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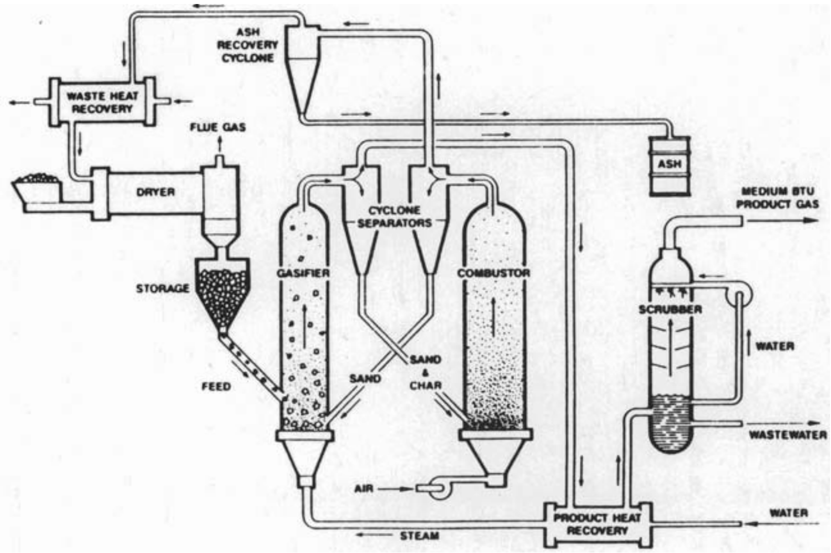
Subcontractor Report

Gasification of Refuse Derived Fuel in the Battelle High Throughput Gasification System

July 1989



Prepared for the
U.S. Department of Energy
under Contract DE-AC06-76RLO 1830

Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
by Battelle Memorial Institute

Battelle

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GASIFICATION OF REFUSE DERIVED FUEL IN THE BATTELLE HIGH THROUGHPUT GASIFICATION SYSTEM

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July 1989

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Richland, Washington 99352

EXECUTIVE SUMMARY

Battelle has conducted a testing program to evaluate the application of its High-Throughput Gasification Process to non-wood biomass fuels. The feedstock chosen for this study was a prepared municipal solid waste, Refuse Derived Fuel (RDF).

The successful application of gasification as a disposal method has advantages over state-of-the-art approaches such as land filling or mass burn technology. A more readily usable form of energy is produced and at a cost significantly lower than mass burn technology.

Experimental Program

The experimental results discussed in this report demonstrate the similarity of RDF, as a gasification feedstock, to wood. The Battelle Gasification Process has been extensively tested with wood and this data base then can be confidentially applied to RDF gasification. In the two-stage Battelle process, RDF is gasified to a medium Btu gas (500-550 Btu/scf) without oxygen in a high-throughput gasifier and residual char is consumed in an associated combustor. A circulating sand phase provides heat transfer between the separate reactors.

The process is environmentally simple with gaseous emissions from the combustor being well within new source performance standards. Waste water from the process contains only trace quantities of organic materials. The outlet of a simple industrial treatment system at Battelle's PRU site showed waste water to be within EPA's drinking water standards. This treatment consisted of a sand filter followed by a simple charcoal filter.

Process Economics

A preliminary economic evaluation was made to compare the performance of the Battelle process to mass burn technology. The throughputs possible in the Battelle gasification process (over 2000 $lb/hr\text{-}ft^2$) result in extremely compact reactor vessels. Capital costs are thus greatly reduced providing capital advantages over mass burn technology. A 2000 TPD RDF gasification plant is projected to cost $89 million compared to $170 million for a similarly sized mass burn facility. Both cost estimates assume electric power is the prime product from the plant and so include the costs of turbines necessary for power production.

The gasification plant will produce more power per unit of RDF-fired than will a similarly sized mass burn plant. For the same 2000 TPD plant size, 60 MW would be produced from the mass burn facility while 112 MW would be produced by gasification. This dramatic difference is possible because of the higher thermal efficiencies of gas combustion turbines over steam turbines.

These economics show that the Battelle Gasification Technology can compete favorably with mass burn technology in the marketplace both in terms of capital cost and in quantity of power produced. The program described in this report provides data on the Battelle process that demonstrates the following benefits to users of the technology.

- High throughputs resulting in reduced capital costs
- Low capital and operating costs through elimination of oxygen in the gasifier
- High energy density product gas providing ready application in existing combustion equipment
- Low by product production resulting in simple environmental control systems.

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FINAL REPORT

on

GASIFICATION OF REFUSE DERIVED FUEL IN THE BATTELLE HIGH THROUGHPUT GASIFICATION SYSTEM

INTRODUCTION

This report presents the results of an experimental program to demonstrate the suitability of the Battelle High Throughput Gasification Process to non-wood biomass fuels. An extensive data base on wood gasification was generated during a multi-year experimental program. This data base and subsequent design and economic analysis activities led to the discussion to study the gasification character of other fuels. The specific fuel studied was refuse derived fuel (RDF) which is a prepared municipal solid waste (MSW). The use of RDF, while providing a valuable fuel, can also provide a solution to MSW disposal problems.

The disposal of MSW is becoming an increasingly serious problem throughout the United States. With MSW generation rates of 5 to 10 lbs/person/day even modest sized cities have a serious disposal problems.(1) Sites available for landfills are scarce and environmental regulations and other siting requirements further limit available land. Various research and commercial scale programs have been conducted to develop improved methods for disposal of these materials.

Gasification of MSW provides advantages over land fill or mass burn technology since a more usable form of energy, medium Btu gas, is produced. Land filling of wastes produces no usable products and mass burning while greatly reducing the volume of wastes for disposal can produce only steam. This steam must be used on site or very nearby thus limiting the potential locations for mass burn facilities. Such a gas, if produced from currently available supplies of MSW, can contribute 2 quads to the U.S. energy supply.

BACKGROUND

Development efforts on the Battelle High Throughput Gasification Process were initiated in 1977. Detailed process development activities were initiated in 1980 with the construction and start-up of a process research unit (PRU) at Battelle's West Jefferson Laboratory. These PRU investigations, conducted during the mid-1980s demonstrated the technical feasibility of the gasification process and provided the basis for a detailed process conceptual design to be generated.

The PRU design was such that the inherently high reactivity of biomass feedstocks could be exploited. Conventional reactor systems, i.e., fixed bed and bubbling fluid bed gasification processes could not provide sufficient throughput of the biomass materials to take advantage of the biomass reactivity.

The Battelle process employs a circulating fluid bed gasifier to provide sufficiently high throughputs of biomass material. Heat necessary for the gasification reactions is provided from a stream of circulating sand which passes between the gasifier and an associated combustion reactor. The process is shown schematically in Figure 1. A small amount of char is produced as a result of the gasification reactions (typically 20 percent of the feed material). This char provides the fuel for the combustor to reheat the circulating sand. The combustor like the gasifier is a circulating fluid bed reactor and also is capable of high throughputs.

Experimental data were generated in the PRU in gasifiers of 6 in. diameter and 10 in. diameter. Data from these two reactors showed that extremely high throughputs (over 4000 $lb/hr\text{-}ft^2$) could be achieved. A wide range of feed materials has been tested in the system including:

- Hardwood and Softwood Chips
- Shredded Bark
- Sawdust
- Whole Tree Chips
- Shredded Stump Material

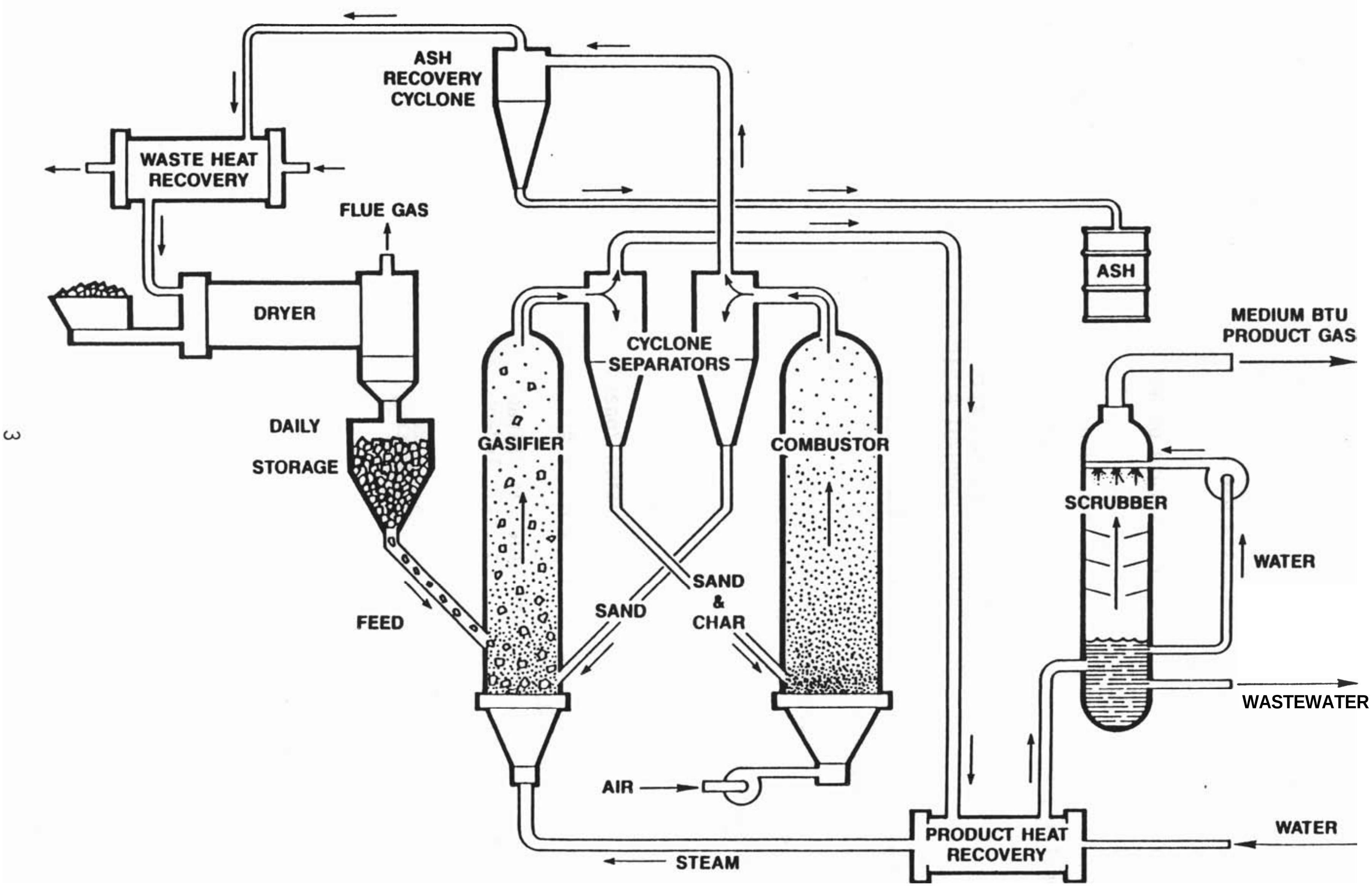


FIGURE 1. BATTELLE'S BIOMASS GASIFICATION SYSTEM

These tests demonstrated the flexibility of the system to handle a variety of diomass forms with little or no preparation. This flexibility in feedstock acceptance led to the use of RDF as a feedstock for the process.

As an additional process benefit, the product gas heating value was consistent regardless of the moisture or ash content of the feed material tested.

The Battelle process was found to have the following important benefits, shown in Table 1, when compared to other available technologies.

TABLE 1. FEATURES/BENEFITS OF THE BATTELLE HIGH THROUGHPUT GASIFICATION PROCESS

High Throughput

- Reduced Investment
- Modularized Construction

No Oxygen Plant Required

- Low Operating Costs
- Reduced Plant Investment

Separation of Gasification/Combustion Zones

- High Energy Density Product Gas -- Directly Substitutes for Oil or Natural Gas
- High Temperature Flue Gas Valuable for Heat Recovery
- Product Gas Heating Valve Independent of Feed Moisture

No Significant Byproduct Production

- Process/Environmental Simplicity

Ability to Handle Wide Range of Feedstocks Without Preparation

- Minimized Feed Costs
- Increased Flexibility

PROCESS DESCRIPTION

The **Basic** Concept

The Battelle biomass gasification process produces a medium-Btu product gas without the need for an oxygen plant. The process schematic in Figure 1 shows the two reactors and their integration into the overall gasification process. This process uses two physically separate reactors: (1) a gasification reactor in which the biomass is converted into a medium Btu gas and residual char and (2) a combustion reactor that burns the residual char to provide heat for gasification. Heat transfer between reactors is accomplished by circulating sand between the gasifier and the combustor.

The Battelle Process provides a cooled, clean, 450-500 **Btu/scf** product gas with wood as the feedstock. Waste heat in the flue gas from the combustor can be used to preheat incoming air and then to dry the incoming feedstock. Although these unit operations are not required, they provide a means of increasing product yield by returning waste heat to the process. The condensed organic phase scrubbed from the product gas is separated from the water, in which it is insoluble, and injected into the combustor. As Figure 1 indicates, the products from the process are the cooled cleaned product gas, ash, and treated wastewater.

The flexibility of the process and the potential improvements in economics compared to conventional methods of MSW disposal led to the initiation of the current program.

Application of the Technology to RDF

Table 2 shows the chemical similarity of wood and RDF. The analysis shown is a typical analysis for RDF produced by National Ecology in Baltimore, Maryland. This same RDF has been used during the PRU tests described below. The chemical similarity of the two materials suggested that RDF might behave in a similar manner to wood in the Battelle process. The PRU tests conducted during the current program verified this expectation and so demonstrated the

TABLE 2. COMPARISON OF WOOD AND RDF ANALYSES

	% Dry Basis	
	Wood	RDF
Volatile Matter	83.89	77.76
Fixed Carbon	15.78	11.23
Ash	0.33	11.01
C	52.37	47.31
H	6.04	6.16
N	0.02	0.68
O	40.97	34.70
S	0.25	0.14
Cl	0.02	--
Btu	8739	8082

potential of the process to provide an economical alternative to current RDF disposal methods.

