PRODUCTION OF INTERMEDIATE HEATING VALUE GAS FROM MUNICIPAL SOLID WASTE VIA OXYGEN-BLOWN FLUIDIZED BED GASIFICATION

J. L. GUILLORY
University of Southwestern Louisiana
Lafayette, Louisiana

G. O. GOLDBACH
Combustion Power Company
Menlo Park, California

ABSTRACT

An experimental research program, funded by the U.S. Department of Energy, was conducted to investigate the technical feasibility of producing a "medium-Btu" gas from cellulosic wastes by means of oxygen-blown fluidized bed gasification. A 12 in. (0.30 m) I.D. fluidized bed gasifier capable of processing approximately 500 lb/hr (3.8 kg/s) of Municipal Solid Waste (MSW) was constructed at Combustion Power Company's Menlo Park, California facility. A series of parametric tests using MSW, wood and artificially wetted newsprint was conducted. It was shown that product gas heating values in excess of 400 Btu/sdcf (16,000 kJ/ndcm) and H_2/CO ratios over 0.45 could be obtained. Product gas quality was found to be strongly related to fuel moisture content but relatively independent of throughput rate.

INTRODUCTION

Pyrolysis is the chemical decomposition or destructive distillation of a carbonaceous material by the application of energy from an external source [1]. The energy required by this endothermic process is supplied either by indirect heating of the reactor or direct mixing with essentially oxygen-free combustion products from an external burner. Gaseous products of this process usually have relatively high heating values[1] [often in excess of 500 Btu/sdcf (20,000 kJ/ndcm)] and tend to be rich in methane and heavier hydrocarbons. Unfortunately, true pyrolysis depends upon external energy from a conventional (often fossil) source.

Gasification eliminates dependence on external energy by promoting exothermic oxidation of a fraction of the feedstock to heat, dry and devolatize the remainder. However, whereas energy supply to pyrolysis systems is a relatively simple heat transfer/mixing process, gasification requires direct energy release from the material that is simultaneously undergoing pyrolysis and normally requires a more sophisticated reactor design.

Conversion of carbon and hydrogen to the major gaseous constituents in a gasification process can be conceptually represented by four gas-solid reactions:

$$C + H_2O \rightleftarrows H_2 + CO$$

$$C + CO_2 \rightleftarrows 2CO$$

$$C + 2H_2 \rightleftarrows CH_4$$

$$C + O_2 \rightleftarrows CO_2$$

---

[1] "Heating Value" in this paper will refer to the higher (or gross) chemical heating value at constant pressure on a dry volumetric basis. The English unit is defined at 77°F and the SI unit at 0°C. For brevity, "standard dry cubic foot" and "normal dry cubic meter" will be abbreviated as "sdcf" and "ndcm", respectively.

and two gas–gas reactions:

$$H_2O + CO \rightleftarrows H_2 + CO_2$$
$$CO + 3H_2 \rightleftarrows CH_4 + H_2O$$

This simplification suggests that a multicomponent thermochemical equilibrium calculation with appropriate energy constraints might be used to approximate the product composition. However, Bukens and Schoeter [2] note that the process is most often limited by chemical reaction rate below about 1800°F (1000°C) and by surface or internal diffusion rates at higher temperatures. They suggest that deviations from equilibrium can in some cases be corrected by carrying out the calculations at a lower temperature than actually exists in the gasifier; however, this procedure is only satisfactory in certain long residence time devices and is not suitable for most modern gasifiers that provide residence times on the order of one second.

Gasification naturally results in undesirable dilution of the product gas with products of combustion (e.g., CO_2) and inert diluents associated with the oxidant (e.g., N_2). If the object of gasification is to produce a product gas that will be used on-site (e.g., in a high temperature process that would not be compatible with the low melting point inerts often found in wastes), then air-blown gasification with its attendant nitrogen dilution is often satisfactory. However, if the purpose is to produce a gas for transport or a feedstock to a noncombustion process, nitrogen dilution can be minimized by use of low-purity oxygen as the oxidant.

