PNL-6518
UC-245

18 H

Development of Biomass Gasification to Produce Substitute Fuels

R. J. Evans
R. A. Knight
M. Onischak
S. P. Babu

March 1988

Prepared by the Institute of Gas Technology
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy

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

Battelle

PNL-6518

PACIFIC NORTHWEST LABORATORY
operated by
BATTELLE MEMORIAL INSTITUTE
for the
UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC06-76RLO 1830

Printed in the United States of America
Available from
National Technical Information Service
United States Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

NTIS Price Codes
Microfiche A01

Printed Copy

Pages	Price Codes
001-025	A02
026-050	A03
051-075	A04
076-100	A05
101-125	A06
126-150	A07
151-175	A08
176-200	A09
201-225	A010
226-250	A011
251-275	A012
276-300	A013

PNL-6518
UC-245

DEVELOPMENT OF BIOMASS GASIFICATION TO PRODUCE SUBSTITUTE FUELS

R. J. Evans
R. A. Knight
M. Onischak
S. P. Babu

Institute of Gas Technology
Chicago, Illinois 60616

March 1988

Prepared by Institute of Gas Technology
for Pacific Northwest Laboratory
under Contract DE-AC06-76RLO 1830
with the U.S. Department of Energy

Pacific Northwest Laboratory
Richland, Washington 99352

EXECUTIVE SUMMARY

The development of an efficient pressurized, medium-Btu steam-oxygen-blown fluidized-bed biomass gasification process was conducted at the Institute of Gas Technology (IGT), Chicago, Illinois, for Pacific Northwest Laboratory (PNL) of Richland, Washington, and the U.S. Department of Energy (DOE), Biofuel and Municipal Waste Technology Division, under Contract No. B-C5821-A-Q. The overall program included initial stages of design-support research before the 12 ton-per-day (TPD) process research unit (PRU) was built. These stages involved the characterization of test-specific biomass species and the characteristics and limits of fluidization control. Also obtained for the design of the adiabatic PRU was information from studies with bench-scale equipment on the rapid rates of biomass devolatilization and on kinetics of the rate-controlling step of biomass char and steam gasification. The development program culminated with the successful operation of the PRU through 19 parametric-variation tests and extended steady-state process-proving tests.

The test program investigated the effect of gasifier temperature, pressure, biomass throughput rate, steam-to-biomass ratio, type of feedstock, feedstock moisture, and fluidized-bed height on gasification performance.

A long-duration gasification test of 3 days steady-state operation was conducted with whole tree chips to identify long-term effects of fluidized process conditions; to establish gasifier material and energy balances; to determine the possible breakthrough of low concentration organic species; and to evaluate the mechanical performance of the system components.

Test results indicate that the pressurized fluidized-bed process, which has proven to be simple to operate, can achieve carbon conversions of about 95% with cold gas thermal efficiencies of about 75% and with low oil and tar production.

New information was collected on the oil and tar fraction, which relate to the process operating conditions and feedstock type. The different feedstocks studied were very similar in elemental compositions, and produced similar product gas compositions, but each has a different distribution and character of the oil and tar fractions. This information is important environmentally and would have an impact on the proper design of process clean-up equipment.

TABLE OF CONTENTS

TABLE OF CONTENTS, Cont.

LIST OF FIGURES

LIST OF FIGURES, Cont.

LIST OF FIGURES, Cont.

LIST OF TABLES

INTRODUCTION

The Institute of Gas Technology (IGT), began the investigation of a pressurized, steam-oxygen blown, fluidized-bed gasification process to produce medium-Btu gas or a synthesis gas from biomass in May 1980. A technical report for the period ending June 1981 was submitted to DOE[1] and it contains laboratory and bench-scale data on various biomass species, leading to the design of a process research unit (PRU).

This final report contains the continuation of the same investigation and covers the period from June 1981 through December 1986. It includes additional areas of the bench-scale investigation to define design data for the PRU. The PRU is described and the results from shakedown operations to parametric process variable tests and long-duration operation are presented. The overall program plan is described by the following program objective and scope statement followed by the task description.

The program was divided into three phases. In Phase I we acquired design information from bench-scale experimental tests and cold-flow fluidization model tests. This information was used in Phase II to design a 12-TPD adiabatic process research and development gasification system. Phase III required construction and operation of the PRU over a variety of parameters to generate adiabatic design information for process evaluation and optimization. A long-duration test lasting for 3 days of steady-state operation was also completed.

The selection of a fluidized-bed gasifier filled with inert media offers many advantages for biomass gasification. The small alumina spheres used in the PRU offer uniform fluidization over the entire range of biomass feedrates. Biomass feed size can range from sawdust to pulpwood-sized chips.

The high heat capacity of the inert media along with its circulation most efficiently distributes the heat energy from the combustion fraction to the endothermic gasification reactions of the incoming biomass, while the low bulk density biomass char is retained in the gasifier and reduced in size exposing more char reaction surface area. The 3 to 5 minutes of biomass residence time in the fluidized-bed gasifier and the overall gas residence in the gasifier and overhead freeboard contribute to the high carbon conversion and the low oil and tar production demonstrated in the PRU tests.

Pressurized operation makes the fluidization gas bubbles smaller and therefore the fluidization is smoother than at atmospheric pressure. Producing gas at elevated pressure is required to overcome piping losses and pressure drop through filters or other gas cleanup equipment for pipeline distribution. Pressurized gasification also contributes to improving the process efficiency for synthesis gas process applications such as methanol or ammonia production.

PROGRAM OBJECTIVE AND SCOPE

The objective of this project was to develop an efficient biomass gasification process to produce medium-Btu gas suitable for an industrial fuel gas or for upgrading to substitute natural gas (SNG) or synthesis gas.

The project involved the development of a pressurized, single-stage, oxygen-blown fluidized-bed gasifier for the thermal gasification of biomass fuels. Fundamental information on the simultaneous physical and chemical processes occurring in biomass fluidized-bed gasification was needed for the rational design and scale-up of the process.

The overall program included bench-scale experiments that led to the design and construction of the PRU. Gasification tests were conducted in the 11.5-inch-ID fluidized-bed gasifier and new data were obtained on biomass gasification characteristics as a function of significant operating parameters at continuous, adiabatic, steady-state operating conditions and on a large scale (up to 12 TPD).

The 11.5-inch-ID PRU was designed for maximum operational flexibility in the areas of —

a. Operating pressure, atmospheric to 500 psig

b. Operating temperature, up to 1800°F

c. Fluidized-bed heights, up to 8 feet for L/D ratios from 2 to 8

d. Biomass feed inlet locations 6 to 24 inches above the oxidant distributor.

Critical areas in which design information was incomplete were planned for evaluation; including high-pressure feeder operation, the effect of operating parameters on adiabatic gasifier performance, and the characteristics of process effluents.

The experimental PRU test program addressed these areas and quantified the gasification performance. The performance trends that were found as a function of primary operating variables identified approaches for system optimization and indicated the requirement for various upstream and downstream process equipment modifications or modified operating procedures. This data can be used in the process assessment and evaluation of the economics of pressurized fluidized-bed biomass gasification applications.

PROGRAM TASK RESULTS

The program was divided into the following five tasks:

Task I. Characterization of Biomass

Task II. Biomass Handling Characteristics

Task III. Bench-Scale Experiments

Task IV. Process Research Unit Tests

Task V. Data Review for Scale-Up Tests.

Task I. Characterization of Biomass

Representative samples of selected large resource materials from the Midwest were obtained for characterization and tests. These included forest residues from both hardwood and softwood trees and corn stover as an agricultural residue. Samples were requested from sources that could supply material in quantities of 20 tons or greater.

Each selected biomass material was characterized by standard tests of physical and chemical properties because of the interrelationships between these properties, gasification reactivity, and fluidization. The physical properties of interest included density and particle size; significant chemical properties of interest included proximate and ultimate analysis, calorific value, ash constituents, and ash fusion characteristics. The tests were also used to characterize the chars formed from the biomass materials, which have direct relation to gasifier design and operation. The standard tests and procedures that were used to characterize the chemical and physical properties of the biomass materials are identified in Table 1.

The characteristics of a maple hardwood, Douglas-fir hog fuel, jack pine softwood, and undensified corn stover were determined and presented in a previous report.[2]

The ash fusion characteristics in both reducing and oxidizing atmospheres along with the particle and bulk densities for Douglas-fir hog fuel, maple hardwood, jack pine softwood, and corn stover were determined and reproduced in Table 2 for discussion continuity.

The characteristic ash fusion temperatures measured for the jack pine ash are lower than those for the maple hardwood ash, but similar to the results

Table 1. STANDARD CHARACTERIZATION TESTS

Chemical Tests	Standard Procedure
Ultimate analysis	ASTM* D3176-74 or "Perkin-Elmer" 240 method
Proximate analysis	ASTM 3175
Ash analysis	ASTM D1102-56 or TAPPI** T1505-58
Heating value	ASTM D2015
Cellulose and hemicellulose	TAPPI 53(2):257-261 (Feb. 1970)
Acid insoluble lignin	TAPPI T222 05-74
Physical Tests	**Standard Procedure**
Moisture	ASTM D2016-74
Ash fusion analysis	ASTM D1857
Low-temperature ashing	IGT standard procedure
High-temperature ashing	ASTM D3174-73
Particle size analysis	ASTM D431
Particle density	IGT standard procedure
Bulk density	IGT standard procedure
Surface areas by nitrogen and carbon dioxide adsorption	IGT standard procedure
Mercury and helium particle densities for porosity	IGT standard procedure

* ASTM is the American Society for Testing and Materials.

** TAPPI is the Technical Association of the Paper and Pulp Industry.

171/65058fr-t/RPP

Table 2. DENSITY AND ASH FUSION TEMPERATURES OF SOME BIOMASS SPECIES

	Douglas-Fir Hog Fuel		Maple Hardwood		Jack Pine Softwood		Corn Stover	
	Particle	Bulk	Particle	Bulk	Particle	Bulk	Particle	Bulk
	Density, lb/ft^3							
Air Dried Sample								
(-4+16 Mesh)	42.4	13.1	38.0	10.0	37.0	15.1	36.2	7.9
(-60+80 Mesh)	45.6	18.1	51.8	11.1	48.0	16.3	62.4	17.1
Char								
(-4+16 Mesh)	26.9	9.3	38.7	7.9	20.0	5.7	21.2	6.6
(-60+80 Mesh)	37.3	9.4	41.8	9.2	35.6	6.5	70.5	21.3
	Ash Fusion Temperatures, °F							
	Reducing	Oxidizing	Reducing	Oxidizing	Reducing	Oxidizing	Reducing	Oxidizing
Initial Deformation (IT)	2070	2150	2700+	2700+	1950	2020	2250	2330
Softening (ST)	2195	2295	2700+	2700+	2150	2620	2700	2700+
Softening (HT)	2335	2480	2700+	2700+	2190+	2680	2700+	2700+
Fluid (FT)	2470	2665	2700+	2700+	2280	2700+	2700+	2700+

171/65058fr-t/RPP

for Douglas-fir hog fuel. The density values for the jack pine char are lower than the maple hardwood and Douglas-fir hog fuel char values, whereas the density values for the air-dried samples of the three woody species are very similar.

A sample of corn stover densified into approximate 1.25-inch cubes was obtained from Professor John Goss at the University of California at Davis. The corn stover came from a California harvest, and the densification process did not use any binder additive. The bulk density of the cubes as-received was measured as 77.2 lb/ft^3.

Characterization tests of the corn stover were completed in this program for certain smaller size fractions and are reported in Tables 3, 4, and 5. These are compared with the characterization test results of the undensified corn stover from an Illinois harvest in a similar size fraction. These tables highlight the differences between a densified material and a non-densified material.

