fuel," mols O_2/mol fuel

Δ_{12} = increment of char flow through the gasifier, mols char per mol of O_2 fed as air - a negative number if char is gasified by CO_2 or H_2O

Subscripts

i,1,2,3,etc = subscript denoting chemical "specie", e.g., char, ash, N_2, CO, H_2, CO_2, H_2O, H_2S, CH_x

1,2,3,4 = where specie is denoted by chemical subscript, numerical subscript denotes stream number

Air, Fuel = pertaining to feed streams

c,g,d,s = combustor, gasifier, devolatilizer, separator, respectively

C,O,H,N,S = pertaining to the elements carbon, oxygen, hydrogen, nitrogen, and sulfur, respectively

Appendix F

MATERIAL AND CHEMICAL SPECIES PROPERTIES AND HEAT TRANSFER COEFFICIENTS

TABLE F.1 TABLE OF ACTUAL AND ADJUSTED MATERIAL DENSITIES (REFS. F.9, F.10, F.11)

Location	Material	Actual Density, kg/m^3	Adjusted Density kg/m^3
Gasifier Bottom			
	Silicon Carbide	2563.2	
	Kaotab CS Castable	2658.7	
	K-28 Firebrick	768.8	
	50/50 mix of Kaotab Cs and Crushed K-28 Firebrick	1714.0	
	K-23 Firebrick	496.5	
	K-3000 Firebrick	929.2	
	Carbon Steel	7689.6	
	Kaowool	96.1	
Top of Gasifier			
	Kaocast Castable	2018.0	2997.7
	Carbon Steel	7689.6	14418.0

TABLE F.1 CONT'D

Location	Material	Actual Density, kg/m^3	Adjusted Density kg/m^3
Top of Crossover			
	Kaocast Castable	2018.0	4708.8
	Carbon Steel	7689.6	222171.7
Bottom of Crossover			
	K-28 Firebrick	768.8	1624.4
	Kaocast Castable	2018.0	7846.6
	Carbon Steel	7689.6	34843.5
Top of Devolatilizer			
	Kaocast Castable	2018.0	2659.3
	Carbon Steel	7689.6	20633.8
Bottom of Devolatilizer			
	Kaocast Castable	2018.0	
	Carbon Steel	7689.6	

TABLE F.2 MATERIAL CONDUCTIVITY EQUATIONS (REFS. F.8, F.9, F.10, F.11)

Units: $\frac{\text{KCAL}}{\text{hr}\cdot {}^\circ\text{K}\cdot\text{M}}$

Silicon Carbide	$k = 11.46999 + 2.284821 \times 10^{-3}\ T - 5.02232 \times 10^{-7}\ T^2$
Kaotab CS	$k = 4.962047 - 4.276949 \times 10^{-3}\ T - 1.294516 \times 10^{-6}\ T^2$
K-28 Firebrick	$k = 0.1790266 + 3.72752418 \times 10^{-5}\ T + 8.9717814 \times 10^{-8}\ T^2$
K-23 Firebrick	$k = 0.077187126 + 9.0657337 \times 10^{-5}\ T + 1.9578549 \times 10^{-8}\ T^2$
K-3000 Firebrick	$k = 0.2836668 - 1.1380847 \times 10^{-4}\ T + 1.6013019 \times 10^{-7}\ T^2$
Kaocast	$k = 1.3026305 - 1.0754459 \times 10^{-3}\ T + 5.296965 \times 10^{-7}\ T^2$
Kaowool	$k = 0.977500$
Carbon Steel	$k = 44.60$

TABLE F.3 MATERIAL HEAT CAPACITY EQUATIONS (REFS. F.8, F.9, F.11)

Units: $\frac{\text{KCAL}}{\text{kg}\cdot{}^{\circ}\text{K}}$

Silicon Carbide	Cp = 0.285 - not a function of temperature
Carbon Steel	Cp = 0.107 - not a function of temperature
All refractories castable and firebrick	$Cp = 0.155861 + 1.184536 \times 10^{-4}\ T - 3.13417 \times 10^{-8}\ T^2$ (for T in °K)