Various types of reactors have been developed to gasify solid fuels, especially coal and biomass [3]. The commonest types, in order of the maturity of the technology, are:

(a) Countercurrent Moving Bed Reactors. These reactors typically consist of a vessel partially filled with a fuel charge that rests on a mechanical grate. Adiabatic combustion is initiated at the grate and the combustion products drawn upward through the charge. Ash and unreached char are withdrawn at the grate and pyrolysis products mixed with the combustion products are withdrawn at the top. These devices are simple to operate but subject to channeling and maintenance requirements typical of grate designs. Throughput is typically 20–40 lb/hr/sq ft (100–200 kg/h/m^2) of reactor cross section for biomass.

(b) Entrained (Suspension) Reactors. These reactors ordinarily require a finely divided fuel capable of being entrained in cocurrent flow with the gasification medium and products. The gasification medium and fuel are introduced at the same location and ignited in a manner similar to conventional pulverized fuel combustors. Temperatures are high compared with the moving bed gasifier and tar production is relatively low. However, slagging of entrained ash can occur. They are normally very compact compared with the moving bed design.

(c) Fluidized Bed Reactors. These reactors typically consist of a gas distributor and a bed of inert materials selected such that the velocity of the gasification agent and products of gasification counterbalances the weight of the bed and produces a random homogeneous mixing action. Consequently, chemical reactions between fuel and oxidant occur at nearly isothermal conditions and product quality can be closely controlled. Since fluidized beds are relatively intolerant of slagging, typical operating temperatures are lower than suspension gasifiers. Reduced temperature operation is often associated with undesirable tar production; however, the superior mixing provided by fluidized beds normally compensates for lowered reaction temperature and tar production is relatively low. In addition, allowable throughput rates are high [300 lb/hr/sq ft (1500 kg/h/m^2)] of reactor cross section for biomass are commonly reported in the literature) compared to other types of reactors.

The majority of gasification work reported in the open literature addresses coal and biomass, largely in moving bed and suspension gasifiers [4, 5]. In spite of the desirability of minimizing dilution of the product gas, most earlier work is further limited to air-supported gasification. Data specifically related to oxygen-blown MSW gasification, especially in fluidized beds, is extremely sparce. Work in this latter area includes Kuester [6] and Ando [7], although these studies primarily address pyrolysis.

OBJECTIVES OF THIS STUDY

The general purpose of this study was to assess the technical feasibility of producing intermediate heating value product gas from oxygen-blown gasification of MSW in a fluidized bed reactor and to compare the product (in terms of chemical energy content, composition, etc.) to other fuels for which a more extensive gasification data base exists. This paper will concentrate on certain pilot test data resulting from this program.

PILOT SYSTEM

The MSW gasifier test system developed for this study consists of a 12 in. (0.3 m) I.D. fluidized bed reactor with an 18 in. (0.46 m) I.D. freeboard and 6 in. (0.15 m) rupture disk safety vent. The static inert bed is about 2 ft (0.6 m) deep and consists primarily of 12 × 20 mesh high silica sand. Fuel is introduced via a screw feeder and the oxidant via a distributor especially designed for substoichiometric operation. The product gas leaves through a side port at the top of the freeboard which is close-coupled to a 9 in. (0.23 m) I.D. char removal cyclone. Captured char is routed to a vented collection vessel at grade level. The gases are sampled immediately downstream of the cyclone and then routed to a 3 ft (0.9 m) I.D. × 8 ft (2.4 m) cylindrical afterburner. After mixing with air in a tangential inlet precombustion chamber, ignition by a continuous propane pilot and final burnout in a refractory-lined chamber, the inert products of combustion are released to the atmosphere. A schematic of the system is shown in Fig. 1. Figure 2 shows a scaled elevation of major equipment in the system prior to installation of insulation.

Air for preheat, gasification and afterburner service is provided by a two-stage utility compressor. Oxygen is supplied from a 3000 gal (11.4 m^3) bulk liquid oxygen trailer. Steam (for safety control) is provided by a natural-gas fired steam generator.