Table 3. PROXIMATE AND ULTIMATE ANALYSES OF CORN STOVER

	Corn Stover		Densified Corn Stover	
Proximate Analysis, wt %	As-Received	Dry	As-Received	Dry
Moisture	5.0	--	5.9	--
Volatile Matter	74.2	78.1	60.1	63.9
Fixed Carbon	13.8	14.5	13.7	14.6
Ash	7.0	7.4	20.3	21.5
Total	100.0		100.0	
Ultimate Analysis, wt %	Dry	Daf	Dry	Daf
Carbon	46.50	50.20	37.80	48.20
Hydrogen	5.81	6.27	4.84	6.17
Nitrogen	0.56	0.60	0.65	0.83
Sulfur	0.11	0.12	0.09	0.11
Oxygen (by diff.)	39.67	42.82	35.05	44.69
Ash	7.35	--	21.57	--
Total	100.00		100.00	
Heating Value, Btu/lb	8167		6231	

According to the proximate and ultimate analyses, the densified corn stover composition is very similar to the undensified material, except for the amount of volatile matter and ash. The densification process may have reduced

Table 4. DENSITY AND ASH FUSION TEMPERATURES OF CORN STOVER

	Material			
	Corn Stover		Densified Corn Stover	
	Particle	Bulk	Particle	Bulk
	Density, lb/ft^3			
Air Dried Sample				
(-4+16 Mesh)	36.2	7.9	64.3	17.0
(-60+80 Mesh)	62.4	17.1	71.8	23.5
Char				
(-4+16 Mesh)	21.2	6.6	45.6	12.1
(-60+80 Mesh)	70.5	21.3	66.2	21.0

	Ash Fusion Temperatures, °F			
	Reduction	Oxidizing	Reducing	Oxidizing
Initial Deformation (IT)	2250	2330	2100	2170
Softening (ST)	2700	2700+	2225	2270
Softening (HT)	2700+	2700+	2300	2450
Fluid (FT)	2700+	2700+	>2670	>2550

Table 5. ANALYSES OF CORN STOVER FOR CELLULOSE, HEMICELLULOSE, AND LIGNIN

	Material	
	Corn Stover (-12+16 Mesh)	Densified Corn Stover (-12+16 Mesh)
	wt% (dry)	
Composition of Biomass Materials		
Cellulose	36.8	32.6
Hemicellulose	25.4	23.6
Acid-Insoluble Lignin	16.9	13.6
Ash	7.4	21.6
Unaccounted-for Extractives	13.5	8.6
Distribution of Structural Constituents		
Cellulose	46.5	46.7
Hemicellulose	32.1	33.8
Acid-Insoluble Lignin	21.4	19.5

the volatile matter and also the heating value. No sample of the undensified California batch was available for testing to measure the volatile matter before densification. The ash content differences in these samples can reflect local collection and preparation procedures and are expected to vary widely among various samples.

The particle and bulk densities reported in Table 4 for various screen sizes for both densified and undensified ground material indicate some variation in values, especially in the larger size fraction. The handling, fluidization, and reaction characteristics could be affected by the differences in composition and density.

The various ash fusion temperatures for the densified and undensified corn stover samples are also compared in Table 4. The measured temperatures for the densified corn stover sample from the California harvest are lower than those for the undensified sample from the Illinois harvest. This could possibly result from different ash constituents and amounts in each sample.

Table 5 presents the structural constituents of the two corn stover materials. The values of the three major constituents are similar, but somewhat lower for the densified material. Whether this is related to the lower amount of volatile matter measured for the densified material can only be answered by analyzing the undensified corn stover batch.

Additional tests were made on the samples of maple hardwood char that were prepared for the Task III bench-scale tests of char gasification rates. The surface areas and total pore volume were measured to determine if there was an effect on gasification rates from the physical structure of the chars and/or their reactivity. The results of these measurements and the discussion are presented in the Task III section.

The information on the physical and chemical characteristics of each biomass species and its char developed in this task has been cataloged for process design purposes. As an example, the ash content of a species and the corresponding ash fusion temperatures can have an impact on gasifier design and operation. The PRU gasifier was designed to entrain ash with the raw product gases; therefore, the ash inventory in the bed is maintained low and ash sintering is minimal, especially with a properly designed oxygen distributor. Also, knowledge about the characteristics or behavior of specific particle size fractions is important in interpreting bench-scale experimental results, which could have significant process design consequences if properties are not uniform.

Task II. Biomass Handling Characteristics — Pressurized Fluidization Tests

The results of the cold model fluidization tests that were conducted at atmospheric pressure to determine the fluidization behavior of various mixtures of wood char and inert materials were presented in a previous report[2], as were the results of an investigation of the effect of various gas distributor nozzle designs on gas jet penetration into a fluidized bed. That work showed that the measured minimum fluidization velocities were lower for the mixtures of char and inert materials than for the inert materials alone. The inert materials reduced slugging and improved the fluidization. Furthermore, the fluidization characteristics of the mixtures were quite constant over a large range of char concentration in the fluidized bed. Hence, smooth fluidization behavior is expected over a large range of char inventory in the bed.

Tests of steam-oxygen distributor nozzle sizes and patterns provided information on stable, controlled jet penetration lengths into the fluidized bed as a function of gas jet velocity, the fluidized-bed superficial gas velocity, and the nozzle layout pattern.

This program report presents the results of fluidization tests that were conducted at an elevated pressure and ambient temperature to simulate the increased density of the fluidizing gas that would be in the gasifier at the selected baseline process operating conditions of 1500°F and 300 psig.

The purpose of these pressurized fluidization tests was to determine the effect of the fluidizing-gas density on the fluidization behavior of the low-bulk-density wood char and of mixtures of char with inert materials. The gas density in the steam-oxygen gasification PDU at 1500°F and 300 psig was estimated at about 0.4 lb/ft^3; this density was simulated in the ambient-temperature (80°F) fluidization tests by operating at 87 psia pressure.

Equipment and Test Description

The pressurized fluidization tests were conducted with an 11.5-inch-ID Plexiglas column enclosed in a 3-foot-OD steel pressure vessel as indicated in Figure 1. The pressures inside and outside the clear plastic column were

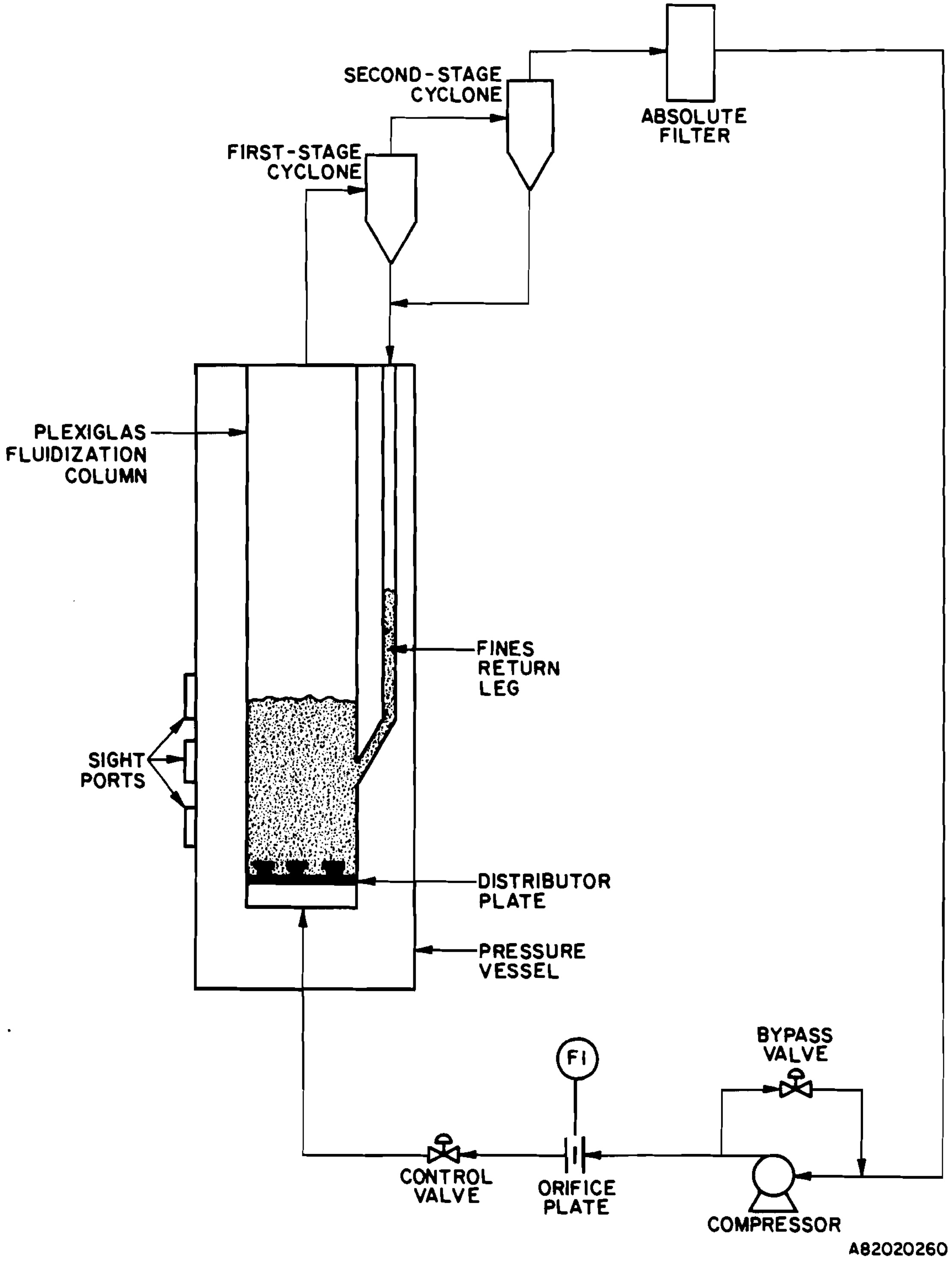


Figure 1. HIGH-PRESSURE FLUIDIZATION APPARATUS

balanced and had the capability to be raised up to 300 psig for a fluidization test. Viewports in the steel pressure vessel shell permitted observation of the fluidization characteristics of the bed materials. The remainder of the equipment consisted of a compressor for the fluidizing gas, two cyclones, and an absolute filter. The fluidization gas was recirculated, flowing through the cyclones and filter before returning to the compressor. The fines collected in the cyclones were returned to the bed.

In a typical test run, solids were loaded into the column to a bed height of about 5 feet. The unit was then pressurized. After the gas reached the test pressure, it was directed at a low flow rate to the gas distributor. The initial flow rate was about 5% to 10% of the maximum test flow, as determined by an orifice meter. The column was given 4 to 5 minutes to reach an equilibrium, and then the gas flow was increased in increments of 5% to 10% over the range of test flow rates. For the pressurized fluidization tests, mixtures of sand (-20+40 U.S. sieve size) and hardwood char (-1/4 inch) were used. Sand-char mixtures of 20%, 33%, 40%, and 50% char by volume were tested (in addition to pure char). The gas distributor plate installed in the test apparatus had a bubble cap type of design. The fluidizing gas in all tests was nitrogen. All of the tests reported here were conducted at 87 psia and 80°F.

Experimental Test Results

The measured values of the minimum fluidization velocity, u_{mf}, and the corresponding pressure drop per unit length or bed density for each char concentration tests are presented in Table 6. The atmospheric fluidization test results are also listed for comparison. Figure 2 shows the bed density variation with the superficial fluidization gas velocity at the elevated pressure. Figures 3 through 5 compare the fluidization runs conducted at 15 psia with the runs conducted at 87 psia.

As shown in Figures 3 through 5, the minimum fluidization velocity, u_{mf}, in all cases is lower for the pressurized fluidization tests. This is expected because the drag force becomes greater as the density of the fluidizing gas increases. As a result, fluidization occurs at a lower superficial gas velocity. The bed density values $\Delta P/L$, appear somewhat lower for the higher pressure tests if extrapolated to the higher superficial gas velocities. This is not expected; however, a possible explanation may arise from variances in the pressurized and atmospheric pressure test equipment,

Table 6. RESULTS OF FLUIDIZATION TESTS

	Atmospheric Pressure Tests at 15 psia in 8-in.-ID Column (Gas Density 0.08 lb/ft^3)				Elevated-Pressure Tests at 87 psia in 11.5-in.-ID Column (Gas Density 0.42 lb/ft^3)				
Char, vol %	u_{mf}, ft/s	P/L at u_{mf}, psi/ft	u_{cf},* ft/s	P/L at u_{cf}, psi/ft	u_{mf}, ft/s	P/L at u_{mf}, psi/ft	u_{cf},** ft/s	P/L at u_{cf}, psi/ft	Calcd P/L, psi/ft
20	0.72	0.69	1.08	0.56	0.38	0.61	0.95	0.48	0.59
33	0.66	0.64	0.99	0.51	0.44	0.58	0.90	0.43	0.52
40	--	--	--	--	0.49	0.53	0.92	0.39	0.49
50	0.71	0.57	1.03	0.48	0.46	0.49	1.05	0.36	0.43
100	†	--	--	--	0.65	0.20	0.90	0.18	0.17

* u_{cf} = complete fluidization velocity.

** Value estimated by graphical extrapolation.

† Poor fluidization behavior at atmospheric pressure.

171/65058fr-t/RPP

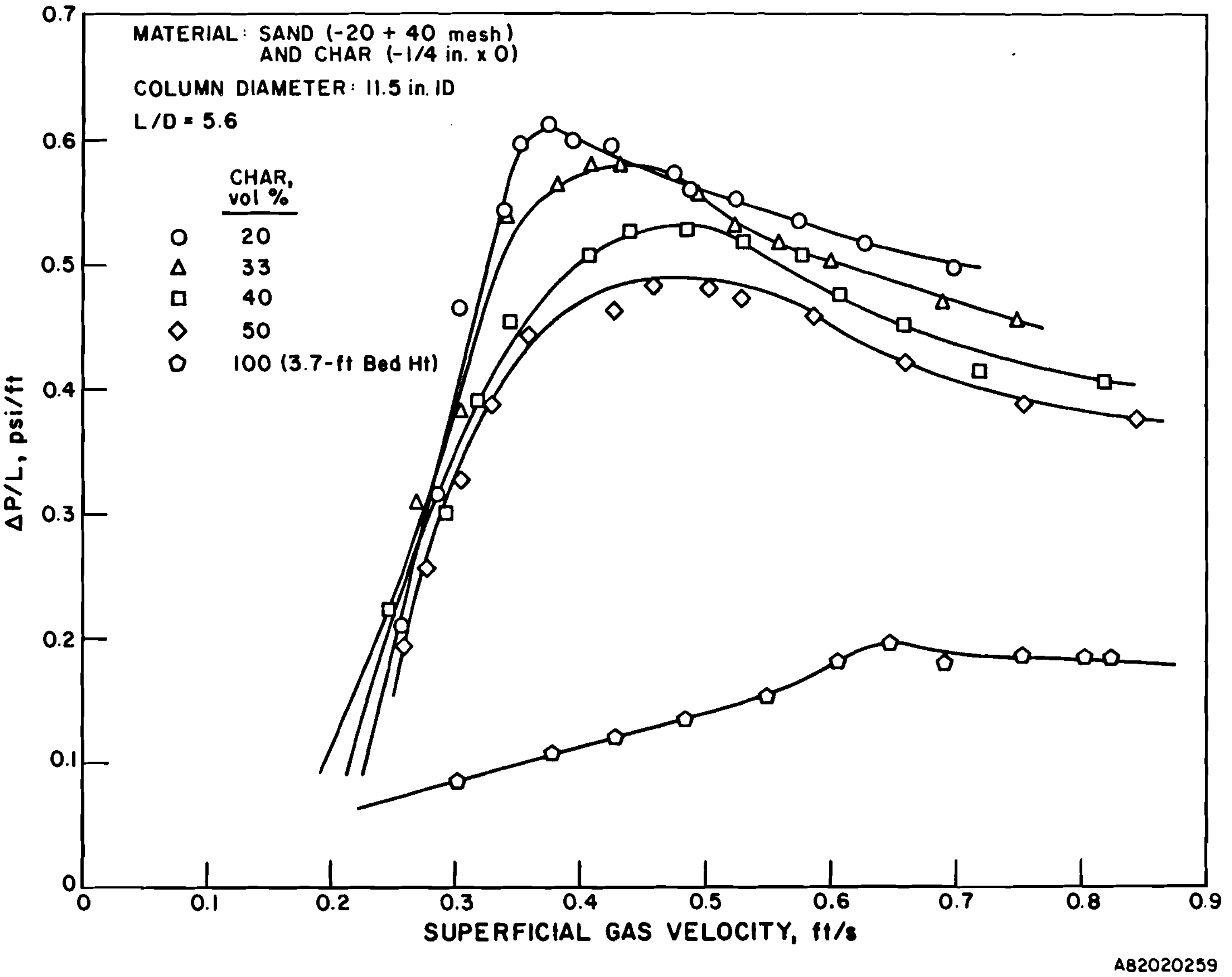


Figure 2. EXPERIMENTAL FLUIDIZATION CURVES FOR -20+40 MESH SAND + CHAR AT ELEVATED PRESSURE (87 psia) AND AMBIENT TEMPERATURE

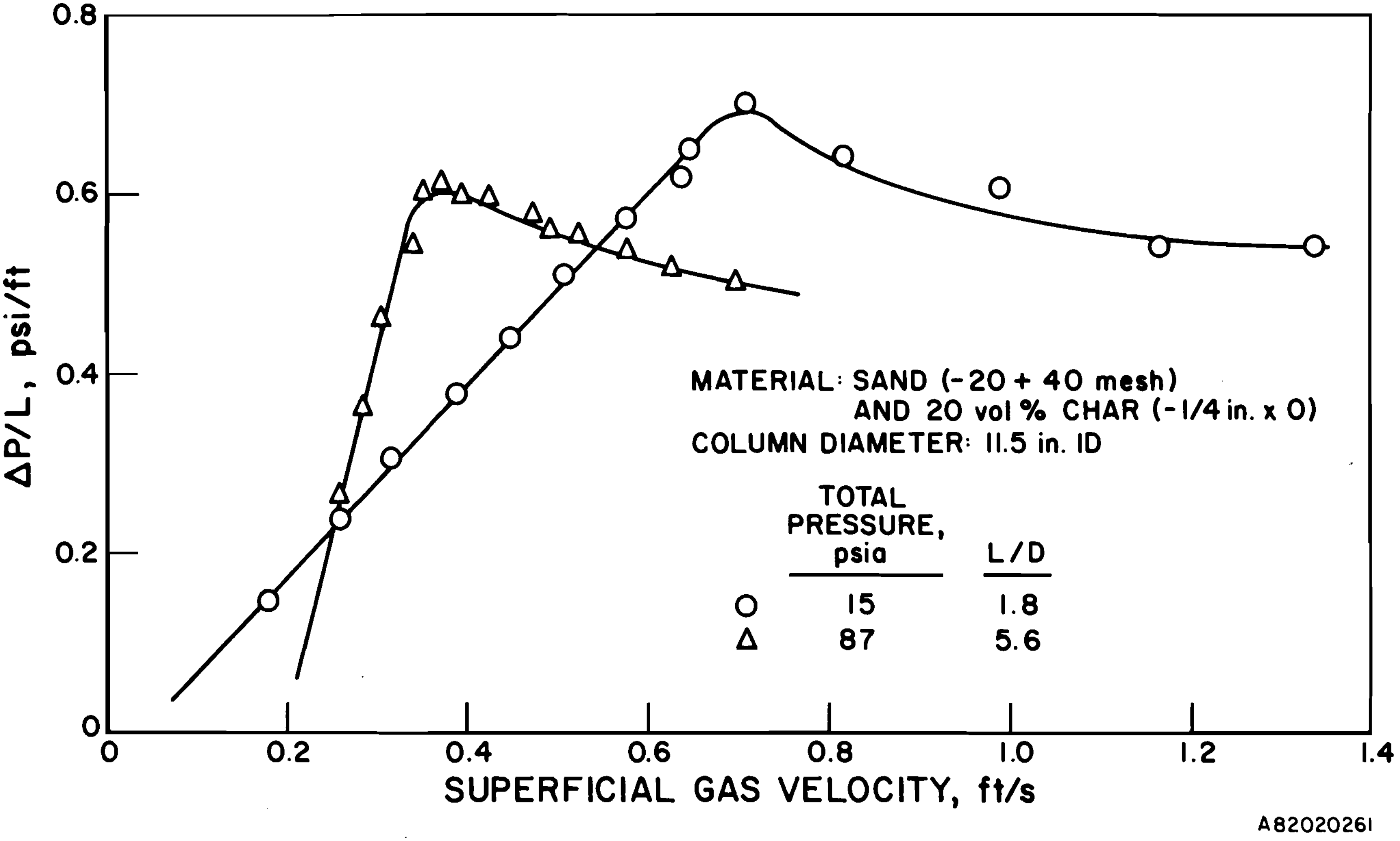
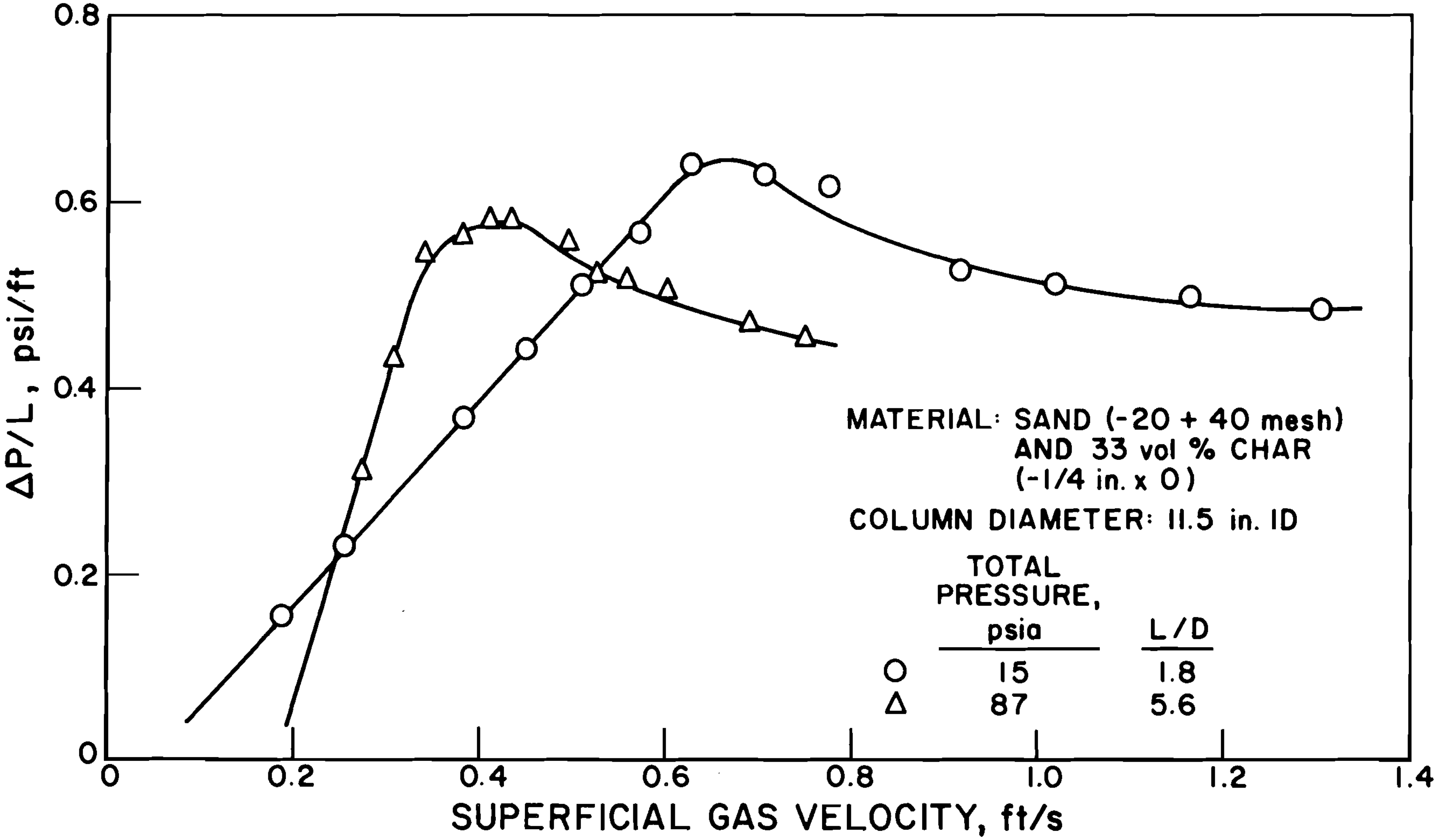


Figure 3. FLUIDIZATION AS A FUNCTION OF PRESSURE FOR A 20 vol % CHAR-SAND MIXTURE



A82020262

Figure 4. FLUIDIZATION AS A FUNCTION OF PRESSURE FOR A 33 vol % CHAR-SAND MIXTURE

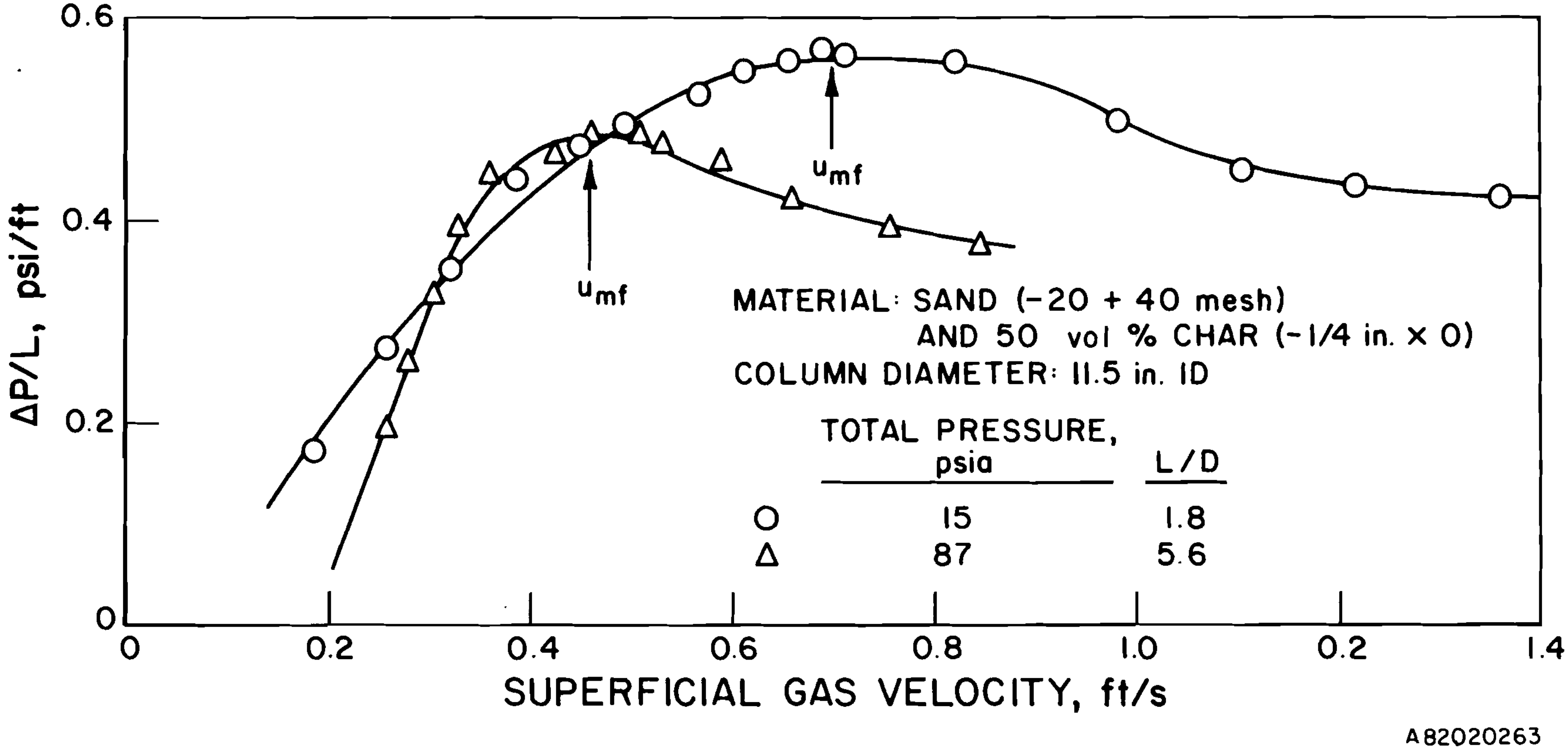


Figure 5. FLUIDIZATION AS A FUNCTION OF PRESSURE FOR A 50 vol % CHAR-SAND MIXTURE

because the difference appears as a constant value of about 0.08 psi/foot, independent of the char concentration. The atmospheric pressure tests compared here were conducted in an 8-inch-ID column where wall effects could possibly be contributing to the measured pressure drop.

Figure 6 presents the relationship between the minimum fluidization velocity and char concentration. As with the atmospheric fluidization tests, there appears to be a range of char inventory in the bed where the value of u_{mf} is approximately constant, providing a steady fluidization behavior.

One significant difference in behavior was observed during the pressurized fluidization tests. The mixtures with higher char concentrations were more easily fluidized at this elevated pressure or simulated gas density than in the atmospheric fluidization tests conducted earlier. In those tests, the mixtures with high char concentrations fluidized, but still showed a slugging tendency. In these pressurized tests, even a bed with 100% char was fluidized with no tendency to slug. The values from the 100% char test agree with the published correlation as shown in Figure 7 for both the 8-inch-ID column at atmospheric pressure and the 11.5-inch-ID column at 87 psia.

Task III. Bench-Scale Experiments

The conversion of biomass to produce a medium-Btu gas can be divided into the following steps:

- Devolatilization — the nearly instantaneous thermal decomposition of biomass, followed by a gas-phase hydrogenation of volatile products into hydrocarbon gases. Hydrogen, carbon oxides, light hydrocarbons, and water are the primary products of devolatilization.
- Char Gasification — a slow gasification of residual biomass char with steam in the presence of hydrogen to produce methane, carbon monoxide, hydrogen, and carbon dioxide.
- Char Combustion — the combustion of residual biomass char, which supplies the energy required for the endothermic char gasification reactions.

The bench-scale experimentation was conducted to investigate these first two reaction steps with maple hardwood chips, corn stover, and jack pine chips. Two types of bench-scale experiments were conducted:

1. Devolatilization experiments in a laminar-flow reactor
2. Isothermal char gasification experiments in a thermobalance using a mixture of hydrogen, steam, and helium.

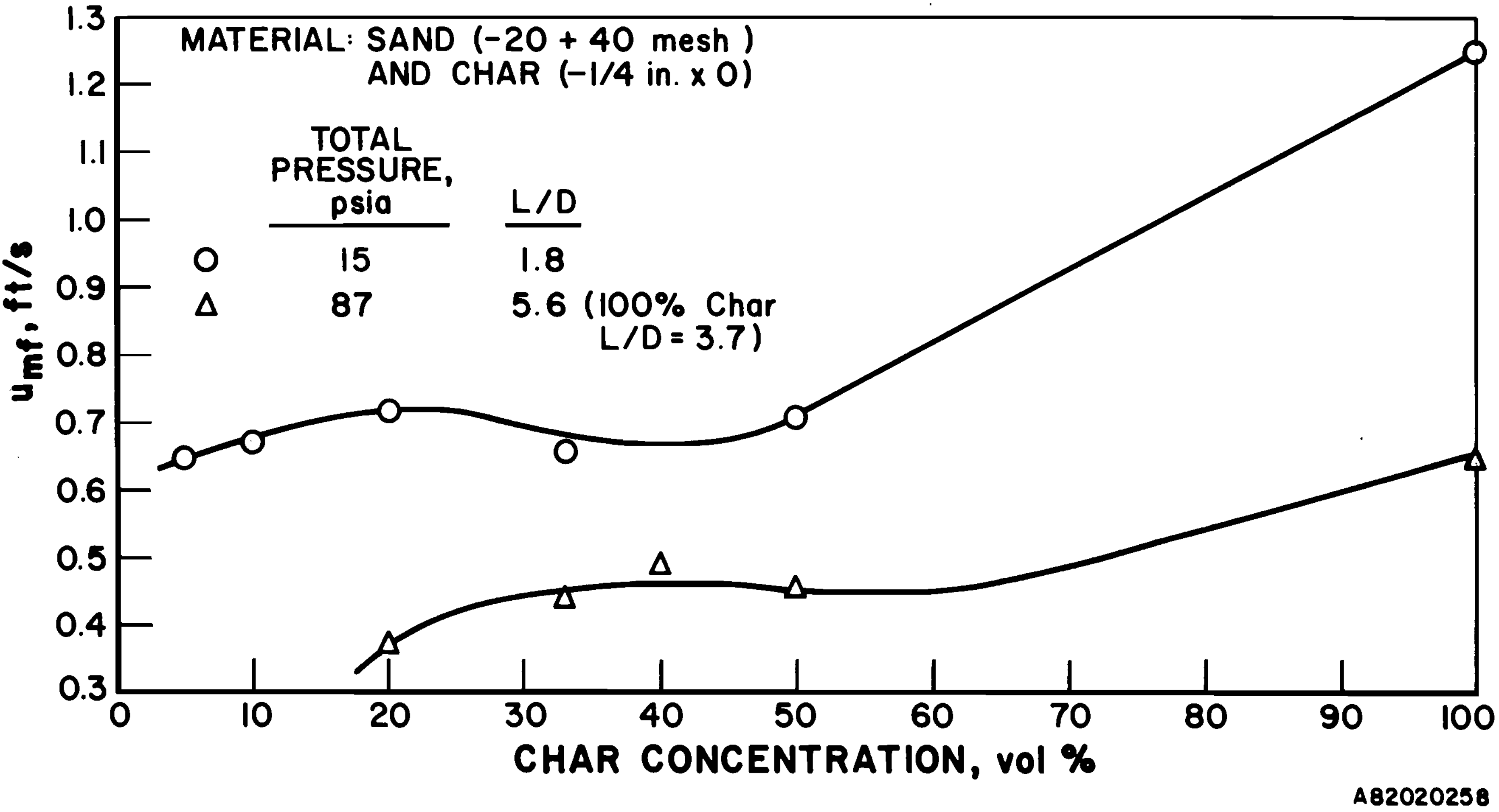


Figure 6. MINIMUM FLUIDIZATION VELOCITY AS A FUNCTION OF CHAR CONCENTRATION AT TWO PRESSURES

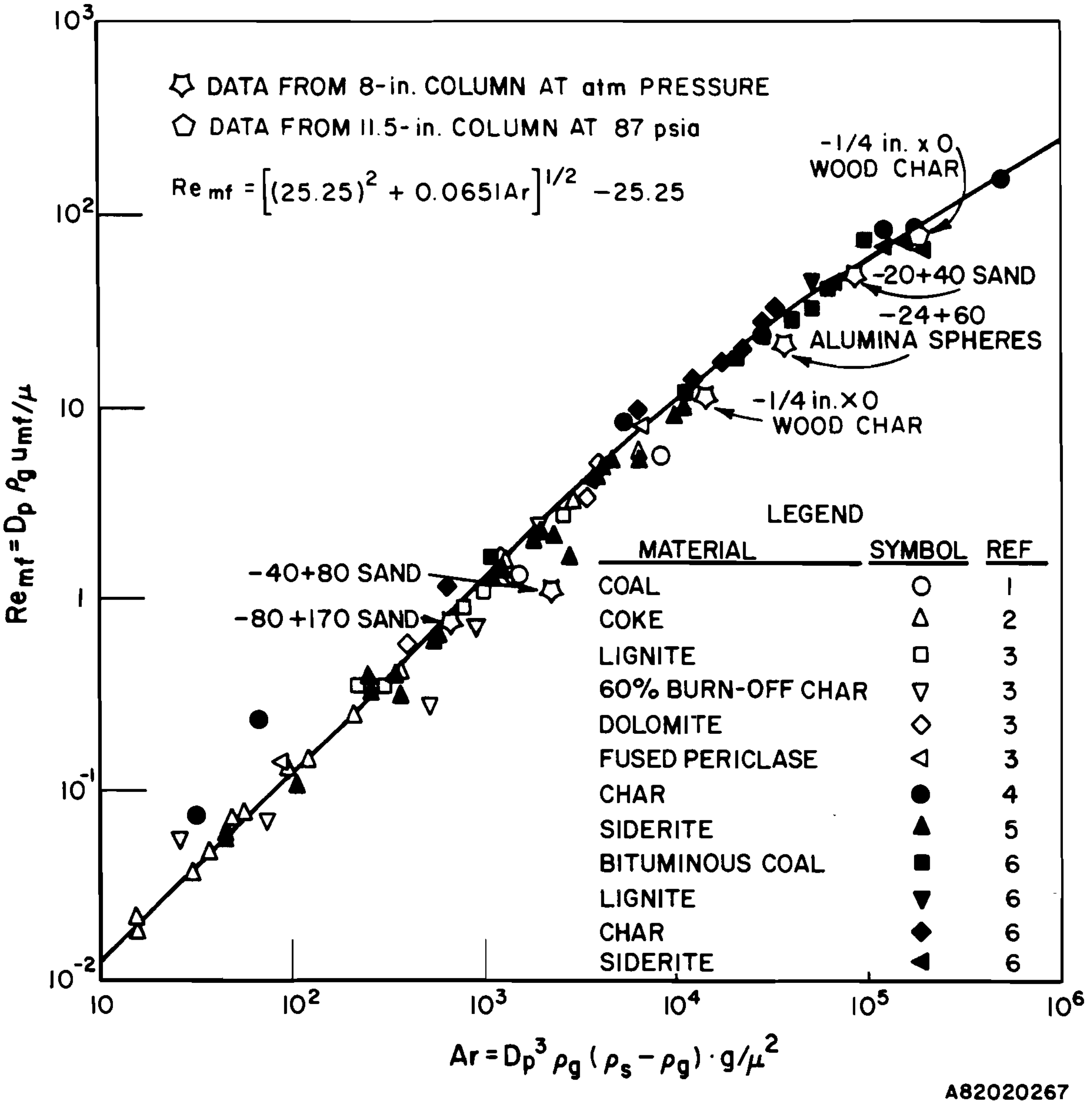


Figure 7. CORRELATION FOR THE PREDICTION OF MINIMUM FLUIDIZATION VELOCITY (Data Points Defined in Reference 3)

The rapid devolatilization experiments produced data on the effect of process variables on product yields and compositions. The isothermal char gasification experiments contributed kinetic data on the slower, rate-controlling steam-char reactions in gaseous atmospheres containing the typical percentages of hydrogen and steam that would be expected in an adiabatic gasifier.

Laminar-Flow Devolatilization Experiments

The rapid devolatilization characteristics of maple hardwood were investigated in a laminar-flow reactor. The apparatus was devised to provide a range of devolatilization temperatures at short residence times. Figure 8 shows a simplified schematic diagram of the laminar-flow reaction system. The system is composed of three distinct sections: 1) feed system, 2) reactor system, and 3) product collection systems.

The feed system was designed to supply the gaseous medium at the temperature, pressure, and flow rate selected for each experiment and to introduce the sized biomass into the reactor. The gas was preheated to the selected temperature and fed to the reactor system at different volumetric flow rates so that the linear velocity of the gas in the reactor was constant for all experiments. The biomass was stored in a high-pressure feed hopper. Its feed rate could be adjusted from 0.1 to 1 gram per minute by changing the rotational speed of the screw feeder located at the bottom of the hopper. The biomass particles flowed through a water-cooled injection probe into the hot reactor zone.

The main section of the reactor system was an 8-foot-long, 2-inch-ID stainless-steel core, which was surrounded by seven electrical heaters. The first two heaters were used to maintain and/or preheat the feed gas to the reaction temperature. The last five heaters were used to maintain the reactor temperature. A balanced-pressure reactor design was employed to facilitate temperature control, reduce heat-up time, and minimize the power required. The 2-inch-ID reactor core was a thin-walled (1/4-inch-thick) cylindrical reactor that did not see any large differential pressures. The reactor core was placed inside a 12-inch pipe as a pressure vessel; the pressure between the reactor and the enclosing shell was adjusted, using nitrogen, to match the pressure inside the reactor core. This reactor system was capable of operating at temperatures up to 1600°F and pressures up to 1500 psig. Inside

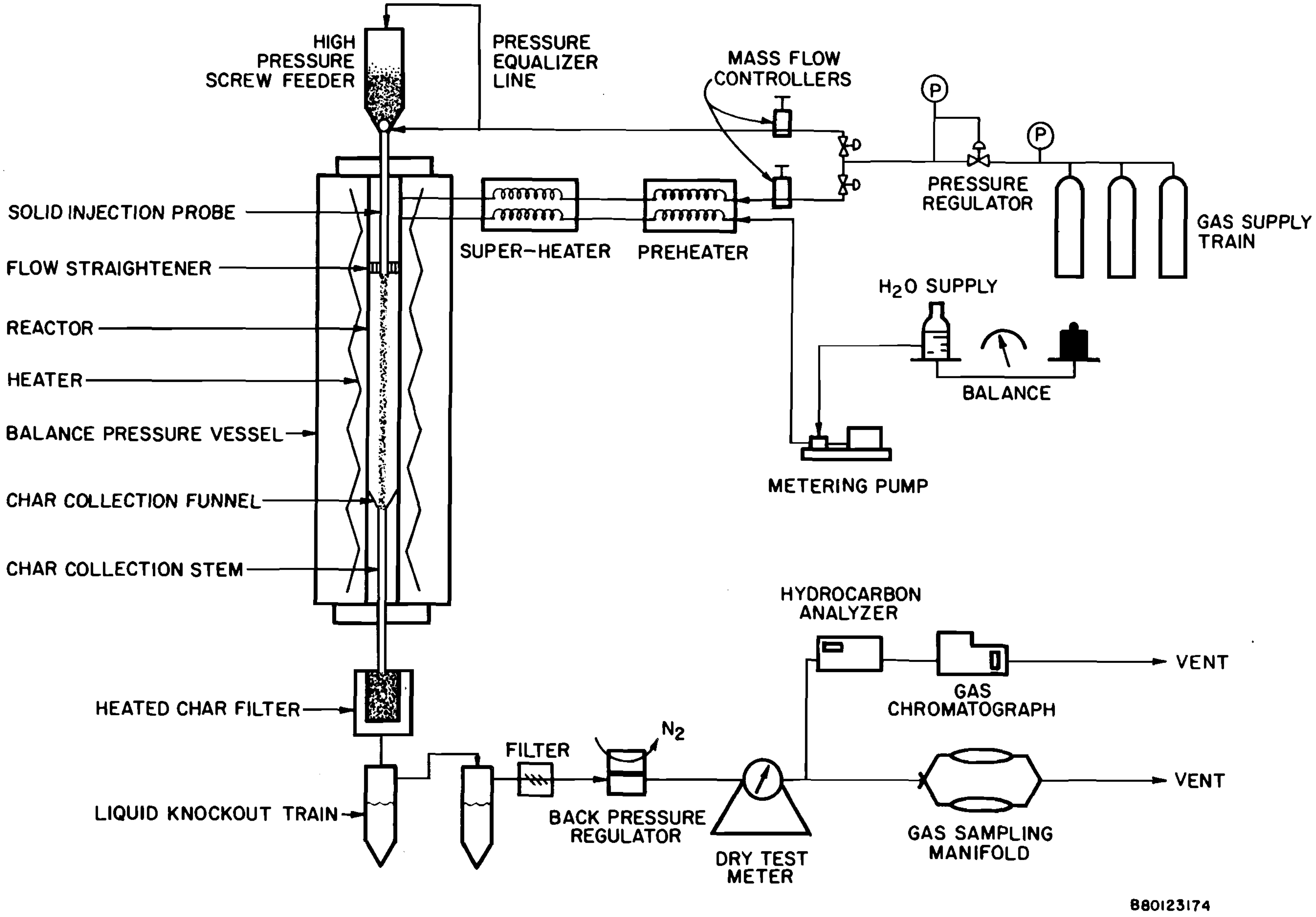


Figure 8. SCHEMATIC FLOW DIAGRAM OF THE LAMINAR-FLOW REACTOR SYSTEM

the reactor core was an adjustable char collection probe. The purpose of this probe was to transmit the char and gas with little or no further reaction to the char filter located at the bottom of the reactor. To quench the reaction, the probe was cooled to below 800°F, either with water or air. The probe length was adjustable so that the free-fall distance of the char particles could be varied from 12 to 48 inches, which varies the contact or residence time.

The gas and char stream passed through the collection probe and into a heated filter, where the char was separated from the gas stream. The porous sintered-metal type filter retained particles greater than 5 micrometers. It was kept at about 450°F to prevent liquid products from condensing in it. The solids-free gas stream was then passed through a series of cold liquid-knockout pots and a filter medium, where oils, tars, water, and heavy hydrocarbons were collected. The pressure of the gas stream was then reduced to atmospheric pressure and metered through a dry-test meter. The gas stream then flowed through a sample manifold, where gas samples were collected intermittently for mass spectroscopy analysis.

At the beginning of each experiment, the feed hopper was charged with 70 to 100 grams of prepared feed (sized to -60+80 mesh). After the system was brought to operating pressure and checked for leaks, the heaters were energized to heat the reactor and then to maintain isothermal temperatures. During the start-up, collection bombs were placed in the sample manifold, and the devolatilization gas flow rate was set. Once the system was at operating pressure and temperature, the gas flow rate was rechecked and the experiment was initiated by starting the feeder.

Usually within 5 minutes of feeding, the infrared analyzer (IRA) began showing a trace of CO and CO_2; at about 15 minutes, steady-state operation was obtained. The steady-state period was determined when the composition of the product gases monitored by the IRA remained constant. The experiment was continued at steady-state operation, generally for more than 4 hours, with gas samples taken periodically. Improved material balances were obtained with longer runs, which reduced the errors of feed rate irregularities and the collection of small quantities of products. To end the experiment, the solids feed was stopped, the gas flow reduced, and the unit depressurized after the reactor cooled.

Experimental Bench-Scale Test Results

The results of the laminar-flow devolatilization experiments presented here derive from a planned, parametric study of the devolatilization behavior of maple hardwood. The rapid devolatilization behavior was investigated as a function of temperature, pressure, devolatilization gas medium, feed moisture variation, and residence time.

The temperature of the reaction zone was varied from 1000° to 1600°F at a total pressure of 300 psig. A few tests were made at 100 and 200 psig. Tests with an inert helium devolatilization atmosphere simulated devolatilization pyrolysis, and a gas with a concentration of 5% hydrogen in helium was selected to simulate devolatilization in a conceptual steam-oxygen gasification process.

Table 7 lists the data from all the experiments. Elemental and overall material balances are given in Table 8. Figure 9 presents the effect of the devolatilization temperature on the yields of gas, liquids, and char for one estimated residence time in the laminar-flow reaction zone of approximately 2 seconds. Results are shown for both the helium and the 5% hydrogen gas mediums.

It is difficult to determine the residence time exactly of the biomass particles in the controlled temperature zone of the laminar-flow apparatus, because the particles undergo a shape change and a weight loss of about 80% or more. Under these experimental conditions, particle heat-up was assumed to be principally through radiative heat transfer, which produces relatively high heating rates. Consequently, the particles would reach the reaction temperature in much less than 1 second. Particle size, density, shape, gas density, and viscosity all are factors that affect the free-fall velocity of the particles. These factors could change dramatically as the particles devolatilize. Nevertheless, an estimate of the residence times of the solid particles was made by measuring the free-fall velocity of sized (-60+80 mesh) maple hardwood chips at ambient, nonreactive conditions. On this basis, the approximate residence times were 1.2, 2.0, and 3.2 seconds, respectively, for the 18-, 30-, and 48-inch reaction zones in the apparatus.

Table 7. SUMMARY OF LAMINAR-FLOW DEVOLATILIZATION DATA

Run No.	MHC 17	MHC 18	MHC 31	MHC 33	MHC 19	MHC 20A	MHC 21	MHC 25	MHC 25A	MHC 28	MHC 22	MHC 22A	MHC 26A	MHC 29	MHC 32	MHC 23	MHC 27A	MHC 30	MHC 39	MHC 41C	MHC 42	MHC 24A	MHC 34	MHC 35	MHC 38
Temperature, °F	1000	1300	1300	1300	1500	1600	1000	1000	1000	1000	1300	1300	1300	1300	1300	1500	1500	1500	1500	1500	1500	1600	1600	1600	1600
Pressure, psig	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	100	200	300
Gas Medium	He	He	He	He	He	He	H_2/He*	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He
Run time, min	200	300	292	210	300	270	152	194	180	266	333	299	240	270	250	284	270	184	134	50	98	360	300	300	210
Amount Fed, g (dry)	30.95	56.44	47.80	35.61	51.55	51.02	17.81	27.28	32.12	30.73	55.25	59.92	52.53	38.21	40.81	47.87	53.64	23.91	15.01	2.14	9.53	78.13	47.29	57.01	28.06
Feed Moisture, %	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	12.1**	25.9**	12.6**	3.1	3.1	3.1	3.1
Reactor Length, in.	30	30	30	30	30	30	30	18	18	48	30	30	18	48	30	30	18	48	30	30	30	30	30	30	30
Devolatilization Yields, wt % of dry feed																									
Gas	45.8	68.3	66.8	70.5	72.5	72.2	48.4	48.3	47.2	60.2	65.7	64.8	58.8	75.4	72.2	79.7	73.3	84.6	83.3	90.4	80.6	80.7	85.8	84.9	79.6
Liquids	25.0	11.4	11.6	14.2	8.0	5.4	33.9	26.3	24.6	18.0	15.1	14.2	12.1	12.9	15.0	9.1	8.5	6.7	4.9	13.7	8.6	6.3	11.4	6.6	6.6
Char	12.4	10.3	7.9	9.7	9.0	6.6	13.6	14.5	12.8	16.0	4.7	4.8	5.6	9.7	6.3	3.5	7.4	9.2	6.6	7.7	9.5†	6.5	5.4	5.1	6.4†
Gas Composition, vol %																									
CO	50	48	50	47	44	45	58	55	54	55	54	56	55	54	54	51	51	52	51	49	48	57	58	58	53
CO_2	15	10	9	11	10	11	14	18	20	16	8	9	10	9	9	8	9	7	10	8	10	9	8	7	7
H_2	12	16	16	17	23	24	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
CH_4	14.0	19.3	18.7	19.7	19.2	19.3	17.8	17.8	17.9	21.6	27.1	25.0	24.7	25.5	26.1	37.8	35.2	38.8	35.4	37.7	38.6	32.5	32.2	33.7	37.6
C_2H_6	2.6	1.5	1.6	1.2	0.3	--	4.1	2.8	3.3	4.3	7.9	7.6	7.5	8.7	7.5	0.7	2.1	0.4	1.5	2.4	1.3	--	0.1	0.4	0.3
C_2H_4	3.5	3.7	3.5	3.5	1.6	--	4.1	1.9	1.6	0.9	1.4	1.4	2.1	1.4	1.7	0.7	1.2	--	1.0	1.2	1.3	--	0.3	0.4	0.3
C_3H_8	1.8	--	--	--	--	--	1.4	0.9	0.8	0.9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
C_3H_6	--	--	--	--	--	--	--	1.9	0.8	0.9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
C_3H_6O	0.9	--	--	--	--	--	1.4	1.9	1.6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
C_6H_6	--	0.7	1.2	0.8	1.6	0.7	--	--	--	0.9	0.9	1.0	0.8	1.4	1.7	1.7	1.8	1.8	1.6	1.2	1.3	1.4	1.7	1.1	1.9

* 5% H_2, 95% He.

** Feed moisture content may affect devolatilization results.

† Corrected by ash balance.

171/65058fr-t/RPP

Table 8. MATERIAL BALANCES FOR LAMINAR-FLOW DEVOLATILIZATION DATA

Run No.	MHC 17	MHC 18	MHC 31	MHC 33	MHC 19	MHC 20A	MHC 21	MHC 25	MHC 25A	MHC 28	MHC 22	MHC 22A	MHC 26A	MHC 29	MHC 32	MHC 23	MHC 27A	MHC 30	MHC 39	MHC 41C	MHC 42	MHC 24A	MHC 34	MHC 35	MHC 38
Temperature, °F	1000	1300	1300	1300	1500	1600	1000	1000	1000	100	1300	1300	1300	1300	1300	1500	1500	1500	1500	1500	1500	1600	1600	1600	1600
Pressure, psig	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	100	200	300
Gas Medium	He	He	He	He	He	He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He	H_2/He
Run Time, min	200	300	292	210	300	270	152	194	180	266	333	299	240	270	250	284	270	184	134	50	98	360	300	300	210
Amount Fed, g (dry)	30.95	56.44	47.80	35.61	51.55	51.02	17.81	27.28	32.12	30.73	55.25	59.92	52.53	38.21	40.81	47.87	53.64	23.91	15.01	2.14	9.53	78.13	47.29	57.01	28.06
Feed Moisture, %	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.1	12.1	25.9	12.6	3.1	3.1	3.1	3.1
Reactor Length, in.	30	30	30	30	30	30	30	18	18	48	30	30	18	48	30	30	18	48	30	30	30	30	30	30	30
Balances, %																									
Carbon	73	84	80	86	85	76	81	81	76	86	80	71	71	95	88	90	89	102	91	109	96	91	95	93	94
Hydrogen	86	90	86	96	91	83	97	85	84	86	95	88	80	102	101	102	95	105	100	115	113	82	96	90	96
Oxygen	92	95	93	103	94	100	103	97	95	102	92	90	83	98	98	95	88	95	98	106	100	104	111	100	91
Overall*	83	90	86	94	90	84	96	89	85	94	85	77	77	98	94	92	89	100	95	112	99	93	103	97	95
Conversion**	85	89	91	90	90	92	86	84	85	83	95	94	93	90	93	96	92	91	93	93	90	93	95	95	93

* Overall material balance = % of dry feed to gas, liquid, char collected.

** Conversion = (gas + liquid)/(gas + liquid + char) (%).

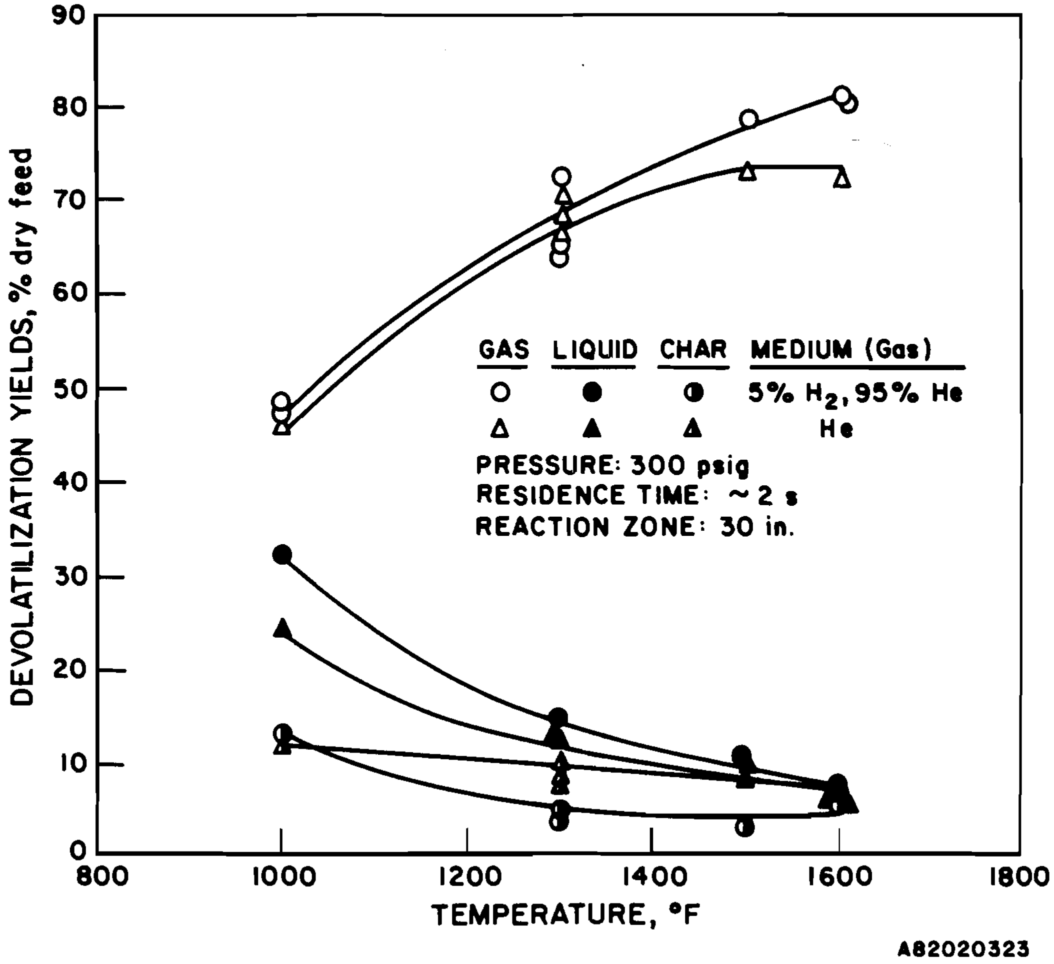


Figure 9. DEVOLATILIZATION YIELDS AS A FUNCTION OF TEMPERATURE IN 5% H_2, 95% He, AND IN 100% HELIUM

Figure 10 depicts the yields for the three residence times or reaction zone lengths as a function of temperature. As expected, the gas production shows a consistent increase as the reaction time and temperature increase. The increased gas yields obtained as the solids residence time is increased could result not only directly from higher conversions, but also possibly through secondary liquid decomposition reactions or even steam-char reactions at the higher temperatures.

The effect of the length of residence time upon the char and liquid yields is not as clear as with the gas yields. Secondary reactions such as thermal cracking of the heavier hydrocarbons may be occurring to cause the observed slight increase, rather than a decrease, in the char yields for the longest residence-time run, assuming that no measurement or collection error is present. If secondary reaction effects are contributing to the char values, then more definitive experiments are required to uncover these effects. These results show definite trends for temperature and residence-time dependence that are useful for process design in general and analysis of the PRU test results.

Figure 11 shows the effect of the temperature and residence time on the ratio of CO, CH_4, and CO_2 gas products to feed carbon. There is a small change in the production of CO_2 relative to the feed carbon as both residence time and temperature are increased; however, larger effects on both CO and CH_4 production are observed. It is the increased production of CO and CH_4 that is primarily responsible for the increased overall gas production shown in Figures 9 and 10. Combined, they account for 75% to 90% of the product gases.

Note that a lower value of methane was measured at 1600°F than at 1500°F. This was confirmed with a duplicate experimental run. Other investigators[4–6] have reported that methane content diminishes as temperatures approach 1800°F and beyond. Such conditions would favor the production of a synthesis gas for methanol conversion. The laminar-flow bench-scale apparatus was limited to controlled temperatures of 1600°F in the reaction zone. The PRU, however, was designed for operating temperatures up to 1800°F.

Figure 12 shows an increase of the conversion of biomass to gases and liquids with temperature for the three residence times. The conversion fraction is defined as the ratio of the gas plus liquid products to the sum of gas, liquid, and char products on a weight fraction basis. A relationship may

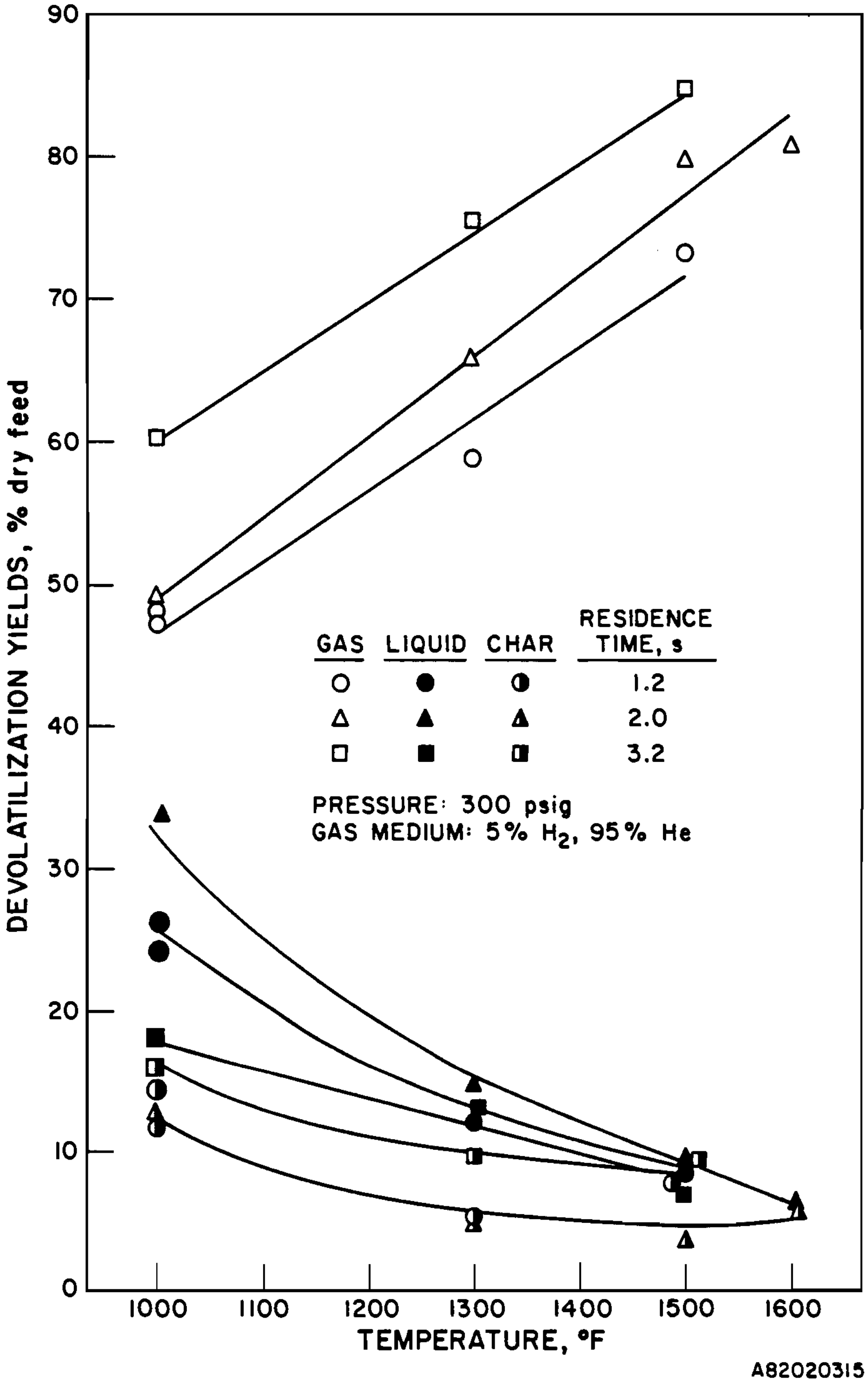


Figure 10. DEVOLATILIZATION YIELDS AS A FUNCTION OF TEMPERATURE FOR VARIOUS RESIDENCE TIMES

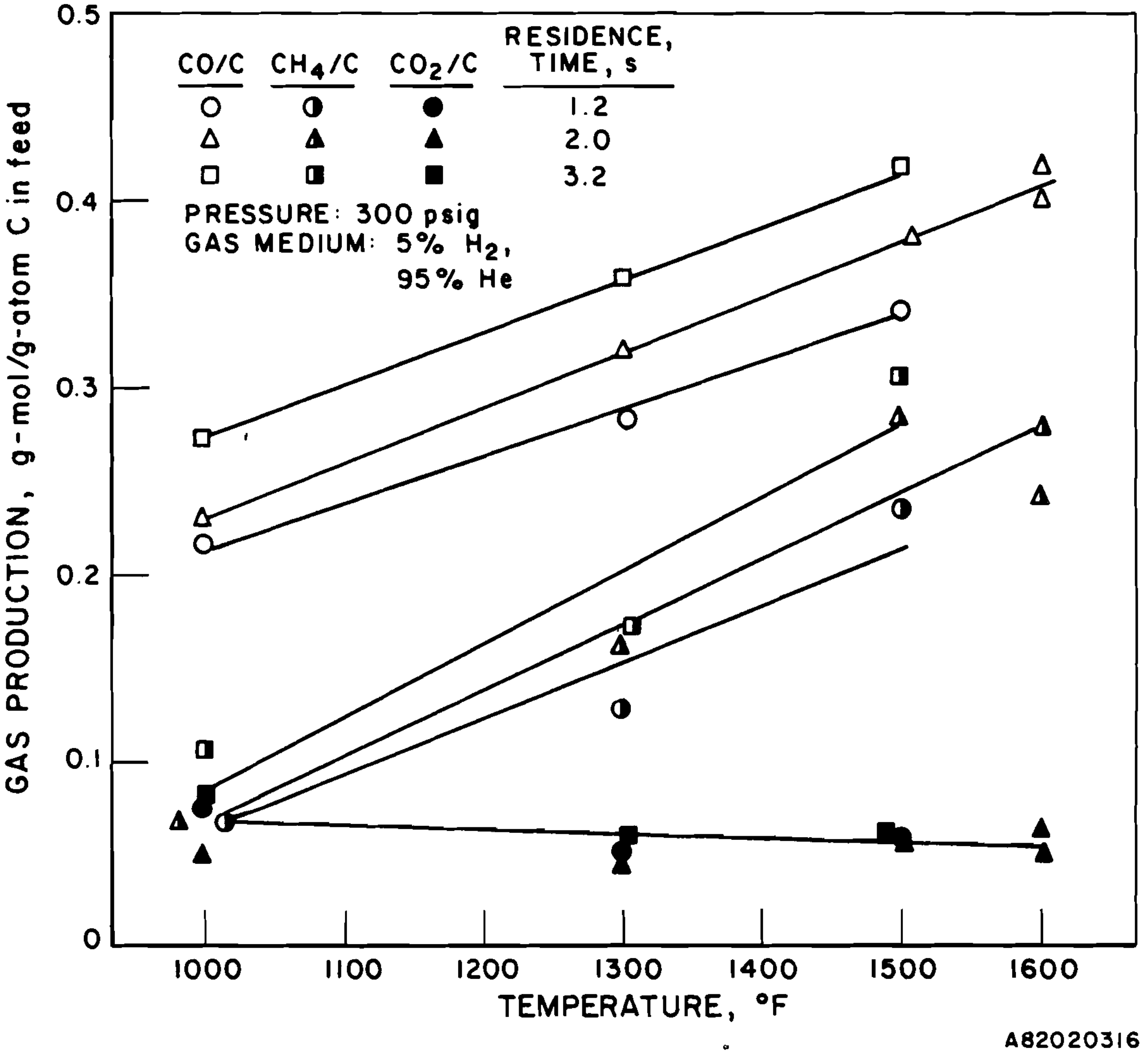


Figure 11. GAS SPECIE PRODUCTION AS A FUNCTION OF TEMPERATURE FOR VARIOUS RESIDENCE TIMES AT 300 psig

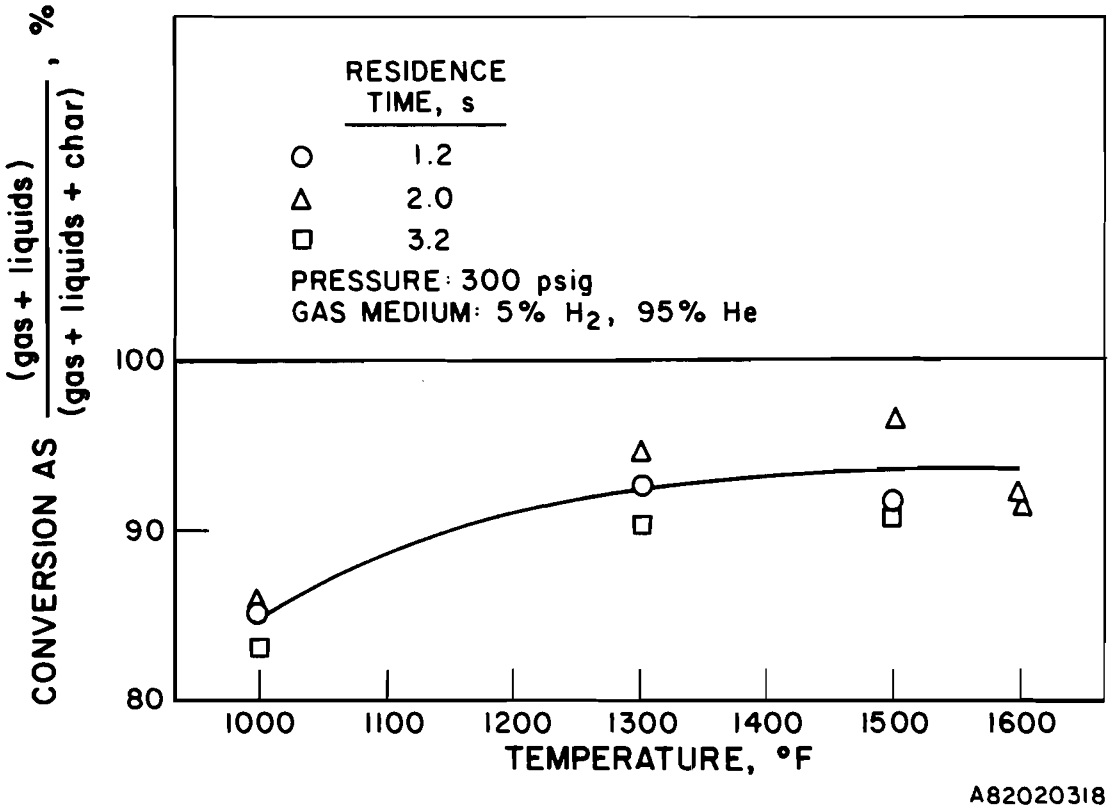


Figure 12. CONVERSION VERSUS TEMPERATURE

exist between the conversion and residence time, as shown in Figure 12; however, the variation is within the experimental uncertainties.

Figure 13 plots the conversion against the reaction zone length, which is a more precise value than the estimate of residence time. For temperatures of 1300° to 1600°F, a slight difference in conversion is shown; however, these differences are still within the experimental uncertainties. The decrease for the longest residence time could be due, perhaps, to the formation of char from a portion of the liquids. More definitive experiments would be necessary to confirm that.

Three runs were made to explore the effect of total pressure on devolatilization. These runs were made at 1600°F and 100, 200, and 300 psig with the approximate 2-second residence time. The pressure did not affect the conversion level or overall gas composition significantly. The most significant differences observed were that about 5% less gas, but 45% less liquids, was measured at 300 psig than at 100 psig.

Three different feed moisture experimental runs were conducted to investigate the effect of feed moisture content upon the yields and conversions. The moisture content was varied from 3 to 12 to 27 weight percent, approximately, for run conditions of 1500°F, 300 psig, and a 2-second residence time.

The duration of the experiments with the 12 and 27 weight percent moisture content values was shorter than for most previous experiments because steady feeding was difficult with the moist -60+80 mesh material. The feeder would feed steadily for only about one-half of the previous run times. Hence, shorter run times were made. As these have greater experimental error, duplicate runs at each condition were planned. Consequently, feeding problems were recurrent with the higher moisture material in the small-diameter screw feeder currently in the laminar-flow apparatus. Very little difference could be discerned among the various runs to attribute to feed moisture variation. A modified experimental procedure or apparatus would be necessary to isolate the effect of feed moisture content.

Isothermal Char Gasification Experiments

The gasification of the biomass char, obtained from devolatilization, is the slowest step in the overall conversion process for the production of

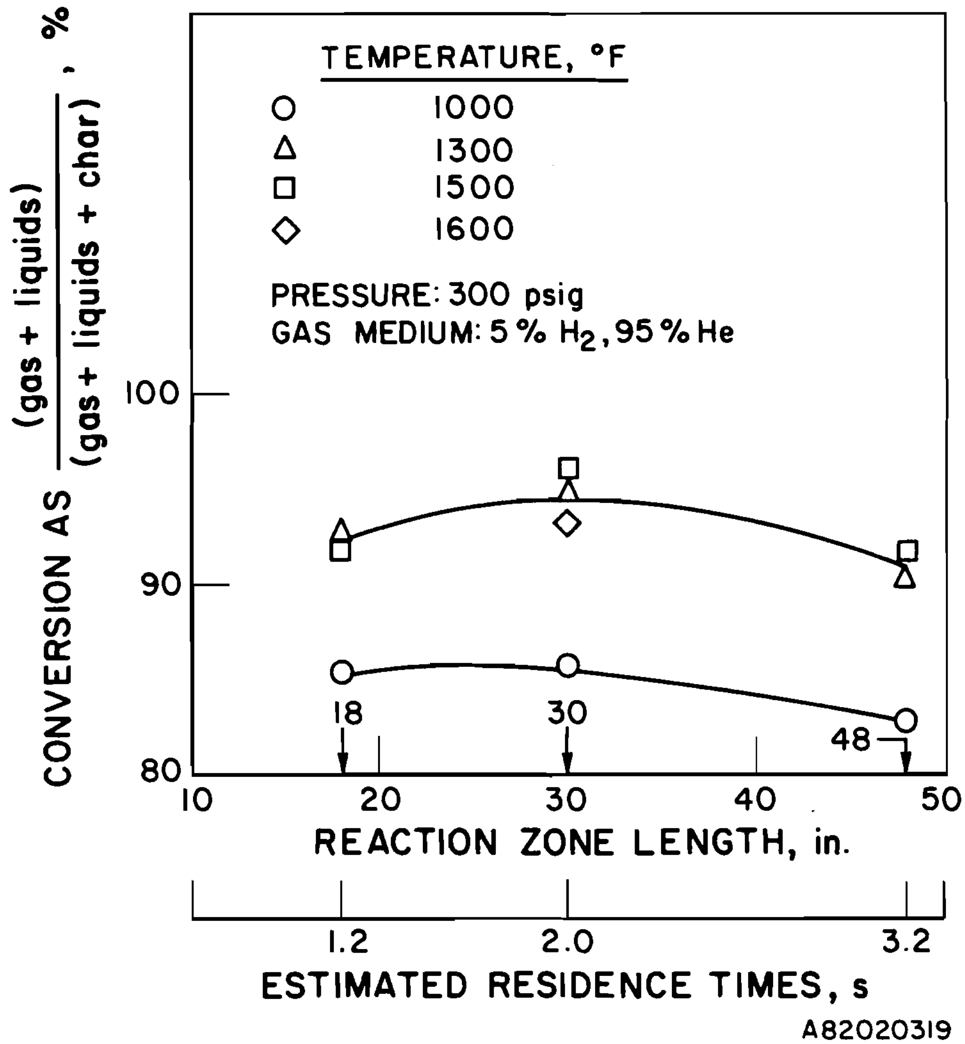


Figure 13. CONVERSION AS A FUNCTION OF REACTION ZONE LENGTH FOR VARIOUS TEMPERATURES AT 300 psig

medium-Btu gas from biomass. To obtain a measure of the rate of gasification of the char under the proposed reaction conditions (temperature, pressure, and gas composition), a series of prepared chars were gasified at a total pressure of 300 psig over a temperature range of 1350° to 1700°F in a gas medium consisting of about 50% H_2O, 5% H_2, and 45% inert gas (He). As mentioned previously, the selection of these main experimental conditions of temperature and pressure was based on the designed PRU operating conditions. Experiments at different total pressures and different gas mediums were also conducted.

All of the char gasification rate experiments were conducted in a thermobalance reactor. This apparatus is capable of continuously monitoring the weight of a sample reacting under simulated process conditions. Figure 14 is a schematic diagram for the thermobalance reactor system. In a typical experiment a representative sample of 1 to 2 grams of the char is suspended in a wire mesh screen basket from a transducer and brought in contact with the gasification medium at predetermined reaction conditions. In this bench-scale experimentation task, two series of char gasification experiments were made with maple hardwood, jack pine softwood, and corn stover. Essentially, the chars were prepared in two different methods.

The chars in the first series of experiments were obtained by devolatilization in nitrogen (1 atm) in the temperature range of 1350° to 1700°F. These were reported previously.[2] The rate of heating was ~20°F/min, and the chars were kept at the maximum temperature for 30 minutes. The reactivity of the chars produced under these slow heating conditions is recognized to differ from that of chars produced in-situ, that is, at high heat-up rates in the gasification reactor. Experience with other carbonaceous materials indicates that the chars obtained under slow heating conditions have a lower reactivity than chars obtained under high heating rates where only a very short time is allowed for char stabilization. The justification of using the laboratory-produced or stabilized chars in the initial experimentation, however, is that their mode of generation is well defined. As their reactivity could be lower than that of the chars produced in-situ, using their reactivity data to estimate the residence time in the PRU reactor would yield a conservative value for the residence time.

A subsequent series of experiments were conducted with in-situ chars produced directly inside the thermobalance reactor. A procedure was devised

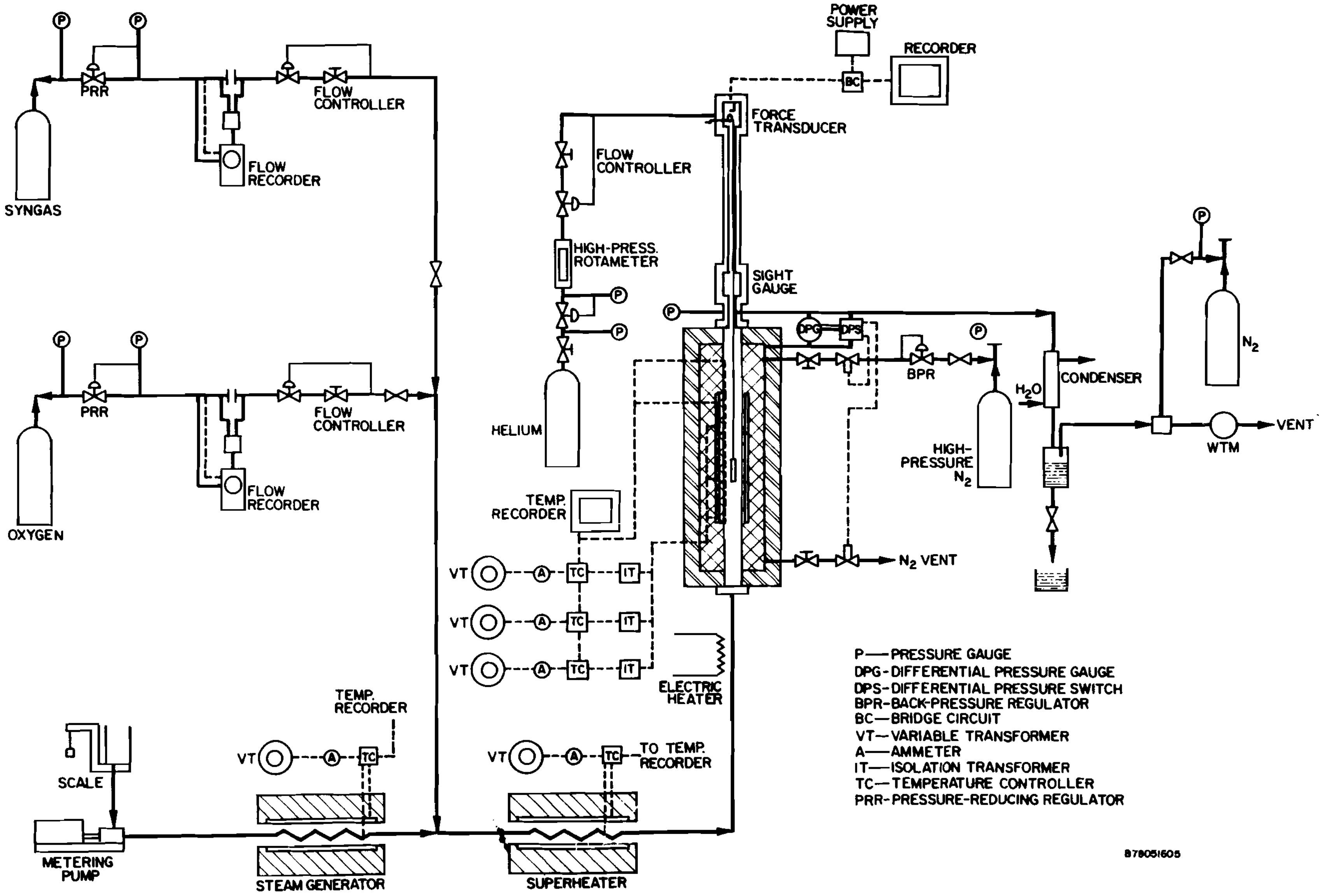


Figure 14. SCHEMATIC FLOW DIAGRAM FOR THE THERMOBALANCE REACTOR SYSTEM

to run the raw biomass materials in the thermobalance reactor and to separate the change in weight due to devolatilization from the change due to char carbon gasification.

The raw biomass (~1 gram) was placed in a wire mesh basket and put into the cooler, near room temperature, upper chamber region of the thermobalance reactor. The preselected temperature, pressure, and gas medium were established in the lower region; then the basket was quickly lowered into it and the weight change continuously monitored. The principal mode of heating is radiation; hence, the heat-up rate was expected to be quite high. In this method, the char produced in-situ reacted immediately upon devolatilization.

A parametric study of the rate of gasification of the in-situ chars of the three representative biomass materials similar to that for the stabilized chars was completed in this program. The corn stover char behavior, as with the stabilized chars, was different from that of chars of maple or jack pine.

Maple Hardwood and Jack Pine Results

Gasification of the in-situ chars of maple and jack pine was conducted in three steam-hydrogen mixtures: 1) 5% H_2 + 45% He + 50% H_2O, 2) 10% H_2 + 40% He + 50% H_2O, and 3) 25% H_2 + 25% He + 50% H_2O.

The experimental results showing the char weight-loss fraction (dry ash-free basis) with reaction time at various temperatures are shown in Figures 15 through 17 for maple hardwood and in Figures 18 through 20 for jack pine. In addition, using the first steam-hydrogen mixