Conversion of Forest Residues to a Methane-Rich Gas

Interim Report

March 1986

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CONVERSION OF FOREST RESIDUES
TO A METHANE-RICH GAS

INTERIM REPORT

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SUMMARY

A process is being developed that produces a fuel gas with a heating value of 500 Btu/SCF from diverse forms of biomass, including shredded bark, wood chips, and sawdust. The system uses a high throughput, non-oxygen gasifier that employs sand circulation to supply process heat.

Results obtained with a 10-inch I.D. gasifier are presented and compared with those in a 6-inch I.D. reactor. Feed rates up to 12 tons/day (dry) have been achieved corresponding to a specific wood throughput of 2,000 lbs/ft²-hr. Gas compositions in the two reactors are in excellent agreement and performance in the larger reactor, as measured by carbon conversion, is significantly improved. Cost projections comparing this process with direct combustion are presented that indicate gasification technology should have very significant cost advantages for both generation of plant steam and cogeneration of electricity.

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INTRODUCTION

This paper presents results of a program conducted by Battelle's Columbus Laboratories aimed at the use of renewable biomass resources to produce a medium-Btu fuel gas without the use of an oxygen plant. The concept utilizes a high-throughput gasifier capable of handling diverse forms of biomass without pretreatment.

In order to be readily accepted by industry, fuel gas derived from biomass sources must be able to replace oil and natural gas in existing units without significant retrofit expenses. In addition, installations switching from oil or natural gas will no doubt want the capability to continue to use the more traditional fuels in a backup mode. It becomes an important advantage then to produce a gas that can be interchanged with these high energy density fuels with minimum retrofit requirements. In general, this means that the product gas must have a higher heating value of at least 300 Btu/cu. ft. In conventional gasification systems, this would require oxygen to be used as the oxidant source to avoid nitrogen dilution of the product gas. At the modest scale of typical biomass gasification plants, however, oxygen is ordinarily too expensive to produce a competitively priced product gas. The Battelle gasifier overcomes this limitation by supplying the heat from an external circulating phase, thus, producing a medium Btu gas without requiring an oxygen plant.

A schematic flowsheet of the gasification process under development at Battelle's Columbus Laboratories is found in Figure 1. The process employs a hot sand phase as a conveying and heat transfer medium. By use of such heat transfer methods, it is possible to produce a 500 Btu/SCF fuel gas from biomass without using oxygen. Wood is fed into the gasifier with no pretreatment except partial drying to utilize sensible heat present in the flue gas from the combustor. The wood (or other biomass) is gasified at throughputs up to 2000 lb/hr-ft² of reactor area to produce the fuel gas and a small quantity of char.

FIGURE 1., BATTELLE'S BIOMASS GASIFICATION SYSTEM

(typically 20 percent of the dry wood fed). The char and sand then are removed from the gas phase and transferred to the combustor, where the char is burned. The combustion reactions reheat the sand, which returns to the gasifier to provide the heat for gasification.

Heat recovery from product and flue gases provides both process and export steam (or other heat sources as might be needed) in addition to drying incoming wood.

Separation of the gasification and combustion zones allows the following two major advantages.

- (1) Medium-Btu gas can be produced without requiring an oxygen plant-which is expensive at the scale of most biomass gasification plants.
- (2) The heating value of the cooled cleaned product gas remains constant, independent of the moisture level of the feed.

Early testing of the process was conducted in a 250 lb/hr process research unit (PRU) at Battelle's Columbus Laboratories.⁽¹⁾ These tests demonstrated the major virtues of this process approach were:

- A medium Btu (400 → 500 Btu/SCF) product gas could be produced from wood without requiring an oxygen plant.
- A wide range of feedstocks could be handled without pre-treatment.
- Constant heating value gas can be produced regardless of feed moisture level.
- Extremely high throughputs can be achieved, resulting in compact, economical reactors.
- Heat necessary for gasification can be supplied totally from an entrained, recirculating sand phase.
- No by-product char remains after combustion.
- Tar production is very low with all feedstocks tested.

The success of these initial studies along with favorable economic projections⁽²⁾ led to the design and modification of the PRU to increase the throughput to 12 tons per day.

SUMMARY OF PROGRAM ACCOMPLISHMENTS

MARCH 1983 - MARCH 1984

During this period project activities were conducted in the following areas.

- (1) Unit Modifications
- (2) Process Research Unit (PRU) Experimental Operations
- (3) Process Engineering Support
- (4) Technology Transfer

The project goals were made or exceeded over this time period and significant accomplishments in each of the above areas are summarized below.

Unit Modifications

Several modifications were made in the PRU to provide data on process scaleability and improve operating efficiency. The initial effort was devoted to testing the "transport wake inducer" (TWI) concept found to greatly improve performance in the 6 inch I.D. gasifier. The specific modifications made are summarized below.

- Installation of a 10-inch I.D. gasifier vessel in place of the existing 6-inch I.D. unit primarily to test process scaleability with and without the TWI's.
- Relining of the combustor to reduce heat losses thereby allowing higher gasification temperatures to be achieved.
- Modification of combustor cyclone to provide a return leg to the combustor to reduce sand losses.
- Increasing the size of the L valve solids circulation circuit between the gasifier and combustor from 3 inches to 4 inches to test L valve scaleability and reduce ΔT between gasifier and combustor.
- Automating and increasing the capacity of the wood feed-system.

Experimental Results

Operation of the 10-inch unit has been smooth and trouble-free and the most significant results achieved in the operation of the 10-inch I.D. PRU are summarized below.

- Performance, as measured by carbon conversion, has improved in the 10-inch unit over that achieved in the 6-inch unit. However, unlike the 6-inch unit, no effect of TWIs on performance was noted in the 10-inch unit.
- Gas composition has remained constant.
- Feedstocks tested thus far include:
 - Sawdust
 - Hardwood Chips
 - Softwood Chips
- Throughputs in excess of 2000 lbs/ft²-hr (on a dry wood basis) have been achieved. Limitations on feed rate appear to be simply the ability to supply heat with the existing combustor even with the improved lining and other modifications to reduce heat loss.
- Yields of condensible organic liquid products have remained approximately the same between the 6 and 10-inch units at approximately 0.5 wt. percent of the incoming feed. More work is being done to physically and chemically characterize these liquids to allow efficient gas cleanup systems to be designed.

Process Engineering Support

- A model has been developed that incorporates experimental data on product distribution, gasifier, and combustor throughputs into a detailed heat and material balance that allows system performance to be estimated as a function of input parameters. This model also provides insight into the interrelationships between process parameters and how the system will respond to "upsets".
- The "base case" conceptual design has been modified and a revised cost estimate made.

Technology Transfer

- Discussions are being held with potential commercial users of this technology to determine a program for proof-of-concept testing at an industrial site.

- Riley Stoker is participating in the conceptual design and cost estimation of commercial units and will participate in proof-of-concept scale-up efforts.

UNIT MODIFICATIONS

The Battelle PRU is an integrated system capable of simulating commercial integrated operation of the gasification/char combustion system. The initial PRU consisted of a 6-inch diameter gasifier, coupled to a 40-inch I.D. refractory lined combustor. The gasifier operates in the high-throughput mode while the PRU combustor is a conventional fluid-bed reactor. The design of the PRU combustor allows it to serve as both a combustor and a surge vessel for the sand phase. The baseline capacity of the 6-inch gasifier was 250 lbs/hr wood feed, however, wood rates up to 350 lbs/hr were achieved.⁽²⁾ This corresponds to a throughput of about 1800 lbs/hr-ft² of reactor area.

The rapid heat-up of the wood particles caused by hot sand contacting them results in a rapid evolution of gases. The wood, of course must dry completely prior to any pyrolysis or gasification reactions taking place. For this reason and the fact that residence times in the gasifier are short, it is reasonable to expect that the wood particles remain well below the bulk temperature of the reactor itself.

During previous phases of the program, a modification to increase the contacting of the hot sand and wood was developed. By increasing mixing and residence time in the reactor, it would then be theoretically possible to bring the temperature of the wood closer to the temperature of the hot sand, and thus, increase conversion levels in the gasifier. Such a system was developed and has been referred to as the Controlled Turbulent Zone or CTZ gasifier mode. The controlled turbulent zone concept is made possible by the insertion of proprietary internals into the gasifier called Transport Wake Inducers or TWI's. The TWI's produce zones of highly backmixed solids resulting in increased contacting between wood particles and hot sand.

The economic implication of this result was reduced investment costs per unit of gas produced. However, since no data base or existing computational models covered scale-up of such a system, it was decided to test the concept in a larger reactor tube to be installed in the existing PRU facility. A 10-inch reactor tube was, therefore, installed and the wood feed system automated to allow operation at the higher wood feed rates required in the larger reactor. The modified PRU is shown schematically in Figure 2 and a photograph of the modified unit is found in Figure 3.