The medium Btu gas generated can be readily used in conventional natural gas fired combustion equipment. Examples of potential users of the gas are: steam boilers, gas turbines, industrial heat treating furnaces, and process heaters.

Anticipated Cost Advantages

For power generation, the lower capital costs combined with the increased power generation efficiency of a combined cycle make the Battelle gasification system especially attractive. Since the final energy product of most waste-to-energy plants is electricity, applying Battelle gasification technology to RDF is a logical extension of its development and demonstration for biomass applications. A more detailed discussion of projected costs is found below.

Gasification Character

A preliminary test was run in a scaled down version of the PRU. Although not directly a part of this program, this test showed that the conversion of RDF corresponded directly to conversion levels measured with wood.

EXPERIMENTAL PROGRAM

Experimental Equipment

The RDF test described above was conducted in a continuous 2 in. entrained gasifier. This test indicated that the 2 in. unit could be used to screen various types of RDF. However, to generate process scale-up data and to process sufficient RDF to reveal any product shifts due to heterogeneity of the RDF requires testing in the larger capacity biomass gasification PRU. A schematic of this facility is shown in Figure 2. The PRU integrates all the critical unit operations required to convert RDF to a medium-Btu gas including:

- Automated transport of the RDF from storage to a lock hopper feeder system.
- Continuously monitored feeding of the RDF into the gasifier.
- RDF gasification with continuous transfer of circulating solids and char into the gasifier.
- RDF char combustion with circulation of hot solids back to the gasifier controlled by an L-valve.

Scrubbing of medium-Btu product gas and continuous analytical monitoring of the product gas composition.

The PRU used throughout the project is described in detail below. This equipment is shown schematically in Figure 2 and Figure 3 is a photograph of the system.

The combustor is a 40 in. internal diameter fluidized-bed with an active height of 11.5 ft. This unit is a refractory-lined vessel with a total refractory thickness of 7 in. The refractory lining consists of a 4 in. cast inner lining surrounded by 3 in. of board insulation. The lining is designed to allow a metal vessel shell temperature of approximately 240 F to minimize

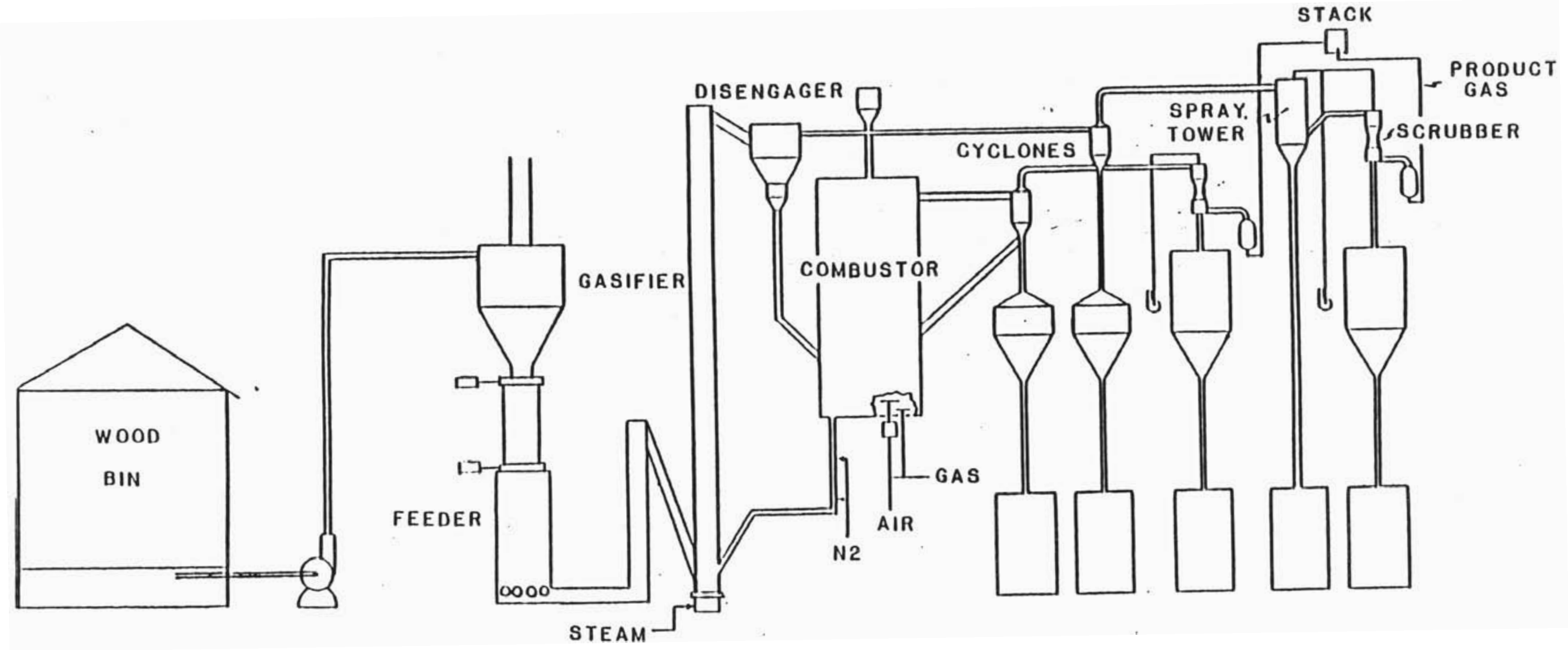


FIGURE 2. BATTELLE'S BIOMASS GASIFICATION PRU

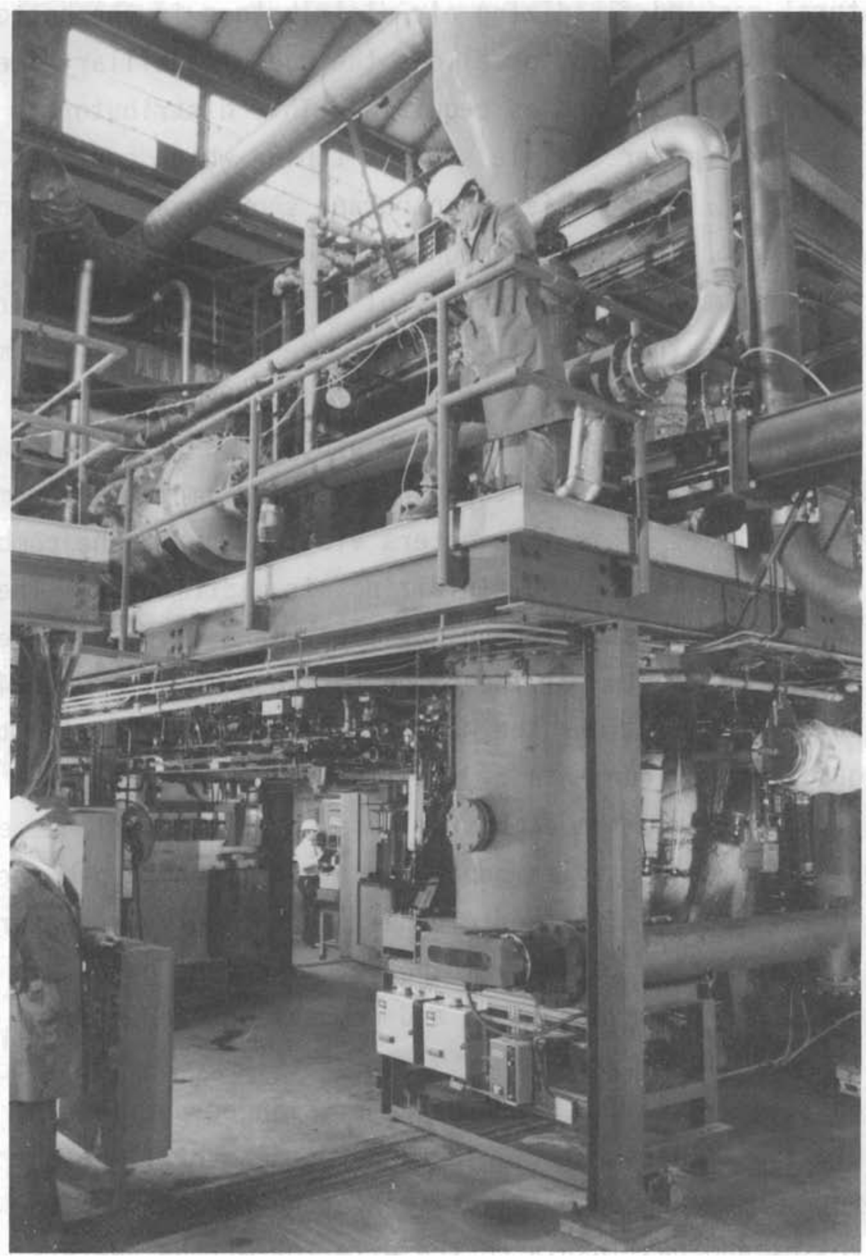


FIGURE 3. BATTELLE'S BIOMASS GASIFICATION PRU

heat losses. The combustor is instrumented with a number of thermocouples and pressure taps around the perimeter of the vessel at various levels to allow both temperature and pressure monitoring. It is heated initially, during start up, by the use of a natural gas fired start-up burner. The combustor is fitted with natural gas and fluidizing air distributors in the bottom of the vessel. The natural gas distributor allows the use of auxiliary fuel for heating the fluidized bed of sand as required. This distributor is constructed of ½-in. diameter stainless steel tubing which contains 40-7/64-in. diameter orifices. Figure 4 is a photograph showing an overhead view of the air and gas distributors looking down from the top of the combustor. The fluidizing air distributor was constructed of 1-in. diameter pipe from a 3-in. diameter header and contained 60 orifices that are 0.149 in. in diameter. Each orifice is protected by a 2/3 section of ½-in. diameter tubing welded over the orifice to prevent the orifice from plugging during shutdown.

Sand enters the combustor through a 6-in. diameter downcomer line from the gasifier cyclone. This line enters via the top of the combustor and extends down to within 8 in. of the fluidizing air distributor. The sand bed is circulated from the combustor to the gasifier via a 4-in. diameter L-valve which enters through the bottom of the combustor to a level about 24 in. above the air distributor. This allows the monitoring of a seal between the combustor and gasifier environments by the fluidized bed of sand.

Exhaust gases from the combustor pass through a cyclone separator which discharges the fine particles separated directly back into the fluidized bed. The flue gases then are further cleaned and cooled by a venturi-type scrubber prior to exhausting to the atmosphere. The flue gases are continuously monitored for oxygen level and combustion products. A sketch of the combustor is shown in Figure 5.

The gasifier vessel is constructed of flanged sections of 10-in. diameter Schedule 40 stainless steel pipe and has an overall height of 22.7 ft. The gasifier is surrounded by electric heating elements of the entire length of the vessel and has insulated the exterior of the heaters with about 2 in. of ceramic fiber insulation to prevent heat losses. Fluidizing gases enter the gasifier through a plenum arrangement at the bottom of the gasifier at a level below the RDF feed entry post and the L-valve sand recycle entry