Instrumentation principally consists of conventional equipment used in combustion tests at Combustion Power Company's test facility. Exceptions included specialized control and safety equipment associated with the oxygen system and a DOE-owned Carle gas chromatograph system provided on contract by Battelle Northwest Laboratories.

TEST MATRIX

Variables addressed in the test series included:

(a) Fuel Type: MSW, newsprint, wood

(b) Oxidant Type: oxygen, air

(c) Fuel Moisture: 5–30%

(d) Reactor Throughput[2]: 1–3 million Btu's/hr/sq ft (10–30 GJ/h/m^2)

(e) Reactor Temperature: 1300–1700°F (700–925°C)

A total of 17 parametric tests are included in this data base. Independent variables and results for 12 individual tests are shown in Table 1.[3]

TEST FUELS

Use of moisture as a test variable meant that, as a practical matter, it was necessary to obtain initially dry fuel to which water could be added rather than attempt to dry an initially wet fuel to a specified level, possibly altering other properties in the process. It was therefore decided to use newsprint[4] as the primary fuel in moisture tests, since it could be conveniently wetted to the desired levels, easily processed, and stored for extended periods without creating a health hazard. Furthermore, this choice was based on the fact that MSW in this country, like newsprint, is largely composed of processed cellulosic materials.

The MSW was household garbage and trash collected locally. Roughly 10–20% of the initial mass of the MSW was lost in air-classification to remove glass, metal, oversized particles, etc.

The wood (used only for comparison purposes to investigate how closely biomass gasification products might resemble those of MSW) was principally log yard debris from the Pacific Northwest estimated to be 80–90% Douglas fir and 10–20% hemlock. Since it was primarily waste material, bark was predominant and inerts level relatively high.

Table 2 shows proximate analyses of these fuels.

Both the MSW and newsprint were shredded to 3 in. × 0 (0.08 m × 0) in order to reliably traverse the 6 in. (0.15 m) feed screw without upset. The MSW was used at its natural moisture level and the wood selected to approximately match the moisture level of the MSW. Only the newsprint moisture was artificially altered.

TEST RESULTS

Effect of Fuel Type

Table 3 shows a direct comparison of gas composition and heating values for oxygen-blown gasification of MSW, wood and newsprint run at comparable conditions of moisture, temperature and throughput rate. It is noted that all have roughly similar hydrogen concentrations, but the carbon monoxide level in the newsprint product is significantly higher than that of either MSW or wood. The heating value of the MSW product is higher than either of the other two, principally due to the higher hydrocarbon level. This is possibly related

---

[2] Based on the higher heating value of the input fuel.

[3] Table 1 data will be primarily cited to show moisture effects in the newsprint data base. Further data shown in Tables 3 and 4 are used to directly illustrate the effects of fuel and oxidant types.

[4] As used here, this term refers to scrap newspaper and related hand-sorted paper. It therefore includes inks, finishing materials, etc. as well as cellulose.