In modifying the gasifier vessel, it was decided to retain the bare metal wall construction in order to decrease the time necessary to change from one steady-state condition to another. The reactor walls are a high-nickel alloy surrounded by electric heating elements sized to balance heat losses from the reactor.

Details of the 10-inch gasifier construction are essentially the same as the 6-inch gasifier. These have been discussed previously.⁽¹⁾ The PRU combustor is a conventional fluid bed reactor capable of burning natural gas to provide heat for gasification and compensate for system heat losses.

The modifications that were made retained the capability of the PRU to operate at high wood throughputs (2000 lb/hr-ft^2), and in fact, the feed capacity of the modified PRU was increased to allow even higher throughputs to be evaluated in future tests. With the modifications complete, the system was made capable of totally automatic operation. This allows much higher wood feed rates to be achieved without the limitations of manual wood loading as had been the case in the 6-inch unit. In order to achieve the continuous feed rates needed, the capability to feed wood from outside storage on a continuous basis had to be added. Previously, wood was loaded in drums and transferred to the feeder manually. Due to the low inherent bulk density of wood, however, this is not a feasible approach for wood rates above about 300 lbs/hr. For the 10-inch unit, therefore, it became necessary to feed the wood pneumatically into the feeder. Referring to Figure 2, wood is augered from an outside storage bin into the air intake of an air blower.

FIGURE 2. BATTELLE'S BIOMASS GASIFICATION PRU

The wood and air are then transported into the PRU where the wood is separated from the conveying gas by a cyclone mounted on top of the wood lock-hopper system.

The wood feed system can be seen in Figure 3. A schematic of the feed system from the cyclone on is found in Figure 4. The feeder itself separates the pressurizing, metering, and conveying functions to provide better control over the wood feeding. The wood metering bin is a live bottom bin containing 4-4-inch screws; these then empty into the two conveying screws that are 8 inches in diameter. The wood then falls into the base of the gasifier where it is contacted by the hot sand and steam.

Sequencing of the lock hoppers to re-load the metering bin is accomplished by a small micro-processor located in the control room. Sequence times as low as 2 to 3 minutes have been successfully achieved resulting in feed rates of about 2000 lb/hr.

In order to successfully feed any material pneumatically, elutriation of fines must be kept to a minimum. Thus far, operation of the wood feed system has shown that elutriation of wood fines from the cyclone has not been a problem. Both wood chips and sawdust with a range of moisture levels (5-50 percent) have successfully been fed through the pneumatic conveying system with no significant elutriation of fines from the system.

During previous phases of the test program, the feeder itself (excluding the pneumatic conveying) was shown to smoothly handle such diverse biomass forms as shredded bark, wood chips, and sawdust. These feed materials are shown in Figure 5.

The first series of tests with the larger gasifier showed that a factor limiting wood throughput to the gasifier was heat transfer from the combustor. This shortcoming was traced to three major areas. These were the combustor refractory lining, sand loss from the combustor, and L-valve (solids transfer) capacity.

Inspection of the refractory lining in the combustor showed significant deterioration of the refractory's ability to insulate the vessel. The refractory lining was, therefore, replaced resulting in a significant improvement in combustor performance.

FIGURE 3. PHOTO OF BATTELLE'S BIOMASS GASIFICATION PRU

FIGURE 4. SCHEMATIC OF FEED SYSTEM⁽⁵⁾

Hardwood

Bark

Sawdust

FIGURE 5. FORMS OF FEED MATERIALS

While the refractory lining was being replaced, it became possible to install a sand return leg from the combustor cyclone so that elutriated sand could be returned to the combustor bed without additional handling. Sand makeup to the combustor bed had previously been a significant heat loss.

In order to provide more sand conveying capacity (and thus, more heat to the gasifier), the PRU-L-valve piping was enlarged from 3 inches to 4 inches. The L-valve is a non-mechanical valve which makes possible the regulation of hot sand flow from the combustor to the gasifier.

EXPERIMENTAL RESULTS

Biomass materials have inherently high reactivities when compared to more conventional fuels such as coal. As a result, a reactor utilizing biomass can achieve high carbon conversions at high throughputs at significantly lower temperatures than would be the case with coal. It is, therefore, possible to operate at much higher throughputs than are possible in conventional fluid bed reactors. A conventional fluid-bed reactor is limited to wood throughputs of about 200 lbs/hr-ft². In the Battelle high throughput gasifier, however, the high reactivity of the wood feedstock is exploited so throughputs an order of magnitude higher than in conventional fluid-beds can be achieved. The result is a much smaller reactor resulting in significantly lower capital cost. Cost projections will be discussed in more detail below.

Initial tests in the 10-inch gasifier have been made in both the baseline (empty tube) and CTZ modes. A brief comparison of these results follows. Table 1 shows the data generated during the current phase of the program. Data designated as test 3.X represents tests conducted prior to refractory replacement while those designated as test 4.X are the tests made after the refractory replacement.

Table 2 shows the locations within the PRU where the data is collected.

TABLE 1. DATA GENERATED DURING CURRENT PROGRAM PHASE

FOREST RESIDUE GASIFICATION RUN DATA (3RD PHASE-10"PRU)

RUN NUMBER	3.1	3.4	3.5	3.6A	3.6B	3.8	3.9
DATE	06/01/83	06/23/83	06/28/83	06/30/83	06/30/83	07/13/83	08/05/83
NITROGEN PRESSURE, PSIG	29	25	25	27	26.5	27	27
NITROGEN TEMPERATURE, F	70	78	80	81	88	87	92
NITROGEN FLOW, % FS	7	12	40	11	16.5	10	10
PLENUM PRESSURE, PSIG	5	10	11.6	11.8	12	9.6	9.1
SUPERHEATER TEMPERATURE, F	550	570	500	575	560	570	585
STEAM FLOW, % delta FS	75.67	50.34	43.35	61.24	48.50	51.52	55.09
AIR PRESSURE, PSIG	50	57	58.8	59.4	59.4	59.4	59.4
AIR FLOW, %FS	40	38	40	40.3	39	40	38
AIR RATE, LB/HR	1199.06	1199.15	1278.01	1299.26	1251.13	1283.22	1219.05
NATURAL GAS PRESSURE, PSIG	38.4	37.2	36.6	35.7	35.4	36.6	39.3
NATURAL GAS FLOW, %FS	14	34	32	47	35	38	84
NATURAL GAS RATE, LB/HR	33.85	52.16	50.31	60.43	65.18	47.73	83.63
CYCLONE INLET TEMPERATURE, F	1060	1376	1432	1329	1345	1309	1312
CYCLONE OUTLET TEMPERATURE, F	990	1264	1326	1297	1251	1212	1211
CYCLONE INLET PRESSURE, IN H2O	N/A	178	243	304	220	171	160
CYCLONE OUTLET PRESSURE, IN H2O	N/A	163	218	217	202	157	140
SPRAY TOWER INLET TEMP, F	990	1764	1326	1297	1251	1212	1211
SPRAY TOWER OUTLET TEMP, F	200	202	224	236	201	202	329
SCRUBBER INLET TEMP, F	200	202	224	236	201	202	328.5
SCRUBBER OUTLET TEMPERATURE, F	135	64	65	65	65	66	66
INITIAL MOISTURE VALUE, %	16.00	19.00	9.00	9.00	9.00	10.00	10.00
INIT PROD GAS RATE, SCFM	53.10	88.75	151.40	118.00	127.70	120.80	92.15
INIT CARBON CONVERSION TO GAS, %	46.8	62.2	79.4	51.3	63.1	59.14	59.05