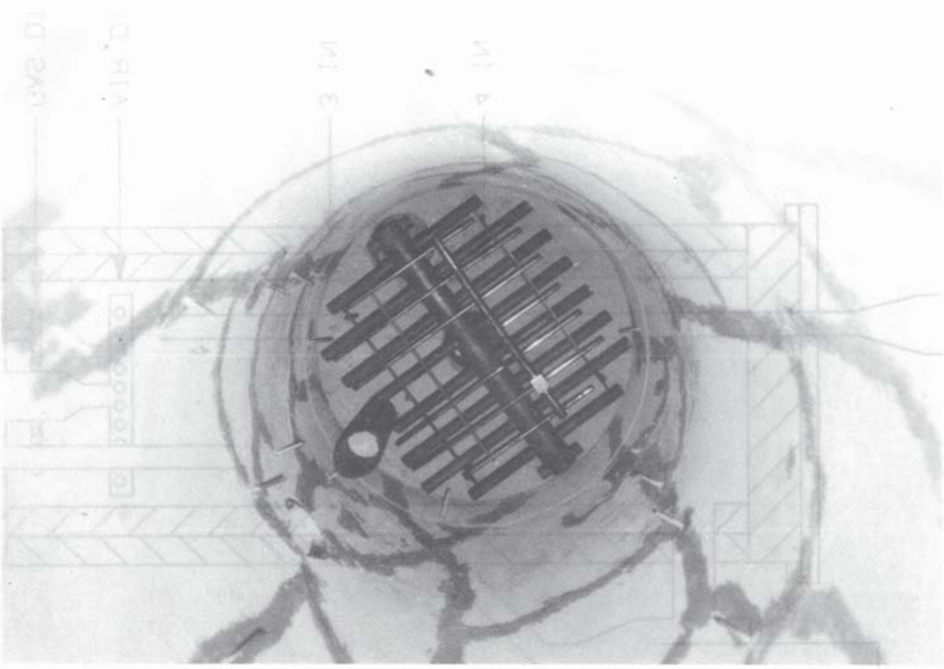


FIGURE 4. PHOTOGRAPH SHOWING OVERHEAD VIEW OF AIR AND GAS DISTRIBUTORS

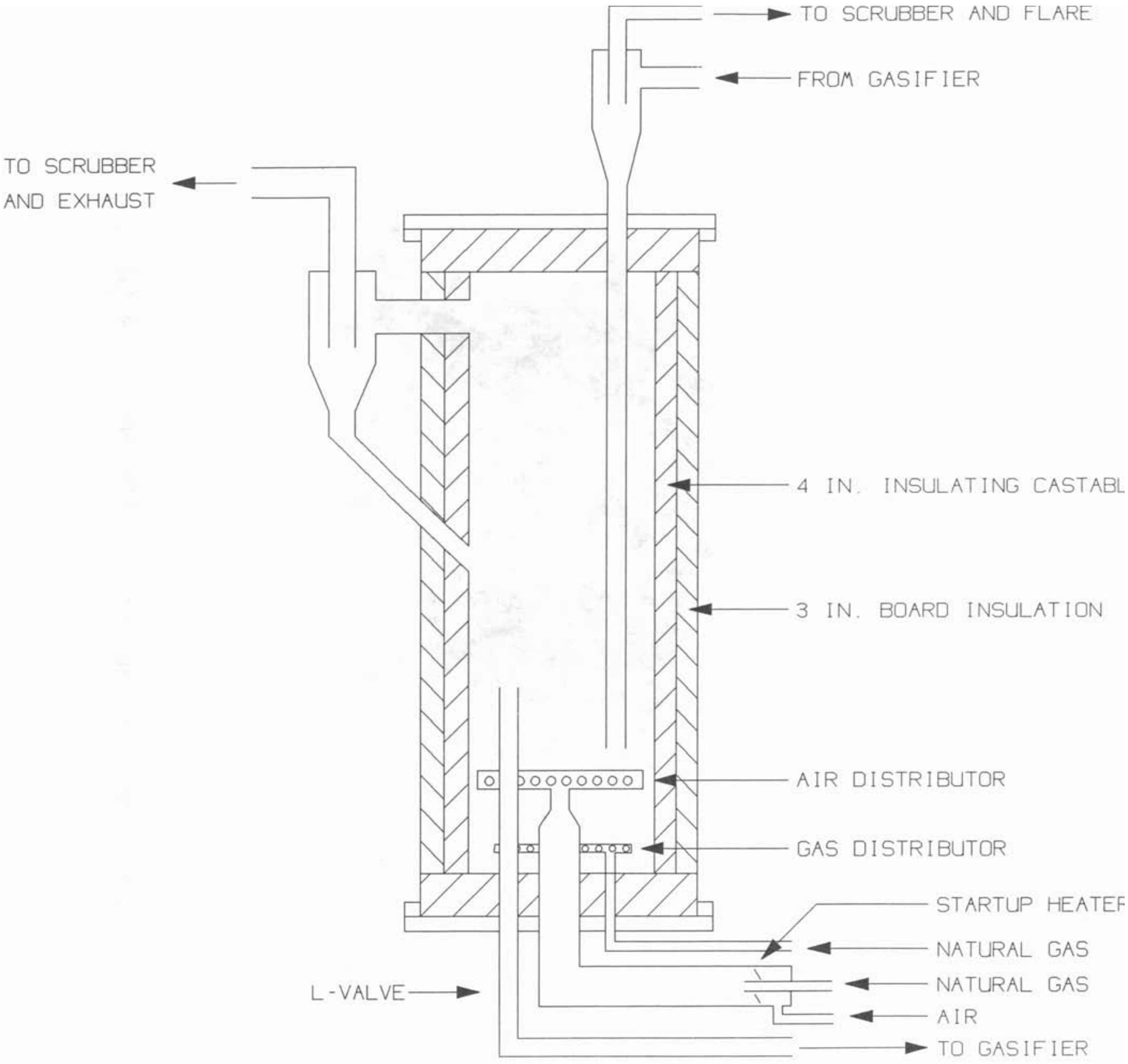


FIGURE 5. DETAILED SKETCH OF COMBUSTOR VESSEL

point. The sketch in Figure 6 shows the base of the gasifier. The gasifier vessel is fitted with 12 temperature measurement locations and 13 pressure taps.

The sand, char and product gas are conveyed out of the top of the gasifier into the cyclone mounted on top of the combustor which disengages the sand and char and allows them to flow back into the combustor by gravity via the 6 in. downcomer. After separation of the sand and char in the cyclone, the product gas passes through an additional cyclone and is then cooled in a spray tower. A sample of the product gas is analyzed for composition and the remainder is burned in a flare.

Hot sand circulation between the combustor and gasifier is accomplished by a conventional L-valve. The L-valve utilizes a low flow of gas to aerate solids thus allowing flow. Figure 7 is a sketch of the L-valve used. It is constructed of 4-in. diameter stainless steel pipe and is insulated on the exterior with ceramic fiber insulation. Sand circulation ratios were controlled by varying the flow of gas introduced into the vertical leg of the L-valve. There is no direct measurement of solid flow rates through the L-valve but the solids flow through the valve is adjusted to provide the desired temperature difference between the gasifier and combustor. Thus, the gasifier temperature and the temperature differential between vessels are parameters of concern and not circulation rate.

Figure 8 shows schematically the feed system utilized for introducing the shredded RDF into the gasifier. The system consisted of a 15-ft diameter storage silo from which the RDF is transported using a screw auger mounted so as to feed from the center of the floor of the silo. The auger feeds into a 10 HP blower which pneumatically transports the RDF into a lock hopper assembly which is mounted on load cells to provide a constant recording of the hopper assembly plus the contained RDF. The metering bin of the lock hopper system is mounted directly over four 4-in. metering augers which carry the RDF into a 9-in. horizontal auger which empties into the bottom of a 9-in. vertical auger. From the top of the vertical auger the RDF falls, by gravity, down a 6-in. diameter pipe at 20 degrees from vertical into the bottom of the gasifier. At the bottom of the gasifier the RDF contacts the incoming hot sand and the RDF/sand suspension is transported up the height of the gasifier.