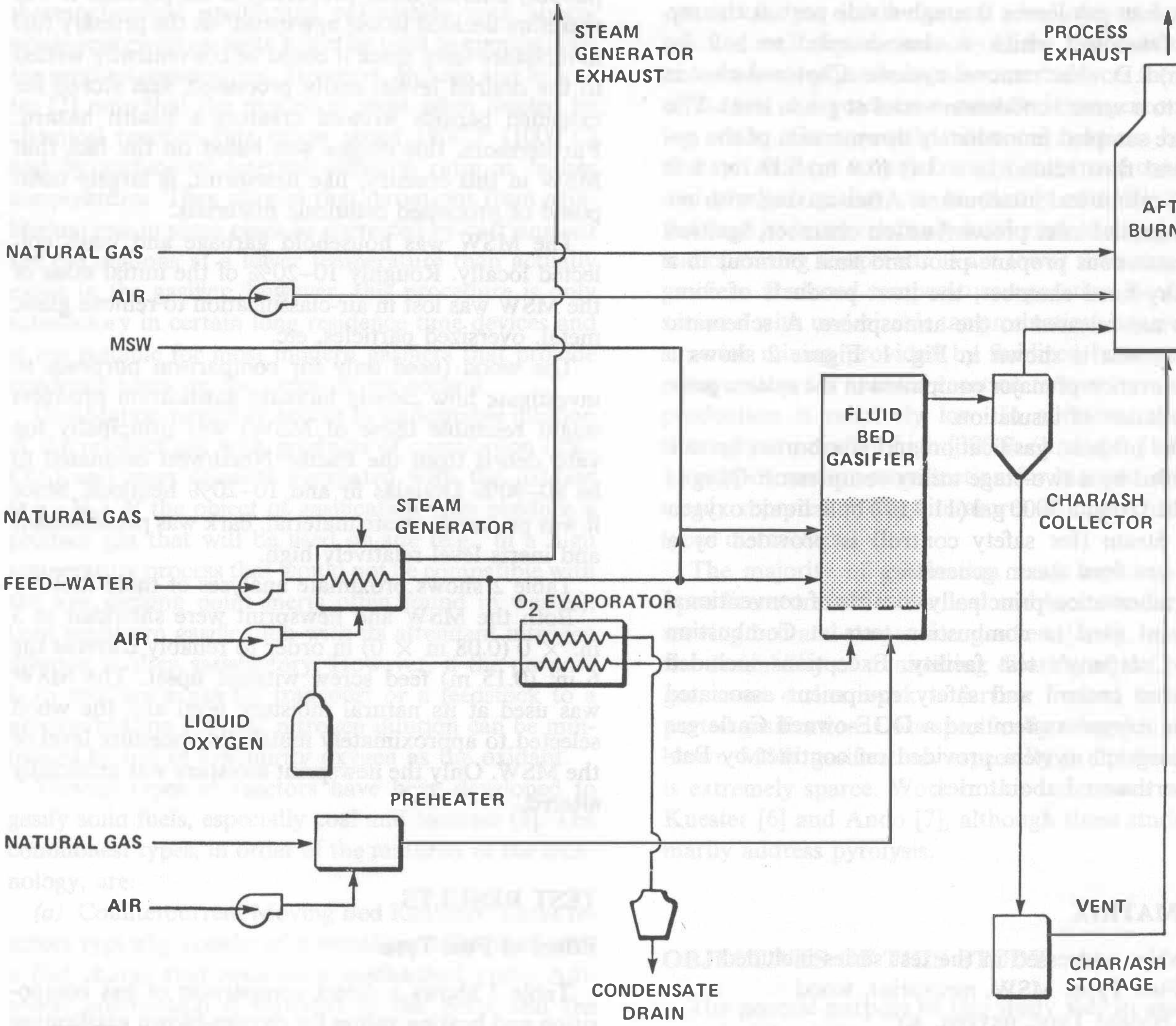

FIG. 1 OXYGEN-BLOWN FLUIDIZED BED MSW GASIFIER PILOT SYSTEM SCHEMATIC

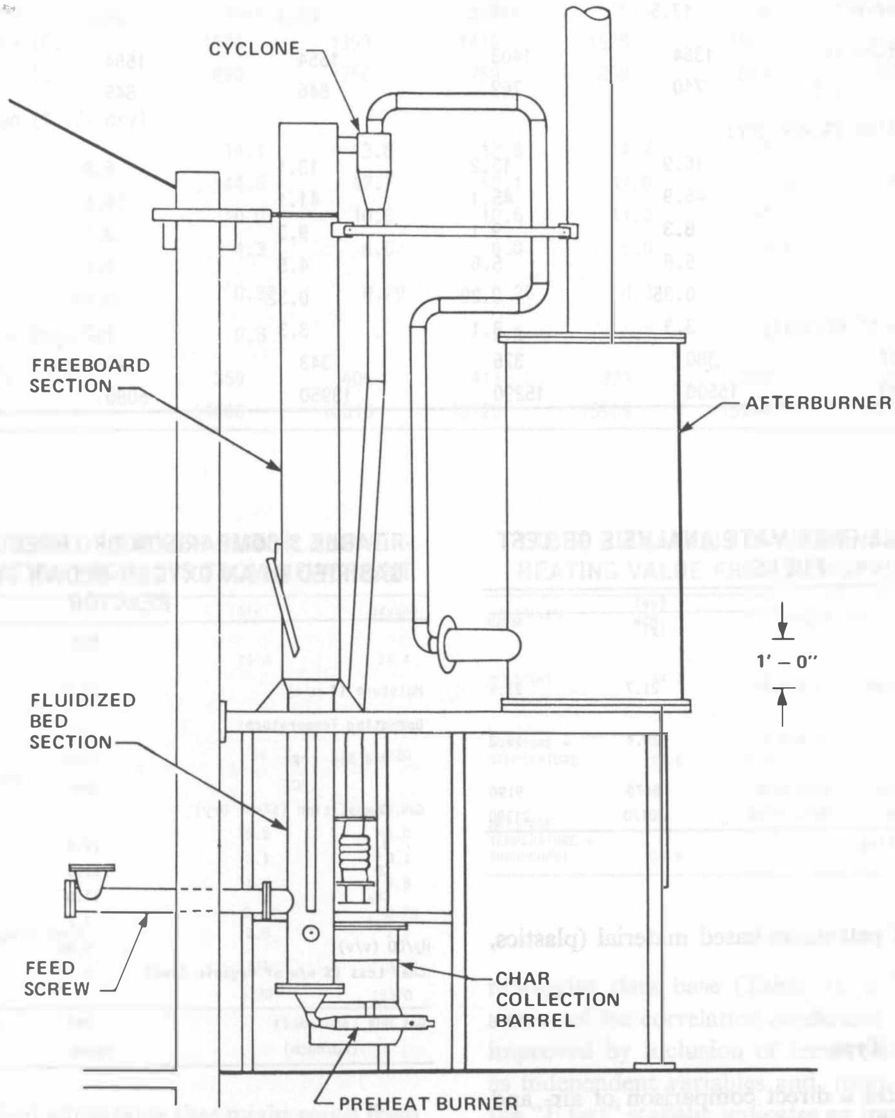

FIG. 2 SCALED ELEVATION VIEW OF MSW GASIFIER TEST FACILITY

TABLE 1 NEWSPRINT DATA BASE
(Oxygen-Blown Unless Otherwise Noted)

Set Number	1	2	3	4*	5
Fuel Moisture (% w/w)	20.7	23.6	26.4	27.8	28.1
Throughput (10^6 Btu/hr-ft^2)	1.54	1.66	2.05	1.76	1.62
(GJ/hr-m^2)	17.5	18.2	23.3	20.0	18.4
Mid-Bed Temperature (F)	1364	1403	1554	1554	1634
(C)	740	762	846	846	890
Product Composition (% v/v dry)					
H_2	15.9	13.2	13.1	6.8	14.1
CO	45.9	45.1	41.1	14.6	47.1
CH_4	8.3	9.1	9.3	3.2	8.1
C_2 +	5.6	5.6	4.5	1.6	5.6
H_2/CO (v/v)	0.35	0.29	0.32	0.47	0.32
Char Loss (% w/w of organic)	3.3	3.1	3.3	1.2	3.9
Gas HHV (Btu/sdcf)	380	376	343	125	370
(kJ/ndcm)	15500	15290	13950	5080	15050

* Air-Blown

TABLE 2 AVERAGE PROXIMATE ANALYSIS OF TEST FUELS

	Fuel		
	Paper	MSW	Wood
Moisture (% w/w as received)	7.6-9.3*	21.7	21.5
Ash (% w/w dry)	2.6-3.7	20.4	16.3
HHV (Btu/lb dry inert-free)	8200-8230	8670	9190
(kJ/kg dry inert-free)	19070-19140	20170	21380

*Prior to artificial wetting.