FOREST RESIDUE GASIFICATION RUN RESULTS

RUN NUMBER	3.1	3.4	3.5	3.6A	3.6B	3.8	3.9
RUN CONDITION	N-5	N-5	N-5	N-5	N-5	B-N-5	B-N-5
WOOD TYPE	RED OAK	RED OAK	RED OAK	RED OAK	RED OAK	BIR+MAP	BIR+MAP
MOISTURE, %	14.42	15.69	6.88	9	9	10	10
WOOD FEED RATE, LB/HR	486	588	700	916	777	786	580
DRY FEED RATE, LB/HR	416	496	652	833	707	707	522
GASIFIER TEMPERATURE, F	1280	1504	1562	1359	1466	1445	1470
GASIFIER PRESSURE, PSIG	3.8	6.2	8.2	8.4	7.8	5.8	5.2
NITROGEN FEED, LB/HR	139	173	315	169	204	160	160
STEAM RATE, LB/HR	389	404	401	461	415	406	412
GASIFIER GAS VELOCITY, FT/SEC	13.67	14.71	16.18	13.62	14.19	14.36	15.16
COMBUSTOR TEMPERATURE, F	1525	1866	1897	1806	1845	1734	1680
COMBUSTOR PRESSURE, PSIG	4.2	6.6	9	8.7	8.4	6.5	5.7
COMBUSTOR GAS VELOCITY, FT/SEC	1.64	1.74	1.68	1.68	1.68	1.79	1.77
PRODUCT GAS RATE, SCF/LB-MAF	7.66	10.74	13.94	8.50	10.84	10.25	10.59
CARBON CONVERSION TO GAS, %	45.50	58.75	76.14	50.29	61.47	57.66	57.31
PRODUCT GAS COMPOSITION, % M2 FREE							
HYDROGEN	13.25	20.59	20.51	14.66	18.15	17.20	20.81
CARBON DIOXIDE	16.32	14.24	17.08	14.39	19.93	12.75	14.78
ETHYLENE	3.81	4.80	3.94	4.18	4.63	4.78	4.28
ETHANE	1.01	.40	.25	1.02	.73	.74	.60
ACETYLENE							
METHANE	16.10	15.90	14.41	16.59	16.30	16.38	15.36
CARBON MONOXIDE	49.52	43.98	43.80	49.18	46.27	48.15	44.17
H2/CO RATIO	.27	.47	.47	.30	.39	.36	.47
PRODUCT GAS HHV, BTU/SCF	444	455	421	459	460	466	444
BTU YIELD, BTU/LB MAF	3401	4882	5863	3897	4981	4778	4704
WOOD ANALYSIS, % DRY BASIS							
VOLATILE MATTER	81.07	70.42	82.82	83.38	83.38	83.99	84.48
FIXED CARBON	16.17	28.37	16.55	15.48	15.48	15.65	14.65
ASH	2.76	1.21	.63	1.14	1.14	.36	.87
CARBON	49.34	57.75	50.00	49.77	49.77	49.85	50.14
HYDROGEN	5.93	5.58	6.05	5.99	5.99	6.12	6.10
NITROGEN	.07	.44	.21	.20	.20	.10	.03
CHLORINE	.03	.03	.08	.02	.02	.03	.03
SULFUR	.13	.87	.00	.00	.00	.09	.03
OXYGEN (by difference)	41.74	34.12	42.72	42.88	42.88	43.45	42.80
BTU/LB (DRY)	8220	9789	8398	8324	8524	8453	8461

B - TWI

C - INTERNAL CATALYST

N - NITROGEN

S - STEAM

TABLE 1. (continued)

FOREST RESIDUE GASIFICATION RUN DATA (3RD PHASE-10"PRU)

RUN NUMBER	3.10A	3.10H	3.14	3.15	3.16	3.17	3.18	3.19
DATE	08/11/83	08/11/83	09/07/83	09/15/83	10/13/83	10/20/83	10/25/83	10/31/83
NITROGEN PRESSURE, PSIG	26	27	27	25	26	25	25	25
NITROGEN TEMPERATURE, F	77	88	70	60	0	38	40	80
NITROGEN FLOW, % FS	10	9	5.3	4.25	17	19	18.5	3
PLENUM PRESSURE, PSIG	8.4	11	8.4	7.2	9.5	8.4	8.2	7.6
SUPHEATER TEMPERATURE, F	600	590	640	610	530	560	590	650
STEAM FLOW, % delta FS	57.65	57.70	64.93	67.98	65.88	64.98	60.32	66.74
AIR PRESSURE, PSIG	59.4	59.4	57.9	58.2	48.9	51	51.2	47.4
AIR FLOW, % FS	41	39	50	51	48	42	45	45
AIR RATE, LB/HR	1815.30	1251.13	1587.70	1622.80	1426.59	1268.71	1361.40	1321.37
NATURAL GAS PRESSURE, PSIG	40.2	39.6	34.8	40.2	30.6	36	34.2	42.6
NATURAL GAS FLOW, % FS	34	50	70	38	38.5	50	38	41
NATURAL GAS RATE, LB/HR	67.61	64.70	73.07	56.71	51.85	62.52	53.52	60.18
CYCLONE INLET TEMPERATURE, F	1399	1309	1305	1252	1292	1318	1289	1264
CYCLONE OUTLET TEMPERATURE, F	1273	1212	1168	1144	1169	1198	1180	1161
CYCLONE INLET PRESSURE, IN H2O	185	194	128	110	123	111	95	73
CYCLONE OUTLET PRESSURE, IN H2O	133	178	109	88	112	74	78	49
SPRAY TOWER INLET TEMP, F	1273	1212	1168	1144	1163	1198	1180	1161
SPRAY TOWER OUTLET TEMP, F	259	299	366	174	NA	N/A	N/A	N/A
SCRUBBER INLET TEMP, F	259	299	366	194	0	N/A	N/A	N/A
SCRUBBER OUTLET TEMPERATURE, F	66	65	65	67	62	61	59	58
INITIAL MOISTURE VALUE, %	8.30	8.30	10.60	7.00	10.00	3.80	4.70	3.70
INIT PROD GAS RATE, SCFH	69.24	117.60	59.70	73.60	49.04	73.66	69.55	68.21
INIT CARBON CONVERSION TO GAS, %	61.32	56.21	49.54	65.45	47.24	62.69	61.31	60.04

FOREST RESIDUE GASIFICATION RUN RESULTS

RUN NUMBER	3.10A	3.10H	3.14	3.15	3.16	3.17	3.18	3.19
RUN CONDITION	B-N-5	B-N-5	N-5	N-5	N-5	N-5	N-5	N-5
WOOD TYPE	BIRMAP	BIRMAP	BIRMAP	BIRMAP	BIRMAP	HARD	HARD	HARD
MOISTURE, %	8.12	8.12	12.37	3.65	10	3	4.7	3.7
WOOD FEED RATE, LB/HR	400	702	457	418	397	425	425	413
DRY FEED RATE, LB/HR	375	719	400	403	357	412	405	398
GASIFIER TEMPERATURE, F	1548	1429	1465	1395	1422	1451	1408	1496
GASIFIER PRESSURE, PSIG	5	6.8	4.4	4.1	3.4	2.6	2.6	2.4
NITROGEN FEED, LB/HR	160	152	119	105	225	221	222	86
STEAM RATE, LB/HR	413	437	430	432	467	447	422	426
GASIFIER GAS VELOCITY, FT/SEC	15.95	14.27	15.48	14.96	19.31	19.75	18.33	16.21
COMBUSTOR TEMPERATURE, F	1804	1675	1722	1707	1629	1672	1628	1575
COMBUSTOR PRESSURE, PSIG	5	6.8	3.8	3.8	3.3	2.4	2.4	2.2
COMBUSTOR GAS VELOCITY, FT/SEC	2.04	1.67	2.50	2.50	2.17	2.12	2.20	2.13
PRODUCT GAS RATE, SCFH-LB-MAF	11.08	9.82	8.97	10.96	8.24	10.72	10.30	10.29
CARBON CONVERSION TO GAS, %	60.22	54.65	50.06	63.17	50.23	62.29	62.52	58.92
PRODUCT GAS COMPOSITION, % N2 FREE								
HYDROGEN	24.18	19.36	20.92	19.81	19.19	18.41	16.65	18.34
CARBON DIOXIDE	15.42	14.57	15.38	16.11	14.82	12.65	13.26	13.62
ETHYLENE	4.15	4.31	4.88	4.83	4.48	4.79	4.89	4.83
ETHANE	.31	.71	.42	1.27	.77	.64	.82	.72
ACETYLENE								.28
METHANE	14.42	15.83	15.91	15.75	17.13	17.06	17.01	16.65
CARBON MONOXIDE	41.91	45.23	42.57	42.29	43.61	46.46	47.38	49.37
H2/CO RATIO	.58	.43	.49	.47	.44	.40	.35	.43
PRODUCT GAS HHV, BTU/SCF	431	450	451	459	461	470	471	462
BTU YIELD, BTU/LB-MAF	4777	4417	4051	5036	3798	5037	4856	4757
WOOD ANALYSIS, % DRY BASIS								
VOLATILE MATTER	83.63	83.63	84.42	84.50	84.09	83.41	84.16	85.65
FIXED CARBON	15.93	15.93	14.95	15.00	15.45	15.66	15.26	13.74
ASH	.44	.44	.63	.5	.46	.93	.61	.61
CARBON	51.13	51.13	50.95	50.37	50.41	49.63	50.12	49.63
HYDROGEN	5.73	5.73	5.70	5.88	6.13	6.00	6.23	6.42
NITROGEN	.14	.14	.13	.19	.39	.31	.13	.16
CHLORINE	.02	.02	.02	.03	.03	.03	.03	.06
SULFUR	.03	.03	.02	.00	.00	.00	.03	.04
OXYGEN (by difference)	42.51	42.51	42.55	43.03	42.58	43.10	42.85	43.08
DTU/LB (DRY)	8513	8513	8300	8394	8464	8280	8402	8365

B - TWI
C - INTERNAL CATALYST
N - NITROGEN
S - STEAM

TABLE 1. (continued)

FOREST RESIDUE GASIFICATION RUN DATA

RUN NUMBER	3.20	3.21	3.22A	3.22B	3.23	3.24	3.25A	3.25B
DATE	11/02/83	11/08/83	11/10/83	11/10/83	11/16/83	11/18/83	12/13/83	12/13/83
NITROGEN PRESSURE, PSIG	25	25	25	25	25	25	25	25
NITROGEN TEMPERATURE, F	60	61	58	20	30	70	46	86
NITROGEN FLOW, % FS	4	6	4	5.5	6	1.5	5	0
PLINUM PRESSURE, PSIG	8	8	8.4	8.8	7.6	7.2	9.6	10.2
SUPERHEATED TEMPERATURE, F	620	630	625	635	600	660	630	660
STEAM FLOW, % Delta FS	66.64	62.11	63.83	64.70	65.00	65.49	55.97	42.40
AIR PRESSURE, PSIG	48	48	49.2	49.2	40	48.6	48	47.4
AIR FLOW, %FS	48	48	50	51	30	23	39	47
AIR RATE, LB/HR	1416.46	1416.46	1409.54	1519.33	885.29	681.96	1150.88	1380.30
NATURAL GAS PRESSURE, PSIG	35.7	36	34.2	34.8	33.6	42.6	43.2	42.6
NATURAL GAS FLOW, %FS	90	48	30	38	39	50	50	43
NATURAL GAS RATE, LB/HR	48.28	61.25	53.52	53.85	58.89	66.46	66.81	61.63
CYCLONE INLET TEMPERATURE, F	1214	1283	1190	1214	1100	1171	1958	1227
CYCLONE OUTLET TEMPERATURE, F	1102	1174	1150	1174	N/A	158	1131	1079
CYCLONE INLET PRESSURE, IN H2O	89	106	104	118	N/A	108	157	99
CYCLONE OUTLET PRESSURE, IN H2O	74	67	95	106	N/A	112	138	90
SPRAY TOWER INLET TEMP, F	1102	1174	1150	1174	N/A	158	1131	1079
SPRAY TOWER OUTLET TEMP, F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SCRUBBER INLET TEMP, F	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
SCRUBBER OUTLET TEMPERATURE, F	50	58	57	57	60	56	52	53
INITIAL MOISTURE VALUE, %	15.00	4.30	10.00	10.00	33.00	45.00	5.00	5.00
INIT PROD GAS RATE, SCFH	50.34	66.43	41.18	40.23	30.00	35.40	47.05	149.00
INIT CARBON CONVERSION TO GAS, %	59.68	56.45	57.45	55.68	41.68	48.18	77.05	55.9

FOREST RESIDUE GASIFICATION RUN RESULTS

RUN NUMBER	3.20	3.21	3.22A	3.22B	3.23	3.24	3.25A	3.25B
RUN CONDITION	N-5	N-5	N-5	N-5	N-5	N-5	N-5	N-5
WOOD TYPE	5 OAK	5 OAK	5 OAK	5 OAK	SAMDUST	SAMDUST	5 OAK	5 OAK
MOISTURE, %	15	5.5	10	10	40	35	5	5
WOOD FEED RATE, LB/HR	348	420	275	275	340	518	200	1008
DRY FEED RATE, LB/HR	296	397	248	240	204	337	190	958
GASIFIER TEMPERATURE, F	1371	1436	1374	1308	1290	1328	1628	1313.5
GASIFIER PRESSURE, PSIG	2.8	2.7	3.6	4.1	3.4	3.2	5	5
NITROGEN FEED, LB/HR	101	124	124	124	128	62	115	0
STEAM RATE, LB/HR	436	419	429	434	430	417	411	357
GASIFIER GAS VELOCITY, FT/SEC	15.71	16.48	15.49	15.34	15.05	13.83	15.61	9.77
COMBUSTOR TEMPERATURE, F	1530	1630	1555	1605	1620	1768	1766	1675
COMBUSTOR PRESSURE, PSIG	2.5	2.6	3.3	3.8	3.4	3	4.8	5.4
COMBUSTOR GAS VELOCITY, FT/SEC	2.15	2.28	2.17	2.23	1.39	1.24	1.79	1.96
PRODUCT GAS RATE, SCF/LB-MAF	10.21	10.04	9.98	9.75	8.82	6.31	14.86	9.34
CARBON CONVERSION TO GAS, %	59.68	56.95	57.56	57.95	47.95	40.98	78.11	54.55
PRODUCT GAS COMPOSITION, % N2 FREE								
HYDROGEN	18.21	20.47	19.38	20.04	14.16	16.81	26.41	15.92
CARBON DIOXIDE	15.04	14.27	14.95	14.92	12.02	10.53	14.75	15.05
ETHYLENE	4.53	4.65	4.41	4.51	4.74	4.96	4.02	3.68
ETHANE	71	72	82	78	1.06	.93	.00	1.24
ACETYLENE	23	27	24	24	.00	.25	.50	53
METHANE	16.61	16.12	16.42	16.58	16.26	15.61	14.75	16.46
CARBON MONOXIDE	44.51	43.51	43.80	43.01	51.75	50.92	40.06	47.11
H2/CO RATIO	41	47	44	47	27	33	66	34
PRODUCT GAS HHV, BTU/SCF	462	461	459	461	472	476	436	458
BTU YIELD, BTU/LB-MAF	4721	4626	4578	4493	4160	3001	6472	4279
WOOD ANALYSIS, % DRY BASIS								
VOLATILE MATTER	83.47	84.33	85.07	85.07	81.92	80.65		
FIXED CARBON	15.72	14.60	14.26	14.26	17.43	18.78		
ASH	81	97	67	67	65	57		
CARBON	49.94	49.69	49.81	49.01	53.92	53.11	50.00	50.00
HYDROGEN	5.30	6.33	6.03	6.03	6.53	6.50		
NITROGEN	16	13	11	11	21	18		
CHLORINE	.02	.02	.02	.02	.04	.04		
SULFUR	.00	.00	.01	.01	.04	.03		
OXYGEN (by difference)	42.77	42.34	43.33	43.33	38.61	39.57		
BTU/LB (DRY)	8500	8459	8448	8440	9011	9095		

W - TWI

C - INTERNAL CATALYST

N - NITROGEN

S - STEAM

TABLE 1. (continued)

FOREST RESIDUE GASIFICATION - DATA SUMMARY (4TH PHASE)

RUN NUMBER	4.2	4.4A	4.4B	4.4C	4.5
DATE	02/23/84	04/03/84	04/03/84	04/03/84	04/11/84
NITROGEN PRESSURE, PSIG	24.3	24.3	24.3	24.3	24.3
NITROGEN TEMPERATURE, F	6	38	40	46	53
NITROGEN FLOW, % FS	3	4.5	4	4.25	4.5
PLENUM PRESSURE, PSIG	11.9	10.4	11.6	12	11.7
SUPERHEATER TEMPERATURE, F	630	700	650	640	660
STEAM FLOW, % delta FS	68.76	65.73	63.84	46.46	68.72
AIR PRESSURE, PSIG	51	48	48	48	47.4
AIR FLOW, %FS	70.5	82	92	92	92
AIR RATE, LB/HR	2129.62	2419.79	2714.89	2714.89	2701.87
NATURAL GAS PRESSURE, PSIG	30.6	48	47.4	47.4	36.8
NATURAL GAS FLOW, %FS	100	100	100	100	100
NATURAL GAS RATE, LB/HR	93.57	98.32	97.85	97.85	89.11
CYCLONE INLET TEMPERATURE, F	1339	1384	1396	1390	1416
CYCLONE OUTLET TEMPERATURE, F	1193	1202	1265	1253	1293
CYCLONE INLET PRESSURE, IN H2O	224.5	284	320	318	164
CYCLONE OUTLET PRESSURE, IN H2O	100	180	190	170	183
SPRAY TOWER INLET TEMP, F	1193	1202	1265	1253	1393
SPRAY TOWER OUTLET TEMP, F	N/A	N/A	N/A	N/A	N/A
SCRUBBER INLET TEMP, F	N/A	N/A	N/A	N/A	N/A
SCRUBBER OUTLET TEMPERATURE, F	45	48	49	50	50
INITIAL MOISTURE VALUE, %	10	5	5	5	5
INIT PROD GAS RATE, SCFH	61.635	78.75	95.7	203.9	102.4
INIT CARBON CONVERSION TO GAS, %	64.75	67.6	63.4	66.1	76.4