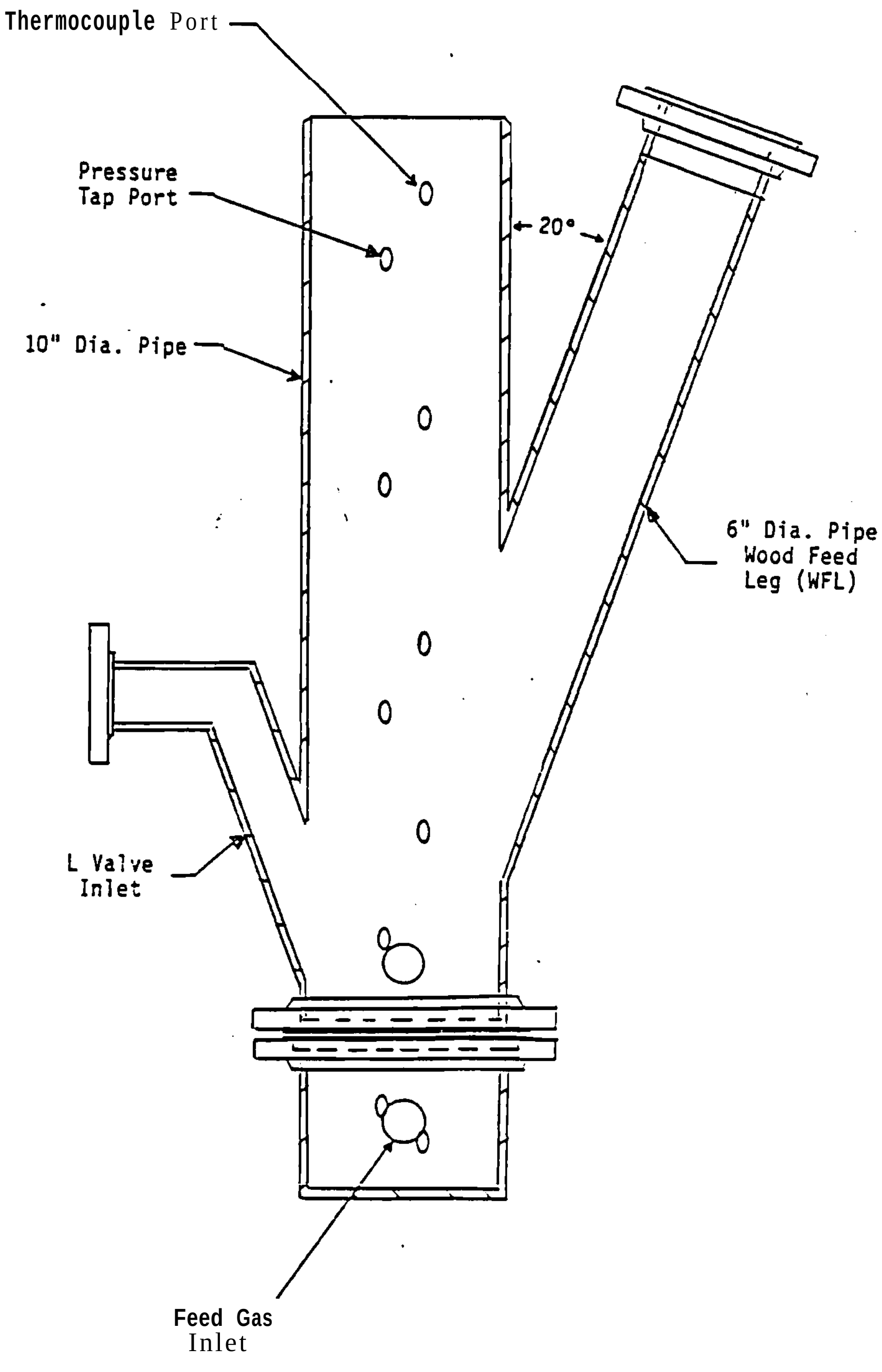


FIGURE 6. BASE OF BATTELLE GASIFIER

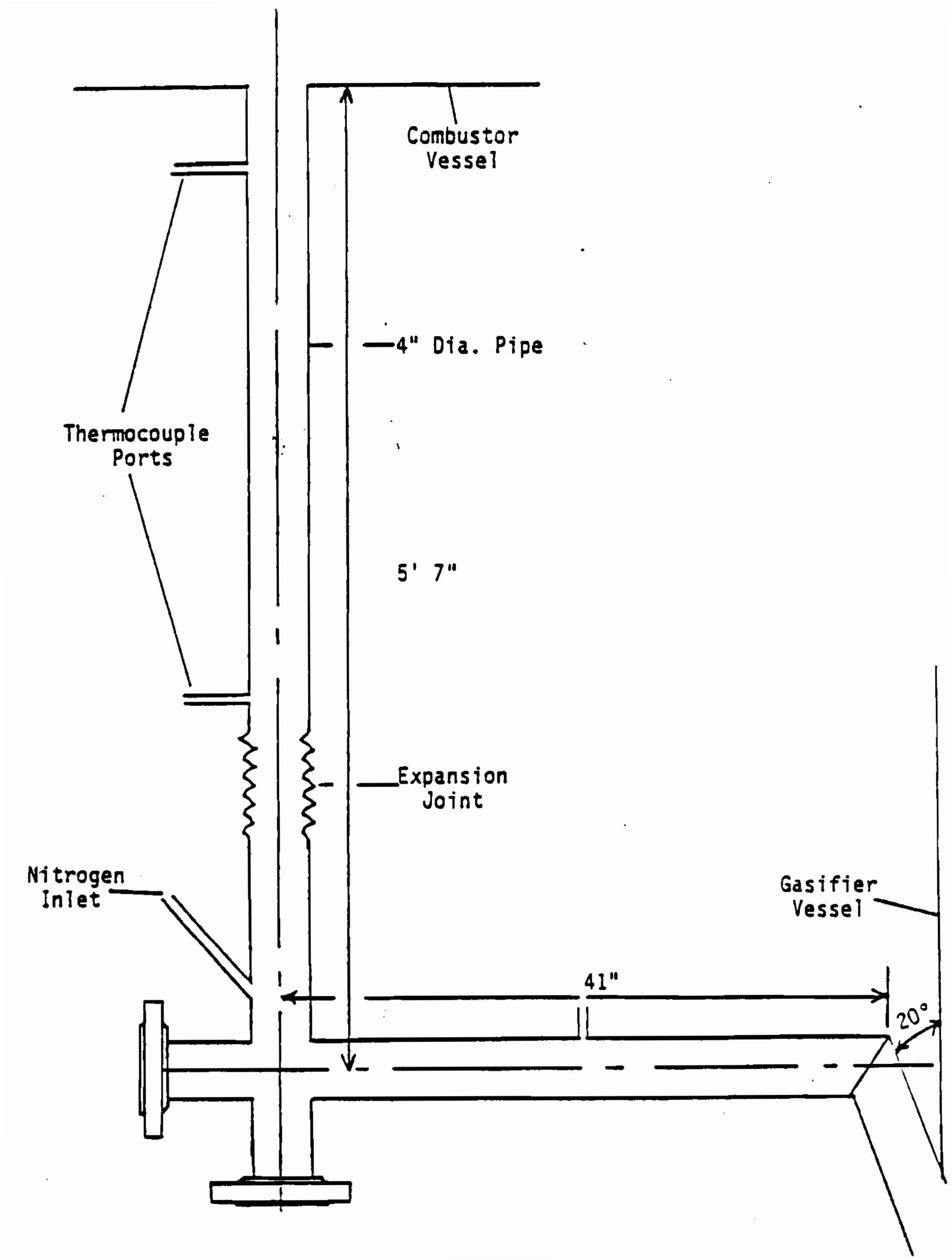


FIGURE 7. L-VALVE SYSTEM

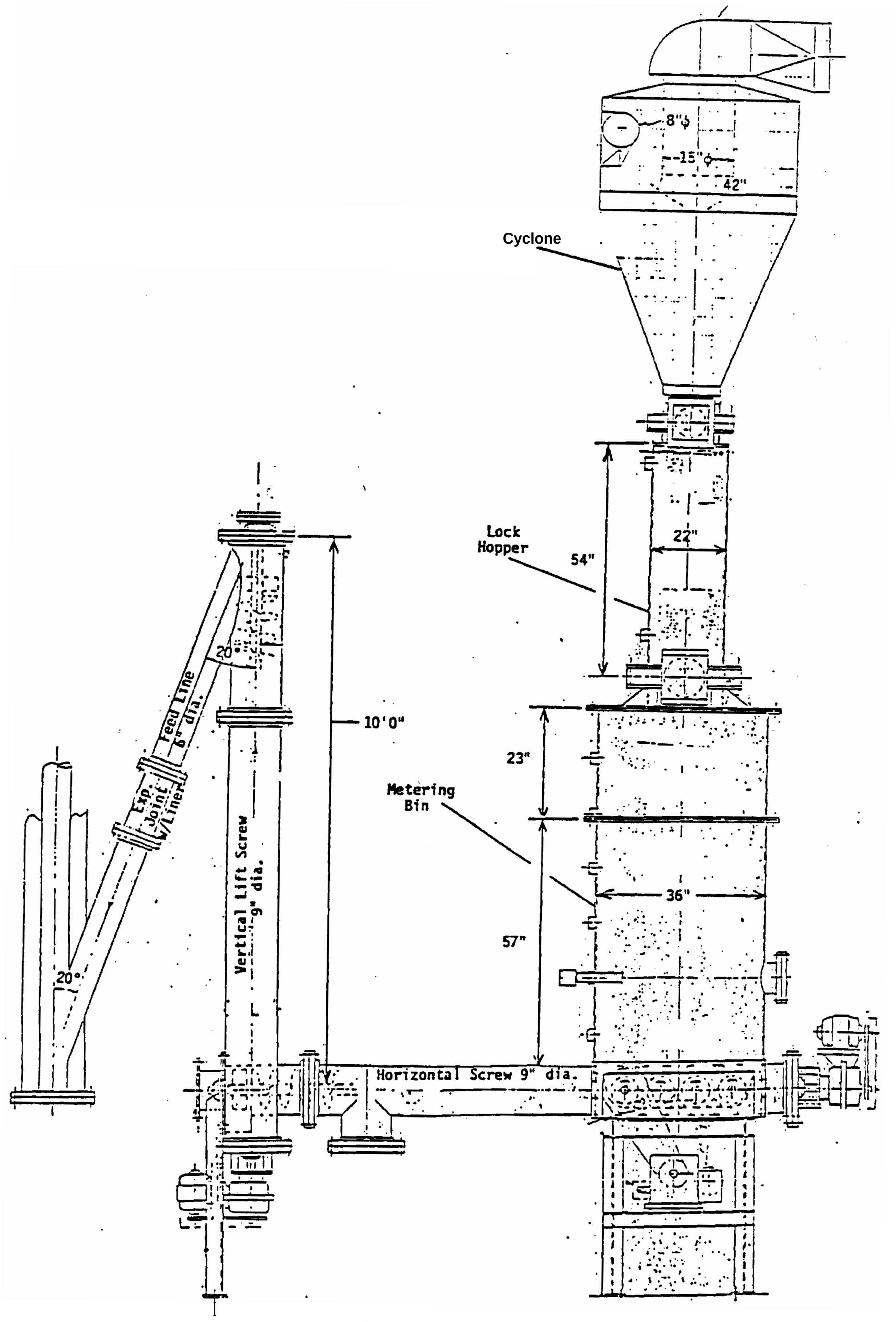


FIGURE 8. WOOD FEED SYSTEM

The transport of RDF to the hopper assembly, charging of hoppers, pressurizing of hoppers, valve operation and auger operation are automatically controlled electronically by level sensing probes in the hoppers. The lock hopper cycle time is approximately 2 minutes.

The pilot-scale experimental equipment is totally instrumented throughout the system to allow measurement of temperatures, pressures, pressure differentials, flow of air, nitrogen, steam, natural gas and RDF as well as flue and product gas composition. Pressure is measured at over 30 locations throughout the system and temperatures are measured at about 60 locations. Gas, steam and air flows are measured using conventional orifice plates and the orifice AP is continually recorded on strip chart recorders as are the temperatures and pressures. A computerized data acquisition system also collects the process data and stores it on floppy disk. The product and flue gases are sampled and analyzed continuously. Infrared analysis for methane and carbon monoxide in the product gas is utilized while Beckman paramagnetic oxygen analyzers monitor the flue gas. Analyses of the product gas is accomplished every 20 minutes using a gas chromatograph.

DATA ACQUISITION AND ANALYSIS

The core of the data acquisition system is an IBM compatible personal computer and a Hewlett-Packard HP3497A data acquisition and control unit. The computer is equipped with an HPIB interface card to allow communication with the HP3497A. A set of BASIC subroutines supplied by Hewlett Packard were used to simplify these communications. Plug in modules are used in conjunction with the HP3497A to allow measurement of specific functions, in this case thermocouples and voltages.

All system temperatures are measured with Type "K" thermocouples. System pressures and differential pressures are measured with pressure transmitters with a 4-20 mA output. These current signals were converted to a 1-5 V signal so they could be read by the HP3497A. The product gas composition is recorded directly by the computer through the computer's serial port from the gas chromatograph.

Oxygen content in the flue gas is also monitored by the HP3497A.

RDF feed rate, moisture content, heating value, carbon content and certain other parameters must be entered by the user and can be updated at any time during operation.

A BASIC program was written to allow monitoring and storage of system parameters. Raw measurements from the HP3497A are first converted to their respective system temperatures and pressures (and flue gas oxygen content). These temperatures and pressures are then used to calculate system flows. These data are then used in conjunction with the product gas composition to calculate performance parameters such as product gas flow, product gas heating value, cold gas efficiency, carbon conversion, and a carbon balance for the system.

Experimental Procedure

The normal operating procedure used during the project was to preheat the sand bed in the combustor prior to making a run. Approximately 2½ tons of sand (4 ft deep bed) is added to the combustor and the sand is preheated using the natural gas fired start-up burner. After the sand bed reached about 800 F and fluidization is established, sand circulation via the L-valve was also established for a short period of time (~1 hr) to heat this part of the system and remove any moisture introduced from the burning of natural gas. The system was allowed to heat overnight with the start-up burner maintained at 1500 to 1600 F. Flue gas and product gas scrubbers are also operated overnight to cool the exhaust gases.

On the day of the run, the start-up burner is discontinued and gas is introduced through the gas manifold to further heat the combustor bed to 1800 to 2000 F. The electrical heaters on the gasifier are turned on and preheated nitrogen and superheated steam are introduced to the gasifier. At this time sand circulation is initiated to heat the gasifier to the desired operating temperature by controlling nitrogen flow to the L-valve. After steady state operation is established at the desired temperatures, the RDF feed is introduced to the gasifier. Combustor temperature and L-valve flows are adjusted to maintain desired steady state operating conditions. The process gas is analyzed throughout the run and the various data recorded and stored to calculate gas production, carbon conversion and fuel utilization efficiency.

Typically, an experiment is completed in an 8 to 10 hr shift after overnight heat-up. This allows for 3 to 5 hrs steady state of data collection.

RESULTS AND DISCUSSION

Objectives

. The primary objective of the program was the demonstration of the feasibility of gasifying a commercial RDF in the existing Battelle PRU. Secondary objectives for the program were (1) to obtain process data from gasification of RDF, (2) to compare this data with the extensive wood gasification data base, and (3) to incorporate this data into an existing heat and material balance model to predict thermal performance of a commercial system using RDF as the feedstock.

All of these objectives were met during the program. A discussion of the results follows.

RDF Selection

Commercial grade RDF was chosen as the preferred initial feedstock for the experimentation in the PRU. Two likely suppliers were identified, the City of Madison, Wisconsin and National Ecology in Baltimore, Maryland. RDF from National Ecology was used for the PRU tests run due to availability and shipping problems in acquiring material from Madison.

The Baltimore facility is a state-of-the-art process which produces a "fluff" material that is later sold as fuel. A large fraction of the fuel is burned in boilers at the local Baltimore Gas and Electric site. In the National Ecology plant, incoming waste undergoes primary shredding, followed by removal of ferrous material. The remaining material is air classified with the light fraction going to a screening operation to remove fine glass and grit. The screen over material undergoes secondary shredding which produces the final 1-inch RDF product. Seasonal variations in ash content of the material have been reported but these are relatively modest with total ash content varying from 6.5% to 13% with an average of 9.24%. No significant variation in ash composition or fusion point has been reported. The level of preparation in the national Ecology plant then produces a relatively stable, reliable feedstock. Later phases of this development program will investigate whether this degree of RDF preparation is necessary or a more modest preparation technique could be used.

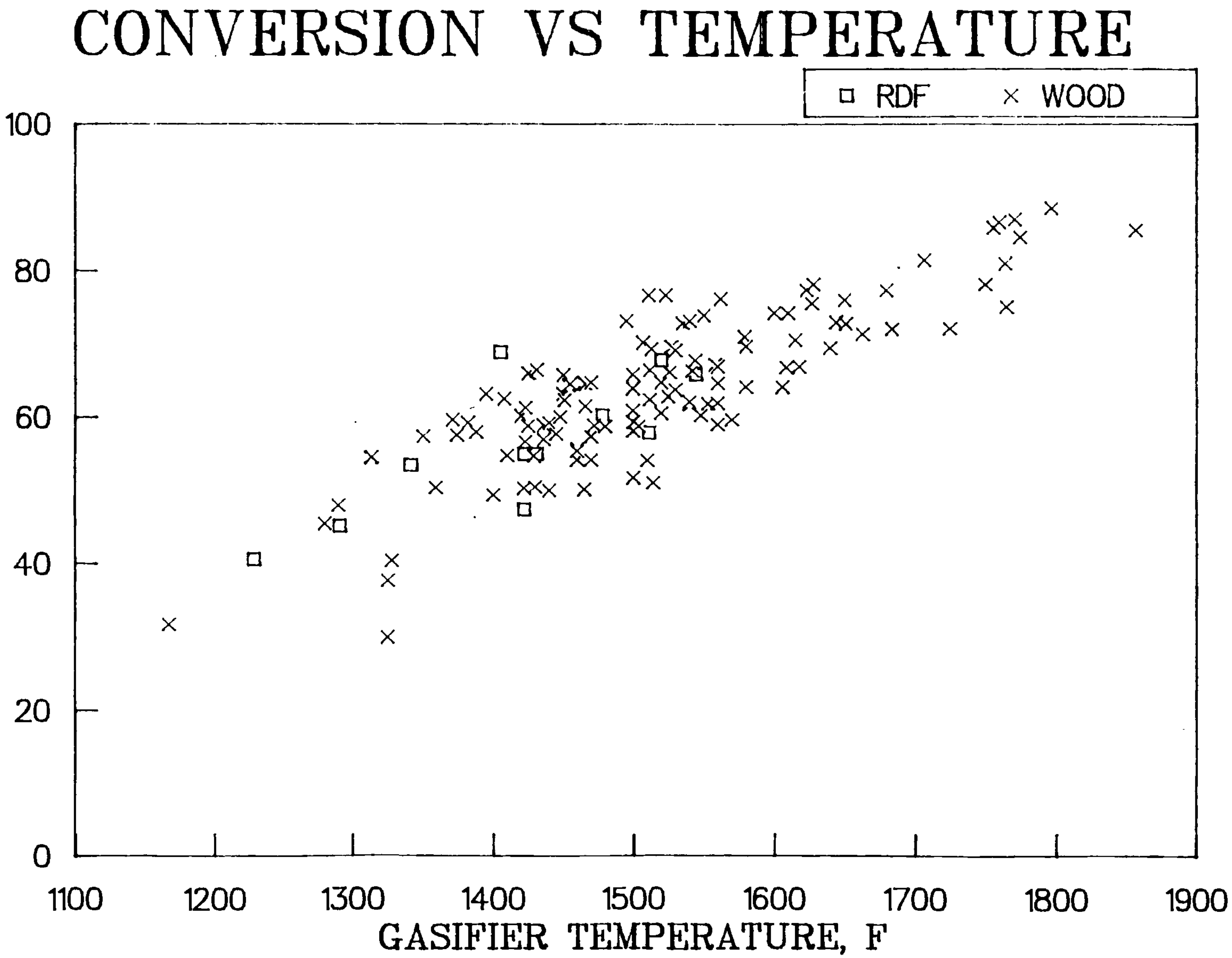
Shakedown Testing

Initial operations in the PRU identified necessary modifications to the PRU feeder so a stable, reproducible RDF feed rate could be obtained. The nature of the RDF fed was such that it tended to pack in the lock hoppers and bridge over the screws in the metering bin. Tom Miles (the designer of the original feed system) was consulted to provide design modifications to the feed system which alleviated the feed problems.

The modifications made to the feed system included, replacement of the metering screws with a different size; addition of a straight sided liner to the metering bin; addition of an inverted conical liner to the lock hopper; and modification of the intersection of the horizontal and vertical conveying augers. An overall view of the feed system was shown in Figure 9. These modifications provided a continuous feed rate of about 400 lb/hr to the gasifier. A feed rate of 600 lb/hr could be reached for short periods of time, but the cycle times required for the lockhopper valves restricted higher rates from being achieved.

A further limitation to high feed rates was related to the RDF itself. The "fluff" material while having a packed bulk density near that of wood (~8 lb/ft^3) became a material with a bulk density in the range of 1 lb/ft^3 after handling. For a 400 lb/hr feed rate 400 ft^3 of material must be handled. This corresponds to 34 fills of the lock hopper per hour or one fill every 1-3/4 minutes. This rate is the maximum that can. be achieved with the existing feed system. As was the case with wood, the feed system was the

FIGURE 9


CONVERSION VS TEMPERATURE
RDF
WOOD
CARBON CONVERSION, %
0
20
40
60
80
100
1100
1200
1300
1400
1500
1600
1700
1800
1900
GASIFIER TEMPERATURE, F

limiting factor in throughput achievable with the system. In commercial operation this type of limitation can be overcome by adding an additional feed system or a large lock hopper system.

Testing and Data Acquisition

Within the 10 PRU runs made during the program, 11 test data periods were achieved that were of sufficient duration to provide data on the system performance. The overall results from these data periods are found in Table 3. The calculational procedure utilized was documented in the wood gasification final report(2) and is included in Appendix B.

In addition to the primary variable of interest, gasifier performance, all other systems within the PRU were evaluated during these tests. The data in Table 3 were generated from steady state periods in which char produced during gasification was completely consumed within the combustor. As in the case of previous testing with wood, carbon (char) losses from the gasifier and combustor outlet gas streams were insignificant. The design of the PRU is such that natural gas is maintained to the combustor during operation to balance heat losses typical in pilot scale equipment. Such operation allows a more accurate simulation of full scale operation to be made, and thus provides better process data to be generated. During most of the data periods, carbon balances around the PRU combustor showed that char conversion was complete, which again agrees with the extensive wood data base.

Gas analyses of the combustor flue gas stream showed that no CO or SO_2 was formed in spite of the low excess air levels normally used during PRU operation (0.1% to 0.5% excess oxygen). Combustor performance was investigated in detail during the wood gasification program and is reported in reference 2.