TABLE F.4 HEAT CAPACITIES, ENTHALPYS, AND HEATS OF FORMATION FOR PROCESS SPECIES

Units: $\frac{\text{KCAL}}{\text{kg mol}}$ for T in °K

$$C_{Pi} = a_i + b_i T + C_i/T^2$$

$$h_i = a_i(T-298) + b_i/2(T^2-298^2) - C_i(\frac{1}{T} - \frac{1}{298}) + h_f$$

	Species	a_i	b_i	c_i	h_f
1	Ash	0.189	0.000081	0	0
2	Char	2.23	0.00291	0	0
3	N_2	6.66	0.00102	0	0
4	CO	6.79	0.00098	-1100	-26416
5	H_2	6.52	0.00078	1200	0
6	CO_2	10.55	0.00216	-204,000	-94,052
7	H_2O	7.17	0.00256	800	-57,798
8	H_2S	7.02	0.00368	0	-4815
9	Coal	5.13	0	0	*
10	CH_4	8.5	0	0	-17,889
11	O_2	7.16	0.001	-4000	0

*Eastern coal -4923, Western coal -19930

TABLE F.5 COEFFICIENTS FOR CALCULATION OF VISCOSITY; CONDUCTIVITY AND MOLECULAR WEIGHT (REFS. F.3, F.5)

Specie i	N_2 3	CO 4	H_2 5	CO_2 6	H_2O 7	H_2S 8	O_2 11
d_i	1.38×10^{-3}	1.35×10^{-3}	7.46×10^{-4}	1.51×10^{-3}	1.60×10^{-3}	1.58×10^{-3}	1.67×10^{-3}
S_i	102.38	88.93	176.13	206.48	510.54	332.00	116.40
k_i	.06702	.06850	.48417	.07287	.11527	.07233	.07323
p_i	.750	.776	.897	.870	1.444	.975	.704
m_i	28.01	28.01	2.016	44.01	18.02	34.08	32.00

TABLE F.6 COAL PROPERTIES

Analysis by Weight

#/# dry coal	Eastern	Western
C	0.727	0.694
H	0.051	0.047
N	0.010	0.009
Ash	0.105	0.078
S	0.032	0.004
O	0.075	0.188
H_2O (l)	0.015	0.150
Total	1.015	1.150
Fixed Carbon (CH_y)	0.489	0.511
Heating Value	13,100	11,830 Btu/# dry coal

Analysis by Atom Ratios

kg atoms/kg atom carbon	Eastern	Western
H , z'	0.863	1.095
N , w'	0.012	0.011
Ash, t'	1.735**	1.350**
S , v'	0.017	0.002
O , w'	0.091	0.347
CH_y, Y'	0.660	0.723
y	0.24*	0.22*
CH_x, β_g	0.06*	0.06*
x	2.5*	2.5*
h_f	-4923**	-19930**kcal/kg atom c

* Typical values found in these tests; individual runs may show slight variance

** Calculated assuming molecular weight of ash is unity and heat of formation is zero

F.1 CALCULATION OF HEAT TRANSFER COEFFICIENTS

INTERNAL WALLS

Coal Firing:

$$N_{RE} \triangleq 0.3537 \frac{\dot{w}}{\bar{\nu} D}$$

$$N_{PR} \triangleq 3.6 \frac{\bar{C}_p \bar{\nu}}{\bar{k}}$$

$$N_{NU} = 0.023 \, (N_{RE})^{0.8} \, (N_{PR})^{0.4} \left\{ 1 + \left[\frac{D}{(N-.5)\,L} \right]^{0.7} \right\} \quad \text{(Ref. F.1)}$$

(N = index number of axial element, L = length of axial element)

Heat Transfer Coefficient For Convection

$$h_c = \frac{N_{NU} \, \bar{k}}{D}, \quad \frac{\text{KCAL}}{\text{M}^2 \cdot \text{HR} \cdot {}^\circ\text{K}}$$

Heat Transfer Coefficient For Radiation

$$h_r = 4.88 \times 10^{-8} \frac{\left[\bar{T}^4 - (T_{wall} + 100)^4\right]}{\left[\bar{T} - (T_{wall} + 100)\right]} \quad \varepsilon, \quad \frac{\text{KCAL}}{\text{M}^2 \cdot \text{HR} \cdot {}^\circ\text{K}}$$

($\bar{T}$ = average gas temp. over element, $\varepsilon=1$ for coal firing)

Heat Flux Density to Internal Walls

$$q = \frac{\bar{T} - T_{Wall}}{\frac{1}{h_c + h_r} + \text{Resistance of Char Layer}}$$

Heat Flux to Wall

$$Q = \frac{q\ (\text{Area})}{\dot{M}_{O_2}},\ \frac{\text{KCAL}}{\text{Kg Mol } O_2}$$

Natural Gas Firing:

The equations for natural gas firing are identical to those for coal firing with the one exception of that for the HEAT TRANSFER COEFFICIENT FOR RADIATION. For coal firing the presence of a large amount of fine char would make the gas emissivity very nearly equal to unity, the value which we assumed. However, for natural gas firing at A/F ratios of 1 or greater very little char would result, therefore the gas emissivity was calculated. This calculation was based on the assumption that CO_2 and water vapor would be the main source of radiant energy. The fact that the emissivity varies as a function of temperature was taken into account by breaking the system up into three main temperature ranges. The calculation of the emissivity is shown below (Ref. F.2):

$$\varepsilon = e^{-(\gamma_m + \delta\bar{T})} + e^{-(\zeta_m + \eta_m\bar{T})} + \theta_m$$

	γ_m	δ_m	ζ_n	η_m	θ_m
Top and Bottom of Gasifier	1.57	2.72×10^{-4}	1.59	2.89×10^{-4}	-.04
Top and Bottom of Crossover Pipe	1.88	2.69×10^{-4}	1.31	2.73×10^{-4}	-.001
Top and Bottom of Devolatilizer	1.62	2.41×10^{-4}	1.76	6.41×10^{-4}	-.012

F.2 CALCULATION OF PHYSICAL PROPERTIES AND FLOW OF PROCESS SPECIES

Individual Species:

Viscosity (centipoise) $\nu_i = \frac{d_i \bar{T}^{3/2}}{(S_i + \bar{T})}$ where $\bar{T}$ is the average temperature over an axial element (Ref. F.4, F.5)

Conductivity $\left(\frac{\text{KCAL}}{\text{M}\cdot\text{HR}\cdot{}^{o}\text{K}}\right)$ $k_i = \left(\frac{\bar{T}}{1200}\right)^{pi} k_{O_i}$ (Ref. F.3, F.6)

Heat Capacity $\left(\frac{\text{KCAL}}{\text{Kg}\cdot\text{mol}\cdot{}^\circ\text{K}}\right) C_{P_i} = a_i + b_i \bar{T} + \frac{c_i}{\bar{T}^2}$ (See Table E-2 for coefficients)

Gas Mixture:

Viscosity (centipoise) $\bar{\nu} = \frac{\sum_{i=3}^{8} \bar{\mu}_i \nu_i M_i^{1/2}}{\sum_{i=3}^{8} \bar{\mu}_i M_i^{1/2}}$ (Ref. F.3)

Conductivity $\left(\frac{\text{KCAL}}{\text{kg}\cdot\text{mol}\cdot{}^\circ\text{K}}\right) \bar{k} = \frac{\sum_{i=3}^{8} \bar{\mu}_i k_i M_i^{1/3}}{\sum_{i=3}^{8} \bar{\mu}_i M_i^{1/3}}$ (Ref. F.3)

Heat Capacity $\left(\frac{\text{KCAL}}{\text{kg}\cdot\text{mol}\cdot{}^\circ\text{K}}\right) \bar{C}_p = \frac{\sum_{i=1}^{8} \bar{\mu}_i C_{pi}}{\sum_{i=1}^{8} \bar{\mu}_i M_i}$

Flowrate $\left(\frac{\text{kg}}{\text{hr}}\right)$ $\dot{W} = \dot{M}_{O_2} \sum_{i=1}^{8} \bar{\mu}_i M_i$

where $\bar{\mu}_i$ is the flow of a given species such as CO, CO_2, etc.,

in $\frac{\text{kg mols}}{\text{kg mol } O_2 \text{ in air feed}}$

M_i is the molecular weight of a species

$\dot{M}_{O_2}$ flow rate of OXYGEN from AIR to system kg mols O_2/hr

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