FOREST RESIDUE GASIFICATION RUN RESULTS

RUN NUMBER	4.2	4.4A	4.4B	4.4C	4.5
RUN CONDITION	N-5	N-5	N-5	5	N-5
WOOD TYPE	SWP OAK	SWP OAK	SWP OAK	SWP OAK	HARD
MOISTURE, %	7.17	4.18	4.18	4.10	5.5
WOOD DEMO RATE, LB/HR	950.5	387.7	505	1122	450
DRY FEED RATE, LB/HR	333	371	484	1075	425
GASIFIER TEMPERATURE, F	1542	1558	1580	1431	1623
GASIFIER PRESSURE, PSIG	6.8	6.4	7	7.4	7
NITROGEN FEED, LB/HR	119.03	107.11	102.78	105.32	107.63
STEAM RATE, LB/HR	459	439	453	391	469
GASIFIER GAS VELOCITY, FT/SEC	15.14	14.75	14.01	11.91	15.67
COMBUSTOR TEMPERATURE, F	1738	1706	1768	1765	1833
COMBUSTOR PRESSURE, PSIG	6.8	6	7.2	7.2	7.4
COMBUSTOR GAS VELOCITY, FT/SEC	2.88	3.48	3.64	3.63	3.67
PRODUCT GAS RATE, SCF/LB-MF	11.11	12.72	11.87	11.38	14.45
CARBON CONVERSION TO GAS, %	66.31	67.15	64.10	66.43	77.36
PRODUCT GAS COMPOSITION, % N2 FREE					
HYDROGEN	24.97	26.08	25.4	19.1	24.58
CARBON DIOXIDE	15.025	14.44	14.33	15.1	13.21
ETHYLENE	4.45	4.22	4.1	4.27	4.06
ETHANE	.40	.35	.33	.94	.23
ACETYLENE	.29	.3	.3	.07	.37
METHANE	14.8	15.5	15.98	18	16.76
CARBON MONOXIDE	40.03	39.13	39.5	42.57	40.75
H2/CO RATIO	62	67	64	45	60
PRODUCT GAS HHV, BTU/SCF	442	446	447	467	455
BTU YIELD, BTU/LB-MAF	4915	5668	5306	5315	6577
WOOD ANALYSIS, % DRY BASIS					
VOLATILE MATTER	83.15	82.92	82.92	82.92	83.80
FIXED CARBON	15.57	14.84	14.84	14.04	14.99
ASH	1.20	2.24	2.24	2.24	1.21
CARBON	50.08	49.78	49.98	49.98	50.22
HYDROGEN	6.06	5.95	5.95	5.95	5.9
NITROGEN	.15	.18	.18	.18	.06
CHLORINE	.02	.02	.02	.02	.02
SULFUR	.04	.12	.12	.12	.07
OXYGEN (by difference)	41.57	41.51	41.51	41.51	42.50
BTU/LB (DRY)	8475	8380	8380	8380	8417

B - TWI

C - INTERNAL CATALYST

N - NITROGEN

S - STEAM

TABLE 2. DATA SOURCES

RUN NUMBER	BATTELLE DESIGNATION
DATE	
NITROGEN PRESSURE, PSIG	UPSTREAM OF NITROGEN ORIFICE
NITROGEN TEMPERATURE, F	AT NITROGEN ORIFICE
NITROGEN FLOW, % FS	RECORDER READING
PLENUM PRESSURE, PSIG	BELOW DISTRIBUTOR IN GASIFIER
SUPERHEATER TEMPERATURE, F	AT STEAM ORIFICE
STEAM FLOW, % delta FS	RECORDER READING
AIR PRESSURE, PSIG	UPSTREAM OF AIR ORIFICE
AIR FLOW, %FS	RECORDER READING
AIR RATE, LB/HR	FLOW INTO COMBUSTOR, CALCULATED
NATURAL GAS PRESSURE, PSIG	UPSTREAM OF N.G. ORIFICE, COMBUSTOR
NATURAL GAS FLOW, %FS	RECORDER READING
NATURAL GAS RATE, LB/HR	FLOW INTO COMBUSTOR, CALCULATED
CYCLONE INLET TEMPERATURE, F	PRODUCT GAS INTO GASIFIER CYCLONE
CYCLONE OUTLET TEMPERATURE, F	PRODUCT GAS OUT OF GASIF. CYCLONE
CYCLONE INLET PRESSURE, IN H2O	STATIC PRESSURE AT CYCLONE INLET
CYCLONE OUTLET PRESSURE, IN H2O	STATIC PRESSURE AT CYCLONE OUTLET
SPRAY TOWER INLET TEMP, F	IDENTICAL TO CYCLONE OUTLET
SPRAY TOWER OUTLET TEMP, F	PRODUCT GAS AT SPRAY TOWER OUTLET
SCRUBBER INLET TEMP, F	IDENTICAL TO SPRAY TOWER OUT
SCRUBBER OUTLET TEMPERATURE, F	PRODUCT GAS TO FLARE
INIT PROD GAS RATE, SCFM	CALCULATED DURING TEST
INIT CARBON CONVERSION TO GAS, %	CALCULATED DURING TEST

RUN NUMBER	
RUN CONDITION	
WOOD TYPE	
MOISTURE, %	FROM ANALYTICAL TEST
WOOD FEED RATE, LB/HR	MEASURED FROM LOAD CELLS
DRY FEED RATE, LB/HR	
GASIFIER TEMPERATURE, F	MEASURED 24 IN. FROM DISTRIBUTOR
GASIFIER PRESSURE, PSIG	MEASURED IN PRODUCT GAS LINE
NITROGEN FEED, LB/HR	NITROGEN IN FEED GAS ONLY
STEAM RATE, LB/HR	STEAM FEED RATE TO GASIFIER
GASIFIER GAS VELOCITY, FT/SEC	SUPERFICIAL BASED ON N2 & STEAM
COMBUSTOR TEMPERATURE, F	MIDDLE OF FLUID BED
COMBUSTOR PRESSURE, PSIG	MEASURED IN FLUE LINE
COMBUSTOR GAS VELOCITY, FT/SEC	SUPERFICIAL VELOCITY AT CONDITIONS
PRODUCT GAS RATE, SCF/LB-MAF	MAF = MOISTURE, ASH FREE WOOD
CARBON CONVERSION TO GAS, %	CALCULATED FROM PRODUCT RATE
PRODUCT GAS COMPOSITION, %	
HYDROGEN	
CARBON DIOXIDE	
ETHYLENE	
ETHANE	
ACETYLENE	
METHANE	
CARBON MONOXIDE	
NITROGEN	
H2/CO RATIO	
PRODUCT GAS HHV, BTU/SCF	CALCULATED VALUE
BTU YIELD, BTU/LB-MAF	MAF = MOISTURE, ASH FREE WOOD
WOOD ANALYSIS, % DRY BASIS	
VOLATILE MATTER	
FIXED CARBON	
ASH	
CARBON	
HYDROGEN	
NITROGEN	
CHLORINE	
SULFUR	
OXYGEN (by difference)	
BTU/LB (DRY)	

Baseline Mode Tests

"Baseline" tests, thus far, in the 10-inch gasifier have shown that wood conversion levels are significantly improved over those achieved in the 6-inch unit. Figure 6 shows the results of these tests compared to the baseline conversion curve generated during earlier phases of the program. The improvement in conversion levels noticed in the 10-inch unit is most likely due to improved contacting between the wood and the hot sand at the base of the gasifier. The gasifier has been operated in the baseline mode at feed rates up to 1160 lb/hr (over 2000 lb/hr-ft²). As can be seen, the combustor modifications that were made have made possible the achievement of temperatures in excess of 1600 F in the gasifier at throughputs up to approximately 1000 lb/hr-ft². However, experience thus far indicates that throughputs will still be limited by the ability to maintain gasifier temperatures with the limiting factor being the maximum heat generation rate of the combustor.

Therefore, in a commercial plant, with its inherently lower heat losses, considerably higher throughput may be achieved. In subsequent phases of the gasification program, we will try to determine the factors that are likely to ultimately limit the throughput in this type of gasifier. Further tests will then be made to evaluate the maximum throughputs attainable in the baseline mode.

Tests in the Modified Gasifier

As mentioned above, during the previous phase of the program, the use of proprietary internals resulted in significant increases in carbon conversion. The TWI's produce zones of highly backmixed solids resulting in increased contacting between wood particles and hot sand. Initial experiments in the TWI mode with the 6-inch reactor showed that carbon conversion levels up to 90 percent could be achieved with no reduction in total reactor throughput. These results have been discussed in a previous publication.⁽²⁾

With the TWI's in place in the 10-inch unit, carbon conversions slightly lower than had been achieved earlier in the 6-inch unit as can be seen in Figure 7. However, as Figure 6 indicates, carbon conversions

FIGURE 6. BATTELLE'S BIOMASS GASIFICATION (10 inch unit results compared to 6 inch unit results)

FIGURE 7. BATTELLE'S BIOMASS GASIFICATION
(TWI results 10 inch gasifier)

with the empty 10-inch tube were significantly above those in the empty 6-inch tube. The fact that the TWI's did not further increase carbon conversion in the 10-inch unit could be due to the physical position of the TWI's in the reactor during these initial experiments. In the 6-inch unit, wood enters at the base of the TWI bank while in the 10-inch gasifier, wood enters well below the base of the TWI's. Thus, the gasifier temperature at which the TWI's were inserted is probably different in the two units. Thus, one may speculate that the effect of the turbulent zone depends on the temperature in the turbulent zone. Thus, tests in the TWI mode focusing on the position in the reactor are planned for a future program phase.

As was the case during earlier testing in the 6-inch unit, char produced during gasification in both baseline and TWI modes was totally consumed in the combustor. Condensibles produced during gasification continue to be low at about 0.5 percent of the wood fed. These are removed from the product gas by a simple water scrubber. Work is currently under way to further characterize these condensibles to allow an efficient scrubber to be designed.

A typical product gas analysis is found in Table 3. The composition has been shown to not change as wood moisture content change; this contrasts with a single zone air blown gasifier where dry gas heating value varies significantly as wood moisture content changes. Figure 8 illustrates these changes. If the gas is intended to be used for cogeneration applications, constant heating value of the fuel gas is critical. Gas turbine combustors can tolerate little change in gas heating value when low or medium Btu gases are utilized as fuels.

PROCESS MODELING

A computer model has been constructed to simulate performance of a commercial Forest Residue Gasification (FRG) system. This consists of a complete mass and energy balance that takes into account heat losses. Heat losses have been accurately calculated for each major process vessel as well as process piping, allowing a realistic system simulation. Flexibility is built in to allow for exploring the effect of operating

TABLE 3. TYPICAL PRODUCT GAS ANALYSIS

	Volume, % Dry
H ₂	16.0
CO ₂	12.8
C ₂ H ₄	6.0
C ₂ H ₆	1.0
CH ₄	16.5
CO	47.7

FIGURE 8. PRODUCT GAS HEATING VALUE VARIES SIGNIFICANTLY WITH FEED MOISTURE IN AN AIR BLOWN SYSTEM

and design parameters on system performance and operation. In addition to helping with process conceptual designs, the model can be used to determine the most critical experimental parameters for future PRU tests as well as to interpret the results of these tests. The model allows the calculation of thermal performance in terms of controllable process and design parameters, as well as determining sensitivities and optimizations of process parameters such as temperatures and flow rates. Performance can be rapidly evaluated under a variety of conditions.

Model Operation

The model predicts performance as a function of twelve variables. These variables include:

- plant size
- wood type
- wood analysis
- wood heating value
- feed moisture
- gasifier temperature, or
- carbon conversion to gas
- gas composition
- carbon conversion to liquid products
- flue gas to steam efficiency
- heat loss from plant
- turndown.

To accomplish these calculations, inputs of feedstock-type, plant size, and operating conditions are employed. The first step in the calculations is a mass balance over the system.

In calculating the mass balance, experimental data generated in the PRU is used to predict the elemental balance around the gasifier and generate numerical values for the gasifier exit streams such as the product gas, char, condensible organics, and circulating sand. In combination with the energy balance, the relative mass flows are balanced so that the char sent to the combustor is enough to satisfy heat loads with no excess char or heat production. PRU testing has shown that this calculated "balance point", in fact, can be achieved at the design temperatures and flow rates.

With mass flows determined, the vessel sizes are calculated in a subroutine using experimental data on vessel throughputs and conventional design methods for other process vessels such as cyclones. These vessel sizes are then used as inputs for determining heat losses from the system.

In predicting "balanced operation", the model adjusts the mass balance so as to achieve thermally balanced operation. That is, each section of the plant is in thermal equilibrium, where heat inputs equal outputs (including heat loss) at steady state. This is accomplished using an iterative technique. An initial condition (gasifier temperature or carbon conversion) is chosen. It is then determined if the char is sufficient for the heat load on the combustor, from which the gasifier heat requirement is supplied. The gasifier and combustor temperatures are then adjusted so that the char produced is just enough to supply the system's heat requirements. Additionally, the drying of the wood is adjusted so that the flue gas dries the wood as close to 10 percent moisture as possible. Each time a new feed moisture is determined, a new balance between the gasifier and combustor is calculated.

However, if one is interested in a particular situation, all these iterations need not be used. A specific condition (e.g., carbon conversion or gasifier temperature) can be stated. The output can then be studied to determine the effect on the net heat requirements, or excess heat production, in the combustor. In addition, if the specified inputs create a net heat requirement then the required amount of auxiliary combustion fuel to meet this requirement will be calculated. For example, if it were assumed higher carbon conversions in the gasifier were possible, a case could be run where the model will predict the additional heat requirement in the combustor due to lack of char, and the auxiliary wood required to supply this heat. This gives the capability to explore alternate options and how operation would be affected. A simplified flow diagram of the program is presented in Figure 9.

FIGURE 9. BATTELLE'S BIOMASS GASIFICATION COMPUTER MODEL

The model output provides a process summary as well as details of each of the process streams. The full output includes:

- production rates of product gas and steam,
- thermal and conversion efficiencies,
- detailed heat losses,
- a total mass and energy balance,
- detailed mass energy data for each stream, and
- a combustion summary.

Figure 10 presents a typical (full) output. A partial output, summarizing the key points of usage and production with an overall heat loss and limited combustion data, is also available.

An important item of interest was to use the model to simulate a conceptual commercial design case. This was done with the most recent data and more detailed calculations than previously employed. The model predicted at what conditions a 500 TPD plant would operate in a balanced mode with hardwood as a feedstock. Figure 10 is the result of this simulation. In the detailed balance, the energy values listed include both chemical and sensible heat. A carbon conversion in the gasifier of 68 percent agrees with earlier calculations⁽²⁾, however, the feed is only dried to 12.4 percent, unlike the 10 percent assumed in past calculations with this type of feedstock. Total heat losses were approximately 5 percent of the wood's heating value which is reasonable for a plant of this size. All results agree closely with earlier calculations for this particular "base case" with more detailed process engineering information now available.

Figure 11 shows a case for a 200 TPD plant using softwood as the feedstock. As can be seen, the outputs are quite similar. The detailed heat loss calculations trace and account for heat losses throughout the plant. This is critical in determining heat transfer requirements between the combustor and gasifier and the resultant sand circulation rate. The sand circulating rate predicted ($\sim 29,000 \text{ lb/hr-ft}^2$) is well within experimentally determined transfer capabilities of the L-valve. Earlier heat loss estimates were more conservative and not as representative of the true performance of the system. However, since heat losses

CASE # 1

PLANT SIZE (TPD)	500.0	HARDWOOD		
DRY FEED RATE (LB/HR)	41666.67			
FEED MOISTURE CONTENT (%)	12.4			
STEAM RATE (LB/HR)	12716.33		COMBUSTION DATA	
NITROGEN FEED (LB/HR)	169.9			
CARBON CONVERSION TO GAS (%)	60.0		AIR REQ (LB/HR)	100666.4
PROD GAS RATE (SCF/HR)	498061.3		FLUE GAS RATE (SCF/HR)	1366108.2
ENERGY PRODUCT (MM-BTU/DAY)	5777.0		SAND RATE (LB/HR-FT ²)	28829.8
PRODUCT HHV (BTU/SCF)	483.0			
EXPORT ENERGY (MM-BTU/HR)	18.1 ⁴	(LB-STEAM/HR) 12791.2		
COLD GAS EFFICIENCY (%)	60.1			
TOTAL HEAT LOSS (MM-BTU/HR)	17.9 ⁴	(% OF FEED HHV) 5.1		
GASIFIER GAS VELOCITY (FT/SEC)	10.5			
GASIFIER TEMPERATURE (F)	1600.0			
COMBUSTOR TEMPERATURE (F)	1900.0			

VESSEL SIZES (FT)			HEAT LOSS SUMMARY		
	ID	OD	HEIGHT	BTU/HR	% OF HHV
GASIFIER	2.2	6.2	29.7	843254.89	.24
COMBUSTOR	8.9	10.1	59.7	1431767.81	.41
GASIFIER CYCLONES	3.0	4.4	14.4	298991.04	.08
COMBUSTOR CYCLONES	6.0	7.4	27.2	988319.86	.28
SURGE POT	0.7	0.9	17.9	476695.01	.13
L VALVES	.7	1.3	15.0	149774.93	.04
			PIPING	6323783.60	1.80
			SUM	10942583.88	2.98
			(HEAT EXCHNG)	7435755.78	2.10
			TOTAL	17978339.66	5.09

FIGURE 10. MASS AND ENERGY BALANCE SUMMARY FOR FOREST RESIDUE GASIFICATION MODEL

ELEMENT BAL-GASIFIER		
(LBS/HR)	IN	OUT
C	20950.33	20950.33
H	4214.13	4214.13
N	257.30	257.30
O	34163.07	34163.07
ASH	725.03	725.03
S	25.00	25.00
TOTAL	60530.76	60530.76

OVERALL ENERGY BALANCE			
(MMBTU/HR)	IN		OUT
WOOD	355.30	PROD GAS	299.73
STEAM	10.13	FLU GAS	59.51
AIR	.01	CONDENSIBLE	3.76
		DIRECT LOAD	10.15
TOTAL	375.45		373.15

Detailed Mass and Energy Balance

			PRODUCT GAS			CHAR		
IN	LB/HR	MM-BTU/HR	GAS	LB/MOLE/HR	MM-BTU/HR	OUT	LB/HR	MM-BTU/HR
WOOD	41666.7	354.6	H ₂ O	209.4	20.0	C	6556.67	96.5
MOISTURE	5885.9	.7	CO	621.9	82.2	H	455.90	20.1
STEAM	12914.3	10.1	C ₇ H ₈	166.1	3.0	ASH	745.03	.4
NITROGEN	149.9	.0	C ₄ H ₄	215.3	87.0			
			C ₂ H ₄	70.0	30.1	TOTAL	7750.40	125.1
TOTAL	60530.8	373.4	C ₂ H ₆	13.3	9.4			
			H ₂ O	1170.9	39.3			
			N ₂	9.2	.1			
			TOTAL	2493.1	299.7			

AIR REQUIREMENT			FLUE GAS			CONDENSIBLES		
	LB/MOLE/HR	MM-BTU/HR		LB/MOLE/HR	MM-BTU/HR		LB/HR	MM-BTU/HR
O ₂	729.5	.00	CO ₂	346.4	12.0	C	150.00	2.2
N ₂	2761.0	.01	H ₂ O	220.0	8.3	H	25.00	1.5
			O ₂	69.1	1.0	O	33.33	.0
TOTAL	3490.2	.01	N ₂	2761.0	37.9	TOTAL	208.33	3.8
			TOTAL	3604.5	59.1			
			ASH(LB/HR)	745.0	.3			
			SUM(LB/HR)	100410.9	59.5			

FIGURE 10. (continued)

DETAILED MASS AND ENERGY BALANCE

IN		
IN	LB/HR	MM-BTU/HR
WOOD	16666.7	141.5
MOISTURE	1051.9	.2
STEAM	5179.5	7.9
NITROGEN	30.0	.0
TOTAL	23727.9	149.0

PRODUCT GAS		
GAS	LBMOLE/HR	MM-BTU/HR
H2	114.9	15.9
CO	244.2	32.4
CO2	80.1	1.4
CH4	90.5	36.5
C2H4	26.1	16.5
C2H6	4.0	2.0
H2O	431.7	14.1
N2	1.0	.0
TOTAL	993.3	119.0

CHAR		
OUT	LB/HR	MM-BTU/HR
C	2521.94	97.0
H	242.62	15.0
ASH	168.33	.1
TOTAL	2932.29	52.1

AIR REQUIREMENT		
	LBMOLE/HR	MM-BTU/HR
O2	270.4	.00
N2	1129.3	.00
TOTAL	1427.7	.01

FLUE GAS		
	LBMOLE/HR	MM-BTU/HR
CO2	210.1	4.4
H2O	121.3	4.3
O2	27.4	.4
N2	1129.3	14.0
TOTAL	1408.1	24.0
ASH(LB/HR)	175.0	.1
SUM(LB/HR)	44100.2	24.0

CONDENSIBLES		
	LB/HR	MM-BTU/HR
C	60.00	.9
H	10.00	.6
O	13.33	.0
TOTAL	83.33	1.5

FIGURE 11. MASS AND ENERGY BALANCE FOR A 200 TPD PLANT USING SOFTWOOD AS THE FEEDSTOCK

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

CASE # 1

PLANT SIZE (TPD) 200.0
 DRY FEED RATE (LD/HR) 16666.67
 FEED MOISTURE CONTENT (%) 10.0
 STEAM RATE (LD/HR) 5179.45
 NITROGEN FEED(LB/HR) 30.0
 CARBON CONVERSION TO GAS(%) 68.0
 PROD GAS RATE (SCF/HR) 212853.0
 ENERGY PRODUCT (MM-BTU/DAY) 2329.3
 PRODUCT HHV (BTU/SCF) 456.
 EXPORT ENERGY (MM-BTU/HR) 6.34
 COLO GAS EFFICIENCY (%) 68.8
 TOTAL HEAT LOSS (MM-BTU/HR) 9.19
 GASIFIER GAS VELOCITY(FT/SEC) 10.2
 COMBUSTOR GAS VELOCITY(FT/SEC) 19.7
 GASIFIER TEMPERATURE (F) 1530.0
 COMBUSTOR TEMPERATURE (F) 1830.0

SOFTWOOD

COMBUSTION DATA

AIR REQ (LD/HR) 41179.4
 FLUE GAS RATE(SCF/HR) 563791.0
 SAND RATE(LD/HR-FT2) 31068.9

(LD-STEAM/HR) 4468.0

(% OF FEED HHV) 6.5

VESSEL SIZES (FT)

	ID	OD	HEIGHT
GASIFIER	3.3	4.3	45.4
COMBUSTOR	5.7	6.8	45.4
GASIFIER CYCLONES	2.5	3.1	9.9
COMBUSTOR CYCLONES	4.3	4.9	17.2
SURGE POT	6.6	7.8	13.2
L VALVES	.4	1.1	15.0

HEAT LOSS SUMMARY

	BTU/HR	% OF HHV
GASIFIER	442005.68	.31
COMBUSTOR	729124.33	.31
GASIFIER CYCLONES	137947.03	.10
COMBUSTOR CYCLONES	419342.69	.30
SURGE POT	275075.18	.20
L VALVES	140753.21	.10
PIPING	4018485.38	2.85
SUM	6156753.92	4.87
(HEAT EXCHNG)	3033450.86	2.15
TOTAL	9190404.79	6.52

ELEMENT BAL GASIFIER (LBS/HR)

(LBS/HR)	IN	OUT
C	8781.67	8781.67
H	1336.26	1336.26
N	51.63	51.63
O	13390.03	13390.05
ASH	165.00	165.00
S	3.33	3.33
TOTAL	23727.93	23727.93

OVERALL ENERGY BALANCE (MMBTU/HR)

(MMBTU/HR)	IN	OUT
WOOD	141.72	118.98
STEAM	7.27	24.05
AIR	.01	1.30
		CONDENSIBLE
		DIRECT LOAD
TOTAL	149.00	149.12

FIGURE 11. (continued)

have a major influence on process performance, heat loss sensitivity to plant size was examined. Figure 12 presents a graph of heat loss versus plant size. From this, it appears that a plant smaller than about 100 tons per day would be expected to have "excessive" heat losses.

ECONOMIC EVALUATION

Conceptual process designs, based upon experimental results in the 6- and 10-inch units, have been made. These conceptual designs indicate that the Battelle system is readily adaptable for use at an existing industrial site due to the very compact nature of the system. For example, a 200-ton-per-day (dry wood) plant with all auxiliary equipment, except wood storage, would be contained within a 35' x 40' area.

Figure 13 shows a typical conceptual plant layout. Based upon this layout, a first cut at estimating both capital and operating costs and an effective selling price for the medium Btu fuel gas has been made. In the evaluation, as would most likely be the case for commercial use of the technology, it was assumed that the wood gasification plant would be located at an existing industrial site. As a result, much of the grass-roots type equipment such as control room buildings, and utilities are assumed to be in place and only need to be expanded for the gasification plant.

The gasifier vessel for a 200-ton-per-day plant is 3.3 feet in diameter, while the combustor is 5.7 feet in diameter. A gasifier of this size utilizing softwood produces 100 million Btu per hour of medium Btu product gas.

Investment and operating costs are briefly summarized below for a gasification plant incorporated into an existing industrial plant site.

Preliminary Economic Summary - 100 MM Btu/Hr Biomass Gasification Plant

Total Installed Equipment Cost	= \$2,980,000
Annual Operating Cost (Excluding Wood)	= \$ 240,000
Contribution of Wood to Gas Price, (\$/MM Btu of Cooled Cleaned Product Gas)	= $\frac{\$}{\text{dry ton}}$ 11.4

FIGURE 12. HEAT LOSS INCREASES SIGNIFICANTLY IN SMALLER REACTORS

DM - Dense Bed Makeup Hopper	A - Air	CY - Cyclone
CH - Charge Hopper	ST - Steam	BH - Bag House
LH - Lock Hopper	FC - Feed Conveyor	DCS - Dry Chip Storage
MB - Meter Bin	W - Water	PG - Product Gas
INJ - Injector	WW - Wastewater	FG - Flue Gas
G - Gasifier	HX - Heat Exchanger	AB - Air Blower
C - Combustor	ES - Export Steam	SV - Surge Vessel
SM - Sand Makeup Hopper	RD - Rotary Drier	LV - L Valve
	IG - Inert Gas	SC - Scrubber

FIGURE 13. CONCEPTUAL PLANT LAYOUT

Thus, with the above cost parameters and a company's internal financial criteria, it is possible to estimate the combination of natural gas or fuel oil and biomass prices at which the process is competitive in a particular location. For example, assuming total annual capital related charges of 40 percent of the investment and a dry wood price of \$25/ton (dry), the resulting gas price would be:

$$\begin{aligned} & \text{Gas Price (\$/MM Btu)} \\ & = \left[\$25/11.4 + \frac{.40 \times \$2,980,000 + 240,000}{792,000 \text{ MM Btu/year}} \right] = \$3.99/\text{MM Btu} \end{aligned}$$

Since these plants will be located, at least for the most part, at an existing industrial plant site, more precise cost estimates should be made on a site specific basis.

The above type of cost estimate implicitly assumes an "across-the-fence" user. However, this type of arrangement is probably unrealistic in that the typical user will probably install and operate an onsite gasifier rather than purchase gas "across-the-fence" from a separate operator. Operation of the gasification plant by the ultimate energy user will allow certain investment tax credits and depreciation allowances which will improve the economics compared to those reported above. However, in spite of assuming the rather economically disadvantageous "across-the-fence" arrangement, gasification looks competitive with \$4.50/MM Btu fluid fuels even at plant sizes of 200 TPD of dry wood.

The advantage of gasification increases with increasing plant size.

Direct Combustion Versus Gasification-Cost Feasibility

Steam Generation

The most straightforward comparison is between the Battelle gasification process and a conventional bark or hogged fuel boiler for the production of steam.

In the Battelle gasification process, a portion of the steam is generated by the hot combustion gas prior to using the gas to dry the incoming wood. The product gas, after generating enough steam to satisfy gasifier feed requirements, is cooled and quenched and the 450 Btu/scf product gas is then burned in a conventional gas-fired boiler. The investment requirements and performance, as measured by net steam production for both of these options, are compared in Table 4. The basis for comparison is 200 TPD of dry wood to both facilities.

The thermal efficiency for a conventional wood boiler using 40 percent⁽³⁾ wood fuel at an excess air level of 25 percent was assumed to be 72 percent. In practice excess air levels of 40 to 50 percent are not uncommon resulting in even lower efficiencies. In addition, the relatively large grate area required increases system heat losses per unit of wood fed. For example, the relative cross-section of the grate area of a conventional combustor is compared with the cross-sectional area of a Battelle biomass gasification system in Figure 14.

Performance of the Battelle gasifier was based on heat losses calculated from a design model. The thermal efficiency in going to a cooled-clean gas for the Battelle system is approximately 68 percent. The cooled gas is then burned in a conventional natural gas design package boiler, which typically has an efficiency of 85 percent.

With these assumptions, the steam production per unit of wood consumed is approximately 15 percent higher for combustion than gasification. However, the cost of the gasifier system plus package boiler is only one-third that of the conventional wood boiler!

The reason for the difference in capital investment is due mainly to the compactness of the biomass gasification system and a natural gas packaged boiler compared to conventional moving grate wood boiler.

Electricity Cogeneration

As mentioned above, industry is becoming increasingly interested in cogeneration. The conversion of wood and other biomass products to medium-Btu gas offers an alternative to using natural gas or petroleum-derived fuels or direct combustion with a steam turbine. Therefore, it

**TABLE 4. GASIFICATION VERSUS DIRECT COMBUSTION
FOR STEAM PRODUCTION**

	Battelle Gasification	Conventional Wood Boiler
Wood Rate (dry tons/day)	200	200
Capital Investment (\$mm)	3.75	11.0
Steam Production Rate (lb/hr)	74,000	85,000

FIGURE 14. NEW TECHNOLOGY RESULTS IN MORE COMPACT EQUIPMENT

is interesting to compare how gasification compares with direct combustion for cogeneration of electricity and steam. The results of this comparison are summarized in Table 5 for a plant utilizing 200 TPD of dry wood. As one might suspect, from the previous comparison between gasification and combustion for steam generation, gasification should show a significant advantage for generation of electrical power.

The above comparison indicates that a much higher fraction of wood energy is converted to electricity with gasification for approximately the same capital costs. The major component of operating costs for both gasification and combustion is the cost of wood which would be the same for both systems. Obviously, the comparative economics are dictated by the relative values assigned to electricity and steam. However, with the increasing industrial emphasis on increasing the electricity-to-steam ratio, it appears that gasification of biomass to a medium-Btu gas should be a much more attractive option than direct combustion for many industries. Calculations for larger capacity plants indicate that the economic advantage of gasification increases as the size of the plant increases.

The reason for the similar capital requirements between the two cogeneration systems, in spite of the significant cost differential, in favor of gasification for steam generation is the high cost of a gas combustion turbine compared to a steam expansion turbine. However, as Table 5 indicates, the gasification system generates four times the amount of electricity per unit of wood as does the direct combustion system. Performance data for the wood boiler to produce superheated steam for the expansion turbine and the expansion turbine itself were taken from Reference (5), which also provided the data on the gas combustion turbine used to evaluate gasifier performance.

TECHNOLOGY TRANSFER

Because of the potentially attractive economics, there has been considerable industrial interest in this technology. Riley Stoker, who is Battelle's U.S. licensee for multi-solid fluid-bed combustion technology, is working with Battelle to develop conceptual gasification system

TABLE 5. GASIFICATION VERSUS DIRECT COMBUSTION
FOR COGENERATION

	<u>Battelle Gasification</u>	<u>Conventional Wood Boiler</u>
Wood Rate (dry tons/day)	200	200
Net Electric Power (kW)	8,100	2,100
Steam Production Rate (lb/hr)	50,000	66,000
Installed Equipment Costs (\$mm)	12.4	11.8

designs for various industrial applications. We are hopeful that discussions currently underway will lead to a cost-shared scale-up of this technology.

CONCLUSIONS

Most importantly, results from this program have shown that medium Btu gas from wood can be competitive in today's energy market. Conclusions of experimental work in the Battelle's high-throughput gasifier PRU indicate that:

- The system can be scaled up without any change in product gas composition and demonstrates that higher carbon conversions are achieved at comparable reaction conditions in the larger reactor.
- A medium-Btu gas can be produced from biomass in very compact reactor systems.
- A wide range of physically diverse feedstocks can be gasified without preparation.
- The heating value of the dry gas is constant regardless of wood moisture level.
- No by-product char or tar are produced. (Since there is a separate high-temperature combustor, any tar separated from the gas wood be injected into the combustor.)

REFERENCES

1. Feldmann, H. F., M. A. Paisley, D. W. Folsom, B. C. Kim, October 31, 1981, "Conversion of Forest Residues to a Methane-Rich Gas in a High-Throughput Gasifier", Summary Report.
2. Feldmann, H. F., M. A. Paisley, H. R. Appelbaum, March 16-17, 1983, "Gasification of Forest Residues in a High-Throughput Gasifier", 15th Biomass Thermochemical Conversion Contractor's Meeting, Atlanta, Georgia.
3. Tinderman, E. M., et al, September, 1980, "Technical & Economic Evaluation of Biomass Utilization Processes Technical Report No. 1." Stanford Research Institute, DDE/ET/20605-T4.
4. Oak Ridge National Laboratory, "Handbook of Industrial Cogeneration", Oak Ridge National Lab and TRW, DOE/TIC-11605, October, 1981.
5. Miles, T., "Biomass Preparation for Thermochemical Conversion", April 12-13, 1983, 1st European Workshop on Thermochemical Processing of Biomass, Birmingham, U.K.

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