Gasifier Temperature

Gasifier temperature, as in the case of wood gasification, was the dominant gasifier variable. Carbon conversion levels measured did not vary

TABLE 3. RDF GASIFICATION RUN RESULTS - 10 INCH GASIFIER

TEST NUMBER	RDF05	RDF06A	RDF06B	RDF06C	RDF07	RDF08	RDF09A	RDF09B	RDF09C	RDF10A	RDF10B
RUN CONDITION		N,S	N,S	N,S	N,S	N,S	N,S	N,S	N,S	N,S	N,S
FUEL TYPE	RDF	RDF	RDF	RDF	RDF	RDF	RDF	RDF	RDF	RDF	RDF
MOISTURE CONTENT, %, WET BASIS	20	19	19	19	15	16	19	19	19	19	19
RDF FEED RATE, LB/HR, WET BASIS	266	226	409	409	393	366	535	636	355	430	430
GASIFIER TENPERATURE, F	1611	1422	1341	1291	1405	1228	1628	1478	1644	1431	1422
GASIFIER PRESSURE, PSIG	2	2	1	2	1	2	3	3	2	2	3
NITROGEN FEED, LB/HR	244	377	371	461	292	178	183	183	180	194	200
STEAM RATE, LB/HR	348	168	186	29	126	377	355	319	333	356	347
GASIFIER GAS VELOCITY, FT/S	21	17	16	14	17	18	23	21	21	22	19
COMBUSTOR TEMPERATURE, F	1728	1614	1669	1676	1918	2847	1743	1726	1771	1610	1665
COMBUSTOR PRESSURE, PSIG	3	1	2	2	2	2	2	3	3	3	3
COMBUSTOR GAS VELOCITY, FT/S	2	2	2	2	3	3	3	3	3	3	3
PRODUCT GAS RATE, SCF/LB-MAF	18	10	9	8	12	7	12	10	11	9	8
CARBON CONVERSION TO GAS, %	68	66	63	45	69	41	68	60	66	55	47
PRODUCT GAS COMPOSITION, % N2 FREE											
HYDROGEN	17.4	16.1	13.9	12.6	16.8	11.8	18.0	16.6	18.6	15.7	15.6
CARBON DIOXIDE	9.8	11.6	11.2	12.3	18.3	1 1 . 9 -	9.1	18.8	18.8	11.1	10.8
ETHYLENE	16.7	9.9	18.1	9.9	18.2	9.9	9.8	11.2	10.6	11.2	11.4
ETHANE	1.1	1.1	1.5	1.6	1.2	2.1	.6	1.0	.6	1.3	1.3
METHANE	16.3	16.7	16.1	14.8	16.6	14.2	16.4	16.9	16.7	16.3	16.5
CARBON MONOXIDE	39.6	46.0	47.7	48.3	46.3	49.6	46.2	43.6	41.7	43.9	43.9
H2/CO RATIO	.4	.3	.3	.3	.3	.2	.4	.4	.4	.4	.4
PRODUCT GAS HHV, BTU/SCF	627	541	644	539	550	643	550	672	668	566	572
BTU YIELD, BTU/LB-MAF	6828	6143	4956	4889	6578	3662	6326	5657	6288	5342	4643
RDF ANALYSIS, % DRY BASIS											
VOLATILE MATTER	79.6	79.6	79.6	79.6	79.6	79.6	81.6	81.6	81.6	77.9	77.9
FIXED CARBON	10.0	18.8	10.0	10.0	10.0	18.8	9.3	9.3	9.3	7.9	7.9
ASH	18.6	18.6	18.6	10.6	10.6	10.6	9.1	9.1	9.1	14.2	14.2
CARBON	46.6	46.6	45.6	45.6	46.6	46.6	46.5	46.6	46.6	44.9	44.9
HYDROGEN	5.8	6.6	5.8	6.8	6.8	6.8	6.8	5.8	5.8	6.3	6.3
NITROGEN	.3	.3	.3	.3	.3	.3	.4	.4	.4	.6	.6
SULFUR	.2	.2	.2	.2	.2	.2	.1	.1	.1	.2	.2
OXYGEN (BY DIFFERENCE)	37.8	37.8	37.8	37.8	37.8	37.8	39.0	39.8	39.0	33.9	33.9
BTU/LB, DRY BASIS	7621	7621	7621	7621	7621	7621	7783	7783	7783	7196	7196

N - NITROGEN
S - STEAM

significantly with other measured variables such as RDF composition, ash content, or moisture content.

Carbon conversion figures for the RDF tests were essentially the same as those measured during the wood gasification experiments. This is illustrated in Figures 9 and 10. Figure 9 shows all of the wood gasification data (x's) along with the RDF data (squares). As is seen, no difference in carbon conversion can be detected between the two fuels. This is an expected result because of the chemical similarity of the two materials as discussed below. The non-homogeneous character is reflected in Table 4. Ash content of the RDF varied along with the concentration of other components. Three detailed sample analyses were made of the RDF feed material during the program. One early in the testing, one at the mid point of testing, and one near the end. Data on ash fusion was obtained for each of the samples. These results, shown in Table 5, show that the National Ecology RDF preparation effectively removes low melting ash constituents from the MSW. These ash fusion temperatures (particularly the initial deformation temperature) were useful in determining combustor operating temperatures. If combustor temperatures near the ash fusion temperature were reached, small agglomerates were formed in the combustor bed during the tests. If lower temperatures were used, such agglomerates did not form. Since "balanced" operation is achieved at a gasifier temperature of 1550, severe operating problems should not be encountered using a prepared RDF. Balanced operation of the process provides the capability to completely consume the feed material without producing unwanted solid byproducts. The gas production rates are thus maximized.

Product Gas Heating Value

The medium Btu product gas generated from the RDF had a heating value of 550 to 600 Btu/scf. This level is higher than the heating value expected with wood as the feedstock.

The heating value of the product gas is consistent regardless of the operating conditions in the gasifier or variability of the RDF feed itself. This result again duplicates test data generated with wood. The heating value consistency is illustrated in Figure 11, which shows its consistency with

FIGURE 10

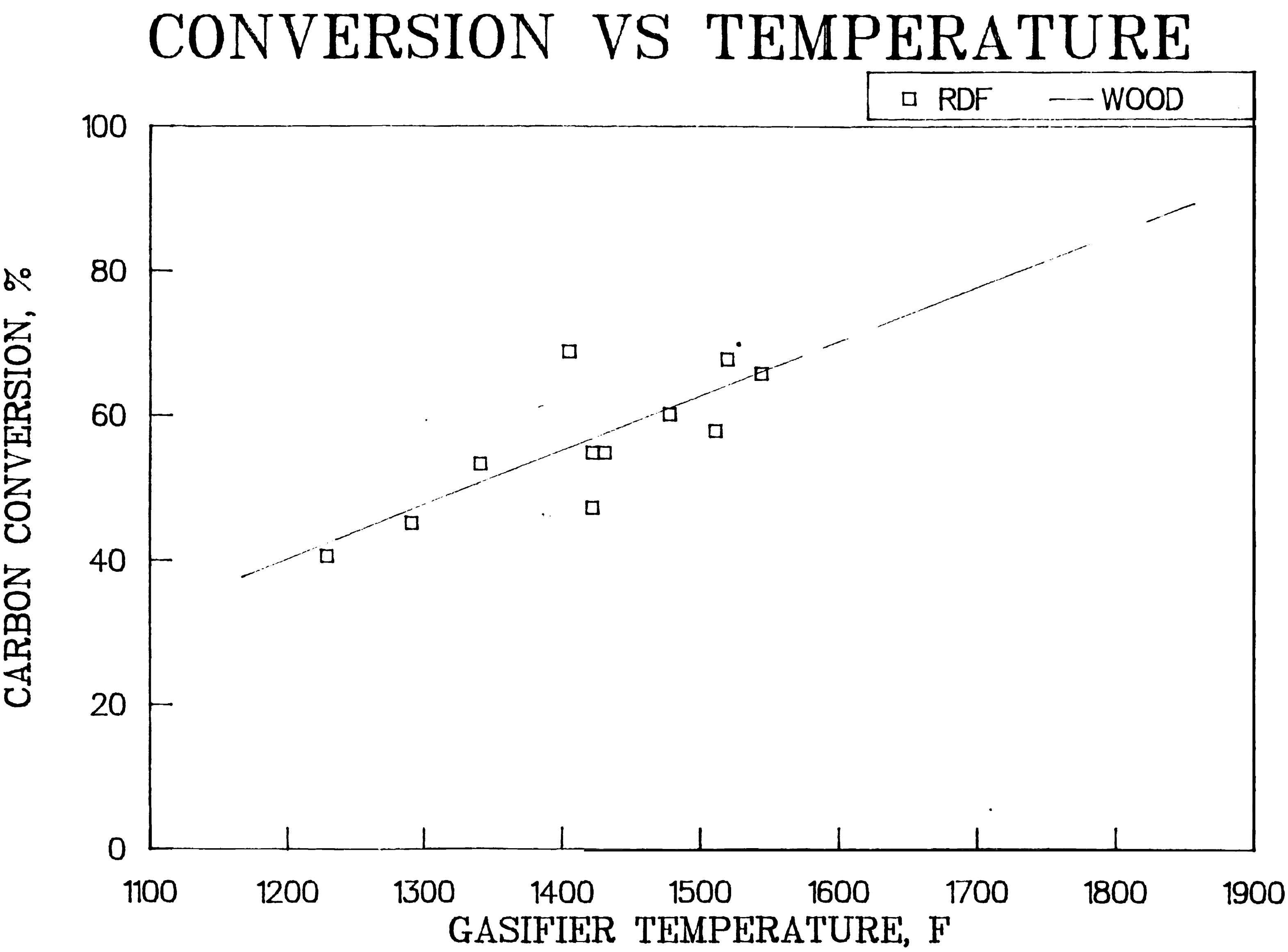

CONVERSION VS TEMPERATURE
□ RDF
—— WOOD
CARBON CONVERSION, %
0
20
40
60
80
100
1100
1200
1300
1400
1500
1600
1700
1800
1900
GASIFIER TEMPERATURE, F

TABLE 4. RDF CHEMICAL ANALYSES

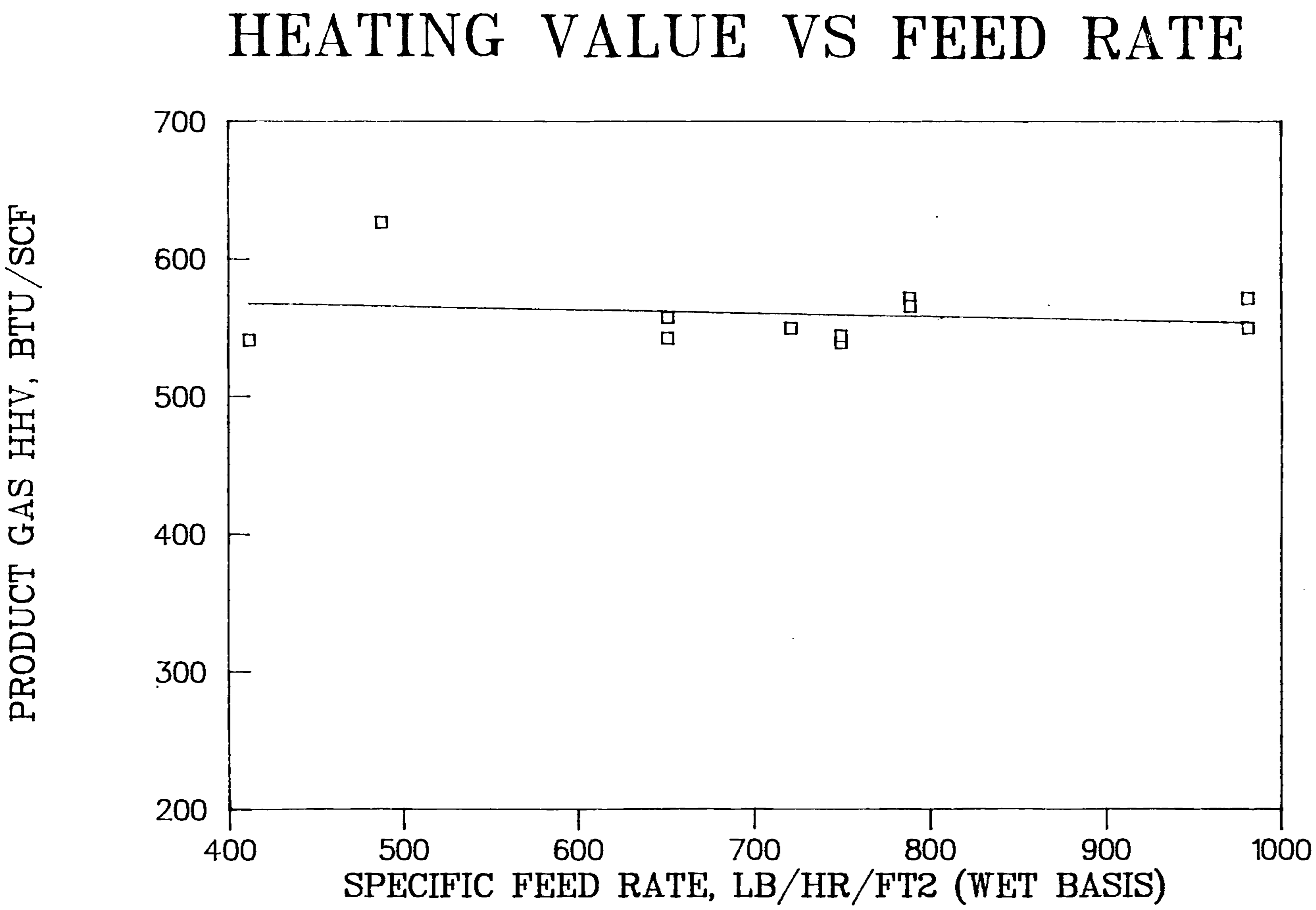
	% Dry Basis		
	4/24/89	5/5/89	5/11/89
Volatile Matter	79.56	81.59	77.92
Fixed Carbon	9.98	9.28	7.92
Ash	10.46	9.13	14.16
C	45.52	47.47	44.87
H	5.75	5.84	6.29
N	0.29	0.38	0.55
0	37.79	39.04	33.94
S	0.19	0.14	0.19
C1	0	0	0
Btu	7621	7783	7196
Moisture (As Received)	19.38	22.49	19.47

TABLE 5. RDF ASH ANALYTICAL RESULTS

	Date		
	4/24/89	5/5/89 (%Weight)	5/11/89
SiO_2	52.01	54.31	52.40
Al_2O_3	20.60	17.00	18.00
TiO_2	3.10	2.60	2.30
Fe_2O_3	2.03	2.14	3.15
CaO	9.80	10.00	9.90
MgO	1.75	1.90	1.90
K_2O	1.36	1.50	1.50
Na_2O	5.50	6.20	7.20
SO_3	2.40	1.85	1.78
P_2O_5	1.10	1.10	1.02
Undetermined	0.35	1.40	0.85

	Fusion Temperature, F					
	0	R	0	R	0	R
Initial Deformation	2135	2060	2100	2025	2015	1985
Softening	2260	2180	2245	2135	2150	2095
Hemispherical	2380	2300	2385	2240	2290	2195
Fluid	2495	2435	2520	2350	2445	2295

FIGURE 11


HEATING VALUE VS FEED RATE
PRODUCT GAS HHV, BTU/SCF
700
600
500
400
300
200
400
500
600
700
800
900
1000
SPECIFIC FEED RATE, LB/HR/FT2 (WET BASIS)

reactor throughput. The consistency of the heating value provides the ability to use conventional (volumetric) control systems on combustion equipment utilizing the gas. Control of the total plant then is simplified since the only adjustment necessary is RDF feed rate -- a simple control. A typical analysis of the RDF derived product gas is found in Table 6. The heating value of this gas is such that combustion equipment designed for natural gas can utilize the gas without burner modifications.

Waste Water

As part of the required Ohio EPA permitting process, waste water samples were taken at the outlet of the Battelle treatment system. This treatment is very simple consisting of a settling chamber, a sand filter, and a charcoal filter. This simple treatment system was adequate to provide a water discharge that is within EPA drinking water standards. These results are tabulated in Appendix A.

These results, although preliminary, show the potential ease of waste water cleanup from the Battelle gasifier. Condensibles were analyzed in detail during the wood gasification development. These analyses showed that the condensibles produced were relatively insoluble in water thus greatly simplifying projected waste water cleanup requirements.

TABLE 6. TYPICAL RDF DERIVED PRODUCT GAS ANALYSIS

Component	% Volume
H_2	15.7
CO_2	11.1
C_2H_2	11.2
C_2H_6	1.3
CH_4	16.3
CO	43.9
HHV, Btu/SCF	566

Tar Production

Within the limited testing program conducted, lower concentrations of condensed organic materials were generated than with wood. A much more extensive evaluation of the tar production will be necessary to quantify this result. Longer PRU tests must be conducted to provide sufficient quantities of tar for analysis, and to accurately calculate a production rate. During the RDF tests run during this brief program, no collectable tar materials were found suggesting more favorable production levels than those measured with wood. The mode of operation with RDF is identical to that with wood so the character of any condensed materials is expected to be similar to that found with wood.

Gasifier Throughput

Although the high throughputs obtained during the wood gasification program could not be reached, the data obtained during operation with RDF showed that no effect on carbon conversion, gas heating value, or performance was noticed with changes in reactor throughput. The highest throughput achieved during these tests was about 1000 lb/hr-ft^2. This throughput is significantly lower than the 4500 lb/hr-ft^2 achieved with wood but is high enough to demonstrate the feasibility of gasifying large quantities of RDF in a compact reactor system. Performance of the system showed that the limitation was the capacity of the feed system. Much higher reactor throughputs can be achieved if the existing feed system was modified.

PROJECTED PROCESS ECONOMICS

The similarity in performance of RDF in the Battelle Gasification Process to that with wood provides a basis for a preliminary estimation of the economics of RDF gasification. RDF plants will generally be located at sites that are somewhat remote from gas users and so the preferred product from a gasification plant will be electric power rather than medium Btu gas. The production of medium Btu gas provides a means to maximize power production from an RDF plant since the efficiency of gas turbine generation is higher than steam turbine based power production.

Data generated during this test program was incorporated into a process heat and material balance model to predict commercial scale production rates with RDF as the feedstock. A copy of the computer printout for a 1000 TPD plant is found in Figure 12.

A 2000 TPD RDF gasification plant will produce 898 million Btu/hr of a medium Btu product gas. This quantity of gas will generate about 112 MW of power. A similar quantity of MSW in a mass burn plant will generate only 60 MW of power.

Capital costs are also quite different for the two systems. Using capital costs generated for a commercial scale, 200 TPD wood gasification system scaled up to the 2000 TPD plant size predicts an overall commercial scale capital cost of $89 million. A major element in this cost is the gas turbines themselves which are estimated to be $44.8 million using cost figures provided by turbine vendors. The overall cost comparison is shown in Table 7. The mass burn figures in the table are from literature references for the Baltimore, Maryland mass burn facility being operated by Wheelabrator. The production of medium Btu gas from RDF provides the ability to produce larger quantities of power from RDF while also providing a user of the technology with the potential to use the gas in other industrial combustion processes.

TABLE 7. ECONOMIC COMPARISON RDF GASIFICATION VERSUS MASS BURN

	Mass Burn	Gasification
Plant Size, TPD	2000	2000
Capital Costs ($X10^6)		
RDF Preparation		25$^{(a)}$
Conversion (Gasifier or Combustor)	*	19.2
Turbines	*	44.8
Total Capital Cost	170$^{(3)}$	89
Power Capacity, MW	60$^{(3)}$	112

```
XXXX MASS AND ENERGY BALANCE SUMMARY FOR FOREST RESIDUE GASIFICATION MODEL XXXX
================================================================================

                                        CASE #   1

PLANT SIZE (TPD)                1000.0            RDF
DRY FEED RATE (LB/HR)          83333.34
FEED MOISTURE CONTENT (%)         22.5
STEAM RATE (LB/HR)             25983.59
PURGE GAS FEED(LB/HR)            309.8
CARBON CONVERSION TO GAS(%)       63.2
PROD GAS RATE (SCF/HR)        825507.5
ENERGY PRODUCT (MM-BTU/DAY)    10773.3
PRODUCT HHV (BTU/SCF)            543.8
COLD GAS EFFICIENCY (%)           69.2
EXPORT ENERGY (MM-BTU/HR)         48.50
  (LB-STEAM/HR85.% EFF)        35116.2
TOTAL HEAT LOSS (MM-BTU/HR)       27.69
  PLANT/HT EXC (% OF FEED HHV)     2.8        5
GASIFIER INLET VELOCITY(FT/SEC    10.17
COMBUSTOR GAS VELOCITY(FT/SEC)    17.49
GASIFIER TEMPERATURE (F)        1480.0
COMBUSTOR TEMPERATURE (F)       1780.0
```

```
            COMBUSTION DATA
            ---------------
AIR REQ (LB/HR)                183058.6
INLET AIR TEMP (F)                750.0
FLUE GAS RATE(SCF/HR)         2427466.7
SAND RATE(LB/HR-FT2)            34753.0
        (GASIFIER)
```

```
 OVERALL ENERGY BALANCE (MMBTU/HR)
 .................................
          IN                    OUT
WOOD    648.68   PROD GAS     590.18
STEAM    36.48   FLUE GAS      96.53
AIR      30.88   CONDENSIBLE    7.06
                 DIRECT LOAD   20.85
------...........................
TOTAL   715.74                714.63
```

```
                 HEAT LOSS SUMMARY
                 -----------------
                            MMBTU/HR  % OF WHV
GASIFIER                      1.382     0.21
COMBUSTOR                     2.407     0.37
GASIFIER CYCLONES             0.403     0.06
COMBUSTOR CYCLONES            2.976     0.46
SURGE POTS                    1.519     0.23
L VALVES                      0.176     0.03
PIPING                        8.986     1.39
.....................................
 SUM                         17.846     2.75
(HEAT EXCHANGE)               9.646     1.52
.....................................
TOTAL                        27.692     4.27
```

```
 ELEMENT BAL-GASIFIER (LBS/HR)
 -----------------------------
                IN         OUT
 C          37891.67   37891.66
 H          10441.91   10441.91
 N            626.47     628.47
 O          77135.23   77135.23
ASH          7608.33    7608.33
 S            116.67     116.67
------------------------------
TOTAL      133820.28  133820.28
```

```
                 VESSEL SIZES (FT)
                 -----------------
                          ID     OD  HEIGHT
GASIFIER                 7.3    8.2   73.5
COMBUSTOR               12.5   13.6   73.5
GASIFIER CYCLONES        4.8    5.4   19.1
COMBUSTOR CYCLONES       8.8    9.4   35.2
SURGE POTS              11.7   12.8   23.3
L VALVES                 1.4    2.1   15.0
```

```
DETAILED MASS AND ENERGY BALANCE
--------------------------------

                 IN
                 --
 IN             LB/HR     MM-BTUIHR
WOOD          83333.3        648.6
MOISTURE      24193.5          0.0
STEAM         25983.6         36.5
NITROGEN        309.8          0.0
..............................
TOTAL        133820.3        685.1
```

```
              CHAR
              ----
OUT          LB/HR     MMBTU/HR
C         13629.29       200.0
H           255.80        15.8
ASH        7725.00         3.2
-----------------------------
TOTAL     21610.09       219.0
```

```
            AIR REQUIREMENT
            ---------------
            LBMOLEIHR    MM-BTUIHR
O2            1326.8         6.63
N2            5021.5        24.05
------------------------------
TOTAL         6348.3        30.68
```

```
               NET PRODUCT GAS
               ---------------
GAS        LBMOLE/HR  MOLE %  MM-BTU/HR
H2            404.9      7.2      53.6
CO            909.0     16.2     120.2
CO2           234.2      4.2       3.8
CH4           362.9      6.5     145.9
C2H4          231.5      4.1     146.4
C2H6           13.3      0.2       9.3
H2O          3439.8     61.2     110.6
N2             22.4      0.4       0.2
.....................................
TOTAL        5617.9    100.0     590.2
```

```
            CONDENSIBLES
            ------------
               LBIHR     MM-BTUIHR
C             314.58         4.6
H              39.32         2.4
O              62.92         0.0
..............................
TOTAL         416.82         7.1
```

```
                  FLUE GAS
                  --------
              LBMOLE/HR MOLE % MY-BTUIHR
C02             1136.8   17.7     23.0
H20              127.9    2.0      4.5
02               119.8    1.9      1.6
N2              6021.6   76.4     64.0
--------------------------------------
TOTAL           6404.9  100.0     93.1
ASH(LB/HR)      7958.3             3.4
--------------------------------------
SUM(LB/HR) 204668.7               96.5
```

FIGURE 12

This analysis, while preliminary, demonstrates the economic potential for the gasification of RDF to produce medium Btu gas.

CONCLUSIONS AND RECOMMENDATIONS

The Battelle High Throughput Gasification Process has been shown to be an effective means to produce a high energy density medium Btu gas from a variety of biomass feedstocks. The extensive data base generated for wood has demonstrated the competitive economics compared to conventional technologies. The successful use of wood in the process led to the current investigation of a means of producing a medium Btu gas from RDF. The use of RDF in the process has been evaluated and shown to produce a gas having a heating value of over 550 Btu/scf without encountering ash agglomeration problems that might be expected with RDF.

The economics of the process, although preliminary, show that the technology can compete favorably with mass burn technology in the market place. The specific return from a commercial plant utilizing RDF is highly site specific and depends to a large extent on tipping fees. The capital costs, on the other hand are projected to be about half of a similarly sized mass burn facility.

Further development of the RDF gasification process is necessary before the technology can be commercially implemented. Detailed design data must be generated so that an architect/engineering firm can have the data necessary to construct such a commercial scale facility. The technology must be at a sufficient scale of development so that municipalities with waste disposal problems can include gasification as a commercially available option for consideration. The development efforts then must continue at a rapid pace to provide the basis for commercial application of the technology.

Decisions by potential users of MSW technologies must be based on available technology and will of necessity prevent developing technologies from being utilized. Developing technologies then will have to wait until the life of the existing plants is over, usually 20 years. The Battelle technology can provide an alternative to current technologies, but only if ready for commercialization before decisions must be made by potential users of the technology.

Further testing is necessary to realize these benefits. Other variables that must be investigated include:

- Determination of the necessary level of RDF preparation.
- Modification of the feed system to provide higher reactor throughputs.
- Alternate sources of RDF.
- Installation of a small gas turbine to evaluate deposits that might form during power generation.

Completion of such a program will provide data for the successful commercial application of the technology.

REFERENCES

1. "Thermal Systems for Conversion of Municipal Solid Waste", Vol. 4, Argonne National Laboratory, DE84-010490, March 1983.

2. Feldmann, H. F. et al., "Conversion of Forest Residues to a Methane Rich Gas in a High Throughput Gasifier", May 1988.

3. Waste Age, Vol. 18, No. 11, p. 203.

APPENDIX A

WASTE WATER EFFLUENT ANALYSES

STILSON LABORATORIES, INC.
170 NORTH HIGH STREET
COLUMBUS OHIO 43215
PHONE - 614-228-2900

BATTELLE MEMORIAL INSTITUTE
505 KING AVE.
COLUMBUS, OHIO 43201
ATTN: MR. PAT GORMAN

LAB NO, 9435
JOB 958245
DATE June 5, 1989

LOCATION COLLECTED BATTELLE RDF EFFLUENT

PRESERVATIVES USED

DATE COLLECTED - - -April 20, 1989

TIME COLLECTED - - - 0

DATE RECEIVED - - - April 20, 1989

Test	Result	Unit
COLOR	15	CU
PH, LAB	7.60	SU
RES TOT NONFILT	6	MG/L
TKN (N)	2.15	MG/L
AMMONIA (N)	0.18	MG/L
NITRITE (N)	0.12	MG/L
NITRATE (N)	0.47	MG/L
PHOS, TOTAL (P)	<0.02	MG/L
SULFIDE	<0.02	MG/L
SULFITE	2	MG/L
SULFATE	50	MG/L
FLUORIDE	0.78	MG/L
CYANIDE,TOTAL	0.011	MG/L
MAGNESIUM	5.2	MG/L
ALUMINUM	<200	UG/L

ANTIMONY	<200	UG/L
ARSENIC	<5.0	UG/L
BARIUM	<200	UG/L
BERYLLIUM	<20	UG/L
BORON	<5.0	MG/L
CADMIUM	<10	UG/L
CHROMIUM, TOTAL	<30	UG/L
COBALT	<20	UG/L
COPPER	<15	UG/L
IRON, TOTAL	160	UG/L
LEAD	<30	UG/L
MANGANESE	<20	UG/L
MERCURY	<0.2	UG/L
MOLYBDENUM	<100	UG/L
NICKEL	<30	UG/L
SELENIUM	<5.0	UG/L
SILVER	<20	UG/L
THALLIUM	<100	UG/L
TIN	<500	UG/L
TITANIUM	<200	UG/L
ZINC	<20	UG/L
TOTAL ORGANIC CARBON	2	MG/L
MBAS	<0.02	MG/L
OIL AND GREASE	3	MG/L
PHENOL	89	UG/L
BOD	2	MG/L
COD	37	MG/L
RESIDUAL CHLORINE	<0.1	MG/L

TOTAL ORG NITROGEN	1.97	MG/L
FECAL COLIFORM	192	/100 ML
BROMIDE	<0.2	MG/L
TTO	COMPLETE	
DIOXIN (SCAN)	NEGATIVE	
METALS	COMPLETE	

PROJECT MANAGER T. Stout
TODD M. STOUT

BATELLE MEMORIAL INSTITUTE
UOLATILES EPA 624
RDF EFFLUENT

SLI# 9435

COMPOUND	CONC MG/L
BENZENE	<0.01
Bis(CHLOROMETHYL) ETHER	<0.01
BROWOOICHLOROMETHANE	<0.01
BROMOFORH	<0.01
BROMOHETHANE	<0.05
CARBON TETRACHLORIDE	<0.01
CHLOROBENZENE	<0.01
CHLOROETHANE	<0.05
2-CHLOROETHYLVINYL ETHER	<0.03
CHLOROFORM	<0.01
CHLOROMETHANE	<0.05
DIBROHOCHLOROMETHANE	<0.01
DICHLORODIFLUOROMETHANE	<0.01
1,1-DICHLOROETHANE	<0.01
1,2-DICHLOROETHANE	<0.01
1,1-DICHLOROETHENE	<0.01
trans-1,2-DICHLOROETHENE	<0.01
1,2-DICHLOROPROPANE	<0.01
1,3-DICHLOROPROPENE	<0.01
ETHYL BENZENE	<0.01
METHYLENE CHLORIDE	<0.01
1,1,2,2-TETRACHLOROETHANE	<0.01
TETRACHLOROETHENE	<0.01
TOLUENE	<0.01
1,1,1-TRICHLOROETHANE	<0.01
1,1,2-TRICHLOROETHANE	<0.01
TRICHLOROETHENE	<0.01
TRICHLOROFLUOROMETHANE	<0.01
VINYL CHLORIDE	<0.05
1,4-DICHLOROBENZENE	<0.01
1,3-DICHLOROBENZENE	<0.01
1,2-DICHLOROBENZENE	<0.01
XYLENE	<0.01

BATELLE MEMORIAL INSTITUTE
BASE NEUTRALS EPA 625
RDF EFFLUENT

SLI# 9435

COMPOUND	CONC MG/L
1,3-DICHLOROBENZENE	<0.01
1,4-DICHLOROBENZENE	<0.01
HEXACHLOROETHANE	<0.01
Bis(2-chloroethyl)ETHER	<0.02
1,2-DICHLOROBENZENE	<0.01
Bis(2-chloroisopropyl)ETHER	<0.02
n-NITROSODI-n-PROPYLAMINE	<0.03
NITROBENZENE	<0.01
HEXACHLOROBUTADIENE	<0.01
1,2,4-TRICHLOROBENZENE	<0.01
ISOPHORONE	<0.01
NAPHTHALENE	<0.01
BIS-(2-chloroethoxy)METHANE	<0.02
HEXACHLOROCYCLOPENTADIENE	<0.01
2-CHLORONAPHTHALENE	<0.01
ACENAPHTHYLENE	<0.01
ACENAPHTHENE	<0.01
DIHETHYL PHTHALATE	<0.01
2,6-DINITROTOLUENE	<0.02
FLUORENE	<0.01
4-CHLOROPHENYL PHENYL ETHER	<0.02
2,4-DINITROTOLUENE	<0.02
DIETHYLPHTHALATE	<0.01
N-NITROSODIPHENYLAMINE	<0.03
HEXACHLOROBENZENE	<0.01
4-BROMOPHENYL PHENYL ETHER	<0.02
PHENANTHRENE	<0.01
ANTHRACENE	<0.01
DI-n-BUTYL PHTHALATE	<0.01
FLUORANTHENE	<0.01
PYRENE	<0.01
BENZIDENE	<0.01
BUTYL BENZYL PHTHALATE	<0.01
Bis(2-ethylhexyl)PHTHALATE	<0.01
CHRYSENE	<0.01
BENZO(a)ANTHRACENE	<0.01
3,3'-DICHLOROBENZIDENE	<0.02
Di-n-OCTYLPHTHALATE	<0.01
BENZO(b)FLUORANTHENE	<0.01
BENZO(k)FLUORANTHENE	<0.01
BENZO(a)PYRENE	<0.01
INDENO(1,2,3-c,d)PYRENE	<0.01
DIBENZO(a,h)ANTHRACENE	<0.01
BENZO(ghi)PERYLENE	<0.01
N-NITROSODIMETHYL AMINE	<0.03

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ACIDS EPA 625
RDF EFFLUENT

SLI# 9435

COMPOUND	CONC MG/L
2-CHLOROPHENOL	<0.01
2-NITROPHENOL	<0.01
PHENOL	<0.01
2,4-DIMETHYLPHENOL	<0.01
2,4-DICHLOROPHENOL	<0.01
2,4,6-TRICHLOROPHENOL	<0.01
4-CHLORO-3-METHYLPHENOL	<0.01
2,4-DINITROPHENOL	<0.01
2-METHYL-4,6-DINITROPHENOL	<0.01
4-NITROPHENOL	<0.01
2-METHYL PHENOL	<0.01
3-METHYL PHENOL	<0.01
4-METHYL PHENOL	<0.01

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PESTICIDES/PCBs EPA 625
RDF EFFLUENT

SLI# 9435

COMPOUNO	CONC MG/L
ALDRIN	<0.01
ALPHA BHC	<0.01
BETA BHC	<0.01
GAMMA BHC	<0.01
DELTA BHC	<0.01
CHLORDANE	<0.01
4,4'-DDD	<0.01
4,4'-DDE	<0.01
4,4'-DDT	<0.01
DIELDRIN	<0.01
ENOOSULFAN-I	<0.01
ENDOSULFAN-II	<0.01
ENOOSULFAN SULFATE	<0.01
ENDRIN	<0.01
ENDRIN ALDEHYDE	<0.01
HEPTACHLOR	<0.01
HEPTACHLOR EPOXIDE	<0.01
METHOXYCHLOR	<0.01
TOXAPHENE	<0.01
PCB-1016	<0.01
PCB-1221	<0.01
PCB-1232	<0.01
PCB-1242	<0.01
PCB-1248	<0.01
PCB-1254	<0.01
PCB-1260	<0.01

APPENDIX B

SAMPLE CALCULATIONS AND STATISTICAL ANALYSIS

APPENDIX

SAMPLE CALCULATIONS AND STATISTICAL ANALYSIS

PRU Calculations

Calculation of the major flows and carbon conversion are accomplished as follows:

The major flows of steam, nitrogen, air, and natural gas are all based on pressure drop across an orifice. This gives an equation of the type

$$\text{Flow} = K\sqrt{p\Delta P}$$

where K is a constant calculated from the orifice and pipe sizes, is density calculated from the material and its temperature and pressure. P is the pressure drop across the orifice.

Product gas flow is calculated from the nitrogen flow and product gas composition using a ratio of nitrogen content of the product gas to nitrogen flow into the gasifier.

$$\text{Product Gas Flow} = \text{Nitrogen Flow/Fraction Nitrogen in Product Gas}$$

The most important calculation is carbon conversion.

$$\text{Carbon Conversion} = \left(\frac{\text{Moles } N_2 \text{ Into Gasifier}}{N_2 \text{ Content in Product}} \times \frac{\text{Carbon Content in Product} \cdot 12}{\text{Wood Feed Rate} \times \text{Wood Carbon Content}}\right)$$

Carbon conversion is calculated by taking the amount of carbon in the product gas divided by the feed carbon. The values are calculated from the product gas composition, flows of nitrogen and wood feed, and feed analysis for carbon. Much effort is given to the accuracy of this calculation since carbon conversion is directly related to gas production and efficiency. This concern led us to conduct a statistical analysis of the data.

Statistical Analysis of Experimental Data

Examination of all the data generated during this program indicates that carbon conversion is primarily a function of gasifier temperature. However, there is a considerable amount of scatter in this data as shown in Figure B-1. Therefore, the following questions were posed.

(1) Is the scatter observed statistically consistent with the methods of measurement, analytical techniques, and calculational methods employed?

(2) What is the best fit to the data and what probability is there that the actual (as opposed to the calculated) carbon conversion will fall within certain values?

(3) How can the methods of raw data measurement and analytical techniques be improved to reduce the scatter in calculated carbon conversion?

(4) Are there other parameters involved that perhaps have a second order effect on carbon conversion?

The first step in the statistical analysis was to eliminate data that, for known reasons, was faulty. Then, carbon conversion, the prime measure of performance, was plotted versus temperature, the main independent variable. Figure B-1 shows the linear regression and that the actual data are linear with gasifier temperature. A standard deviation of 5.8 percent is calculated for carbon conversion with respect to the regression. This is seen graphically by the band bounded by parallel lines in Figure B-1. This shows that another single observation (experimental test run) has a 68 percent probability of falling within this band. A precision analysis was conducted, calculating the variance in carbon conversion as a function of the variance in the operating parameters. This analysis indicates that the scatter observed is easily due to normal experimental errors.

What might be of more critical importance to the design and scale-up efforts is the accuracy of the regression line. That is, if the test set

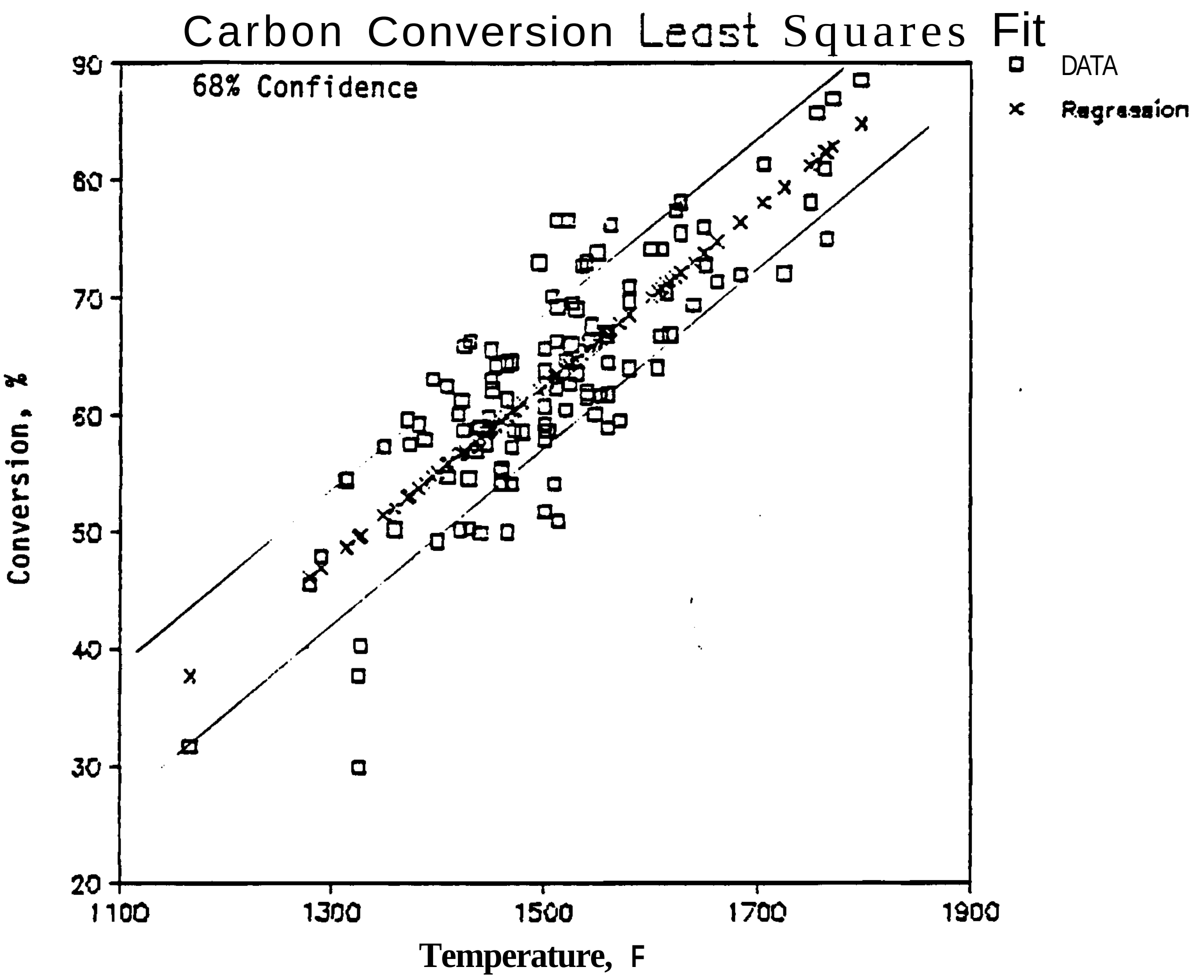

FIGURE B-1

(INCLUDES BOTH 6 AND 10 IN. GASIFIER DATA) were to be replicated, where would the new regression line be? This would indicate how close the given experimentally determined line is to the theoretical one. Figure B-2 presents the regression line with 95 percent confidence limits (i.e., there is a 95 percent probability that the theoretical line or replicate will fall within these bounds). As seen there is excellent agreement, especially in the range where operation is expected. This is almost an expected result in a statistical analysis, that means or averages behave much better with less scatter than single observations, almost by a factor of three in the present case.

It should be noted that performance, whether it be a pilot scale or commercial plant, will follow a curve not a single observation. Nothing can be said of the variance of a single observation in a commercial plant since the measurement techniques may vary from what is presently used. However, the average or theoretical curve should be the same. The only assumption implicit here is that the variances seen are random, which has been verified to some extent.

Contributions to Error

In order to understand and possibly decrease the experimental errors occurring, the relative contribution of individual measurement error to the overall variance in carbon conversion was studied. The total deviation in a dependent variable is the square root of the sum of the relative variance in each independent variable used to calculate it. This analysis also serves as a check on the calculation procedure. Since carbon conversion is the prime measurement of performance it was studied to determine contributions to the variance in the calculated carbon conversions. The measurements used in this calculation are: GC measurements of gas carbon and nitrogen content, nitrogen feed to the gasifier, feed rate of wood, and carbon content of the wood. Each of these component's contribution to the variance was determined. This is seen on a relative basis in Figure B-3. The error in the carbon conversion calculation is most sensitive to the measurements of the nitrogen in the product gas and nitrogen flow. It is somewhat less sensitive to carbon content of the product gas and the feed rate and relatively insensitive to measurement variances in the feed carbon content.

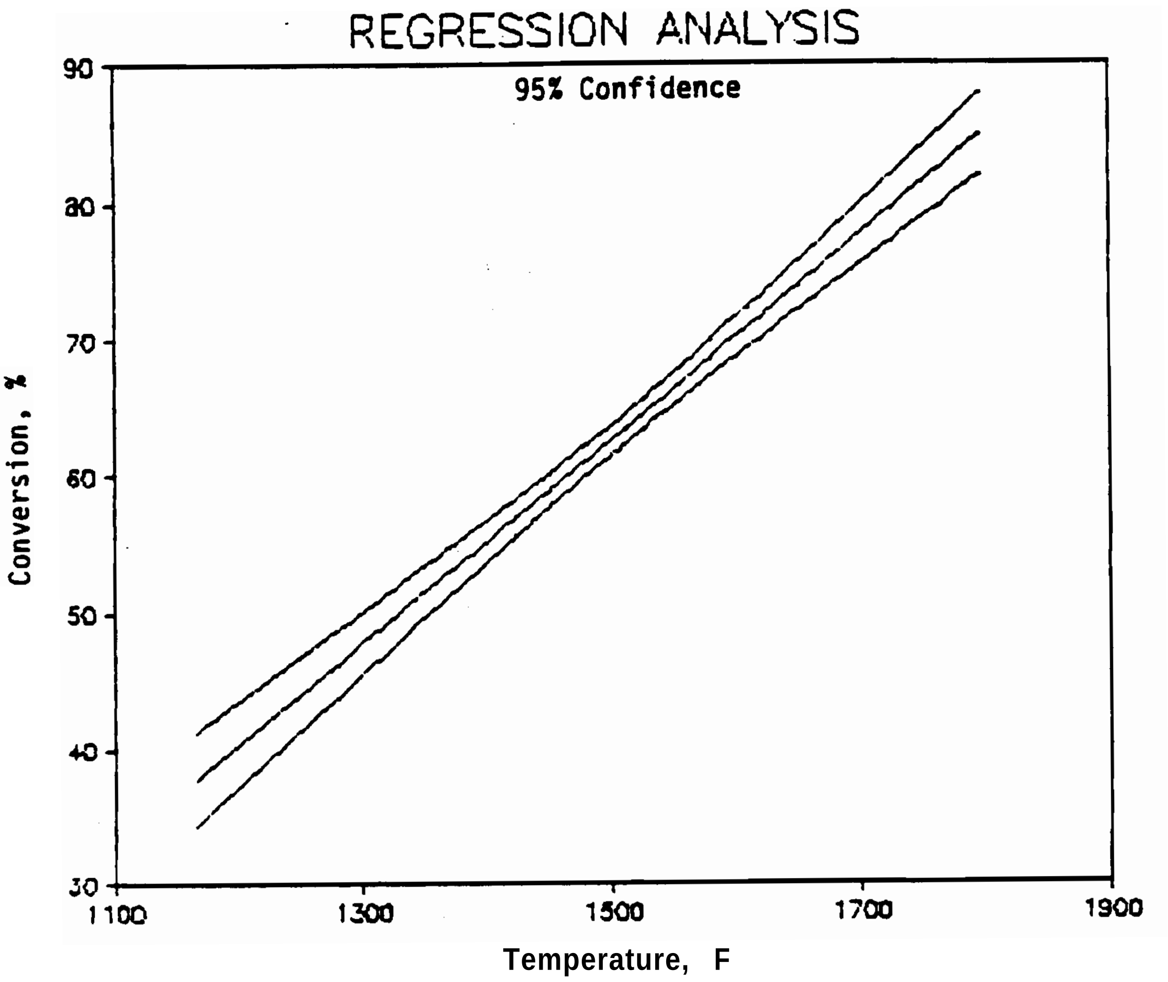
REGRESSION ANALYSIS
95% Confidence
Conversion, %
90
80
70
60
50
40
30
1100
1300
1500
1700
1900
Temperature, F

FIGURE B-2

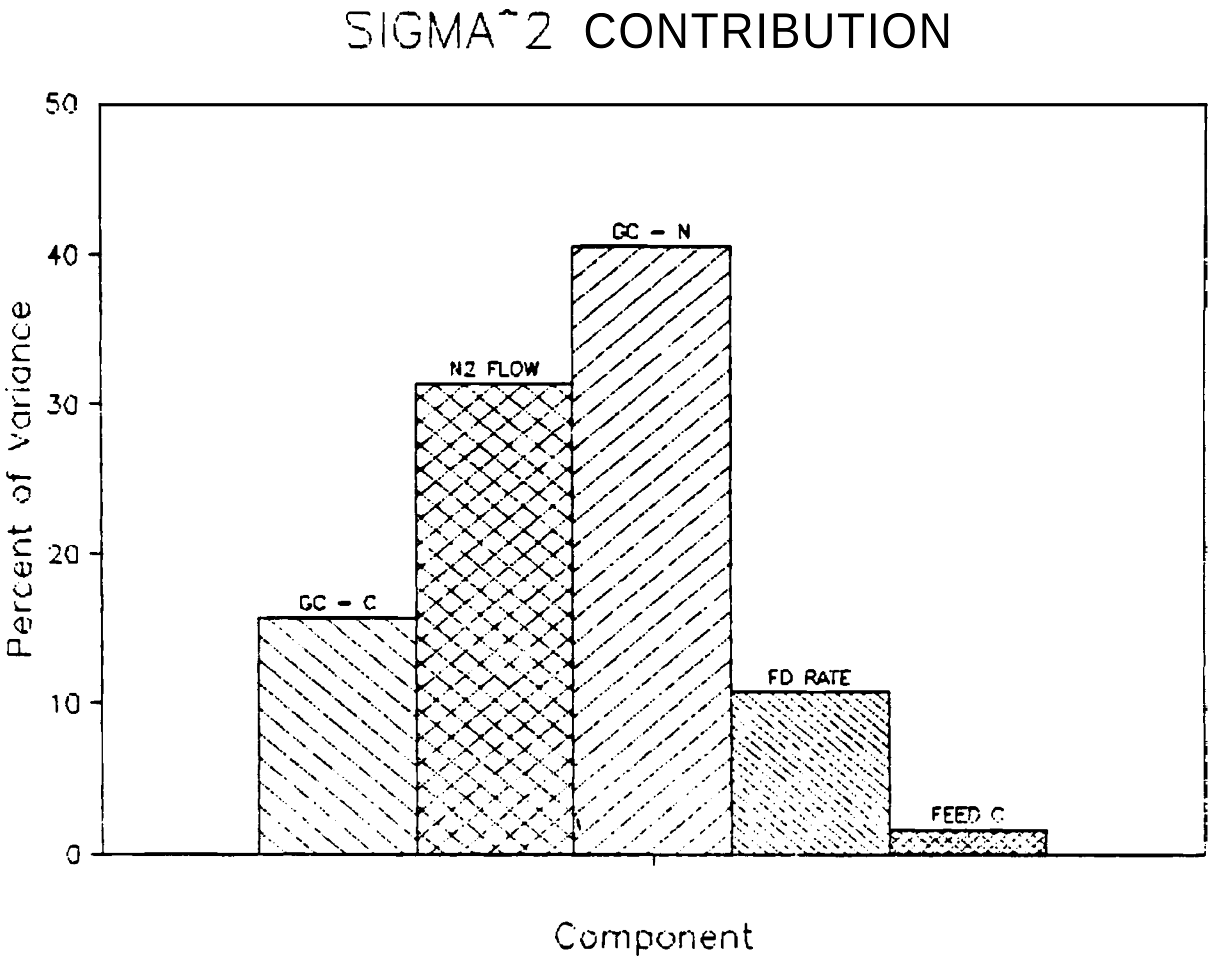
SIGMA^2 CONTRIBUTION
Percent of Variance
0
10
20
30
40
50
GC - C
N2 FLOW
GC - N
FD RATE
FEED C
Component

FIGURE B-3

Second Order Effects

Although temperature appears to have the strongest effect of any independent variables, the data was analyzed for second order effects. To do this, a so called "statistical tree"(a) was constructed. Carbon conversion was again chosen as the performance predictor of importance. All independent variables were individually and equally divided into high and low values with a mean carbon conversion calculated in both ranges. Variables used included: temperature, feed rate, steam rate, feed moisture, gasifier pressure, inlet velocity, and air to the combustor, the last serving as a check for bias since air rate should have no direct effect on conversion. The variable, temperature, which resulted in the greatest difference (most effect on carbon conversion) between these means became the top level of the "tree". Then the process was repeated separately for only high temperature points then low temperature points. The portrayal in Figure **B-4** shows the dominant variable affecting carbon conversion at each level.

A surprising observation is the complete dominance of temperature in high temperature regions masking effects from the other variables studied. However, at low temperatures feed moisture has a significant effect on conversion. This may be due to the reduced rate of moisture vaporization at lower temperatures. Feed rate appears as a minor effect in that lower rates favor marginally higher conversions. At low temperature and high moisture condition's inlet velocity had a slightly greater effect than temperature. That high inlet velocities favored conversion may be due in part to the increased heat input supplied by the steam which helps vaporize the moisture at the lower temperatures. However, these effects are obscured somewhat since inlet velocities varied only over a narrow range at the lower temperatures.

The main conclusion here is that at the 65 to 75 percent control conversion levels of interest for commercial designs temperature has by far the dominant effect suggesting heat transfer in the gasifier will be the primary contributor to conversion, while lower wood feed rates marginally enhanced conversion.

(a) This approach was suggested by Dr. Ralph E. Thomas, retired Battelle staff member.

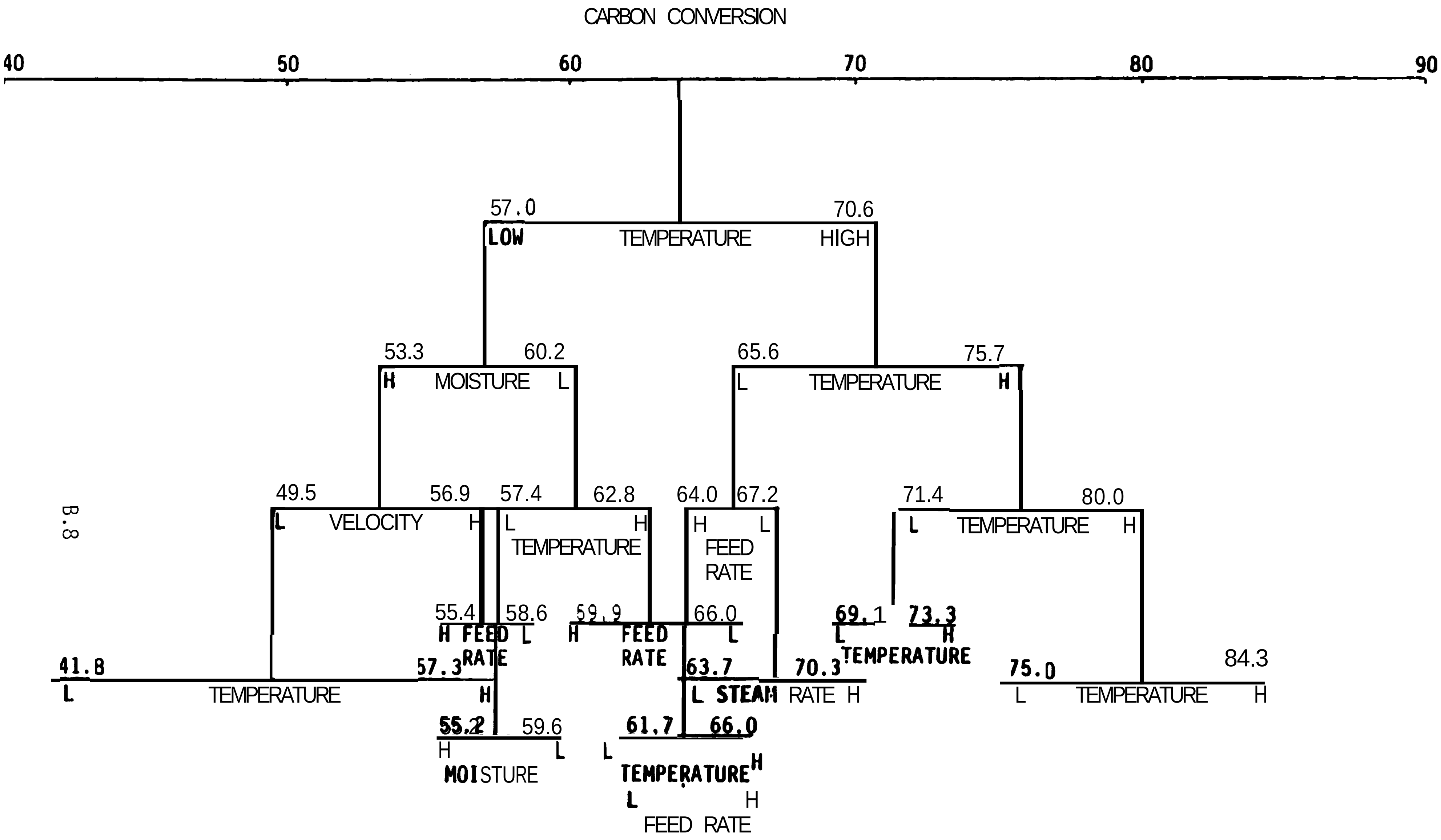

FIGURE B-4. STATISTICAL TREE ANALYSIS

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