TABLE 3 COMPARISON OF THREE FEEDSTOCKS GASIFIED IN AN OXYGEN-BLOWN FLUIDIZED BED REACTOR

	MSW	WOOD	PAPER
Moisture (% w/w)	21.7	21.5	23.9
Operating Temperature			
Mid Bed (°F)	1550	1517	1586
(°C)	844	825	864
Gas Composition (% v/v Dry)			
H_2	14.0	13.9	14.7
CO	31.3	34.8	43.2
CH_4	11.8	9.3	8.9
C_2+	7.2	5.9	4.6
H_2/CO (v/v)	0.45	0.40	0.34
Char Loss (% w/w of Organic Feed)	3	—	2
Gas HHV (Btu/sdcf)	383	349	349
(kJ/ndcm)	15580	14190	14190

to the presence of petroleum-based material (plastics, etc.) in the MSW.

Effect of Oxidant Type

Table 4 illustrates a direct comparison of air- and oxygen-blown gasification of newsprint at comparable reactor temperatures, throughput rates and (roughly) moisture content.[5] Dilution effects naturally reduce the heating value of the air-blown products as well as the combustibles concentrations. However, it was found that, on an undiluted basis, the equivalent heating value of the air-blown products was less than 90% that of the corresponding oxygen products, a consequence of the fact that, due to its greater mass, the sensible component of the air-blown products leaving the reactor is greater than that of the oxygen-blown products. Thus, the energy left in chemical forms is reduced.

Interestingly, the H_2/CO ratio (an important parameter in describing the usefulness of product gas as a chemical feedstock) corresponding to the air-blown case was considerably higher than that for the oxygen-blown case. Unfortunately, nitrogen dilution compro-

---

[5] For purposes of direct comparison, this parameter could only be differentiated as "high" (25–30%) or "low" (5–10%) due to the difficulty of precisely matching the moisture content of batches made for different runs.

TABLE 1 (Cont'd) NEWSPRINT DATA BASE
(Oxygen-Blown Unless Otherwise Noted)

Set Number	6	7	8	9	10	11	12*
Fuel Moisture (% w/w)	8.4	8.1	9.3	8.4	8.4	7.6	8.4
Throughput (10^6 Btu/hr-ft^2)	1.62	1.47	1.82	1.46	1.71	1.17	1.16
(GJ/hr-m^2)	18.4	16.7	20.7	16.6	19.4	13.3	13.2
Mid-Bed Temperature (F)	1634	1393	1416	1576	1564	1584	1600
(C)	890	756	769	858	851	863	871
Product Composition (% v/v dry)							
H_2	14.1	13.8	12.8	14.7	14.2	13.8	7.6
CO	44.6	47.7	50.1	47.0	47.5	47.6	17.3
CH_4	10.0	10.5	10.6	11.0	10.4	11.0	4.6
C_2 +	4.3	6.0	6.0	5.0	5.4	5.3	1.9
H_2/CO (v/v)	0.32	0.29	0.26	0.31	0.30	0.29	0.44
Char Loss (% w/w of Organic)	0.8	-	7.3	5.7	4.4	4.8	8.8
Gas HHV (Btu/sdcf)	359	406	411	391	392	394	155
(kJ/ndcm)	14600	16510	16720	15909	15940	16020	6300

* Air Blown

TABLE 4 COMPARISON OF OXYGEN-BLOWN AND AIR-BLOWN GASIFICATION PRODUCTS FROM NEWSPRINT

	Air	Oxygen
Moisture (% w/w)	29.0	24.4
Operating Temperature		
Mid Bed (°F)	1328	1328
(°C)	720	720
Gas Composition (% v/v dry)		
H_2	6.3	12.7
CO	15.8	45.0
CH_4	3.1	9.1
C_2+	1.8	5.8
H_2/CO (v/v)	0.40	0.28
Char Loss (% w/w of Organic Feed)	1.8	2.2
Gas HHV (Btu/sdcf)	131	378
(kJ/ndcm)	5330	15370

mises most practical advantages that might result from this observation.

Effect of Operational Parameters

TABLE 5 ANALYSIS OF VARIANCE RESULTS FOR HEATING VALUE FROM NEWSPRINT DATABASE

VARIABLES	r^2 (%)	F	Probability of "real" explanation (%)
MOISTURE	44.1	7.9	97
MOISTURE + TEMPERATURE	88.6	34.9	>> 99.9
MOISTURE + TEMPERATURE + THROUGHPUT	88.9	21.3	> 99.9

A formal Analysis of Variance performed on the data base confirmed that fuel moisture was the single most important predictor of most major dependent variables and, combined with reactor temperature, could on average explain about 90% of any observed variation. Table 5 shows the results of this procedure applied to the heating value measurements from the newsprint data base (Table 1). It is noted that the square of the correlation coefficient "r" is significantly improved by inclusion of temperature with moisture as independent variables and, more importantly, that the "F test" statistic indicates an improved probability that the correlation describes a real phenomenon rather than variations resulting from measurement error. However, inclusion of throughput resulted in practically no improvement in correlation and a loss in "real" explanation. Although the relatively modest variation of throughput within this data base may contribute to this conclusion, it should be noted that the absolute variation of the other parameters is of the same order.

Heating value, methane concentration and char loss data are shown in Figs. 3–5 for the newsprint data base. Note that the two temperature curves shown do

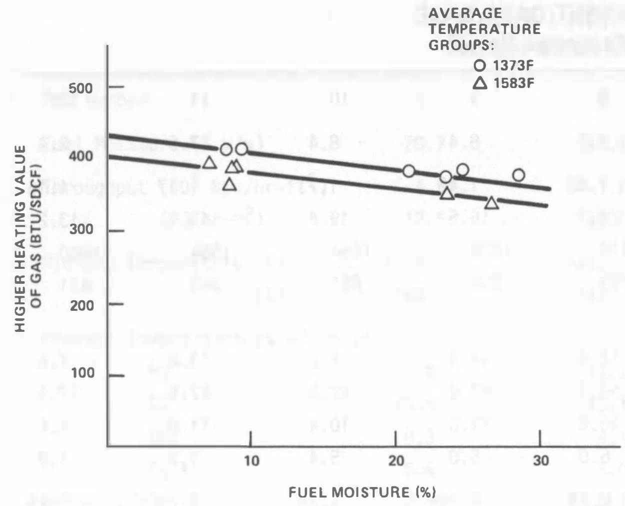

FIG. 3 HIGHER HEATING VALUE OF PRODUCT GAS FROM OXYGEN-BLOWN GASIFICATION OF NEWSPRINT

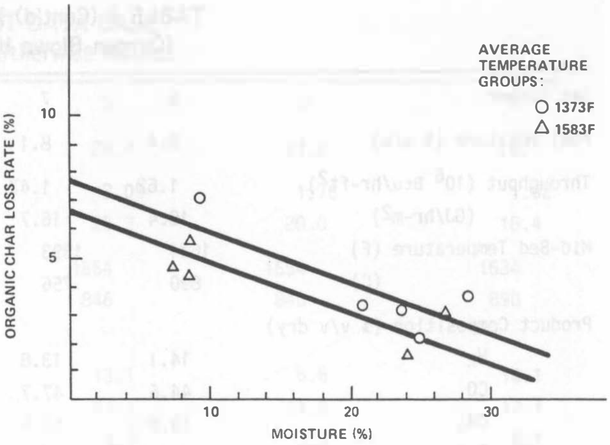

FIG. 5 CHAR LOSS FROM OXYGEN-BLOWN GASIFICATION OF NEWSPRINT

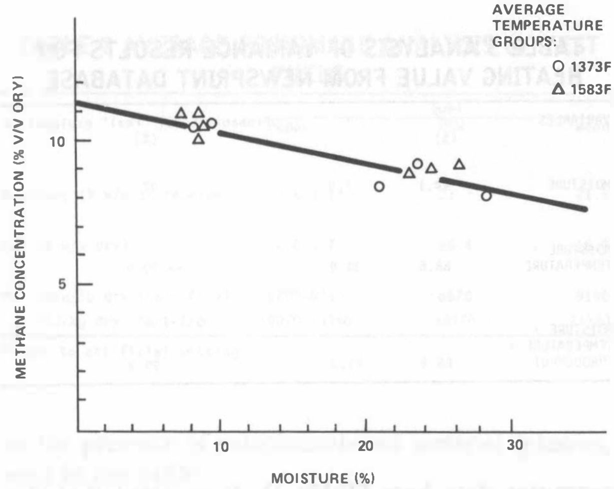

FIG. 4 METHANE CONCENTRATION IN PRODUCT GAS FROM OXYGEN-BLOWN GASIFICATION OF NEWSPRINT

not represent actual tests but merely the "high average" and "low average" of the data base. The positions of these curves, however, represent the best statistical correlation for the stated averages.

Heating value naturally showed an inverse relation to both moisture and temperature, a result consistent with latent and sensible "losses" associated with both these parameters. Methane was also inversely related to moisture but, surprisingly, not significantly influenced by reactor temperature over the range tested. However, as expected, char loss was reduced by both increasing moisture and increasing temperature. Neither hydrogen nor carbon monoxide levels showed a statistically significant relationship to any independent variable and are therefore not shown graphically. The best estimate of the H_2/CO ratio is merely the average of the data base (0.3) with 70% of the data lying between 0.27 and 0.33.

CONCLUSIONS

(a) Oxygen-blown fluidized bed gasification of municipal solid waste and related materials at the scale tested is an easily controlled, rapidly stabilized process.

(b) Newsprint provides a convenient means of empirically modeling the performance trends in MSW gasification. Limited data suggests that newsprint tends to produce a lower H_2/CO ratio than true MSW products and that biomass may be a more accurate model of actual MSW products.

(c) Over the range of variables tested, fuel moisture was the most important parameter in prediction of practically all aspects of gasification performance. Reactor temperature often had an important secondary effect, but throughput rate had no statistically significant influence.

ACKNOWLEDGEMENTS

This work was funded by the U.S. Department of Energy under contract DE-AC03-83SF11723. The authors wish to thank Combustion Power Company for permission to publish this data.

REFERENCES

[1] Schoeters, J. G., and Bukens, A. G. "Pyrolysis and Gasification." In *Proceedings of the International Symposium on Materials and Energy from Refuse* (1981) 1989–1996.

[2] Bukens, A. G., and Schoeters, J. G. "Basic Principles of Waste Pyrolysis and Review of European Processes." *ACS Symposium Series* 130 (1980): 397–421.

[3] Van Swaait, W. P. M. "Gasification—the Process and the Technology." *Resources and Conservation* 17 (1981): 337–349.

[4] Snyder, N. W. "Pyrolysis of Municipal Solid Waste to Fuels and Chemicals." *AIChE Symposium Series* 73 (1977): 150–159.

[5] Hos, J. J. "Concurrent Gasification of Solid Wastes." In *Proceedings of the International Recycling Congress* Vol. 1 (1979): 595–600.

[6] Kuester, J. L. "Fluidized Bed Pyrolysis to Gases Containing Olefins." In *Proceedings of the Specialists Workshop on Fast Pyrolysis of Biomass* (1980): 253–270.

[7] Ando, N. "Disposal of Municipal Refuse by the 'Two-Bed Pyrolysis System.' " In *Proceedings of the International Recycling Congress* Vol. 1 (1979): 575–580.

[8] Guillory, J. L. "Gasification of Municipal Solid Waste in an Oxygen-Blown Fluidized Bed Reactor." Final Report, U.S. Department of Energy Contract DE-AC03-83SF11723 (December 1984).

Key Words: Chemical; Colorific Value; Combustion; Disposal; Fluidized Bed; Gasification; Oxygen; Paper; Pyrolysis; Refuse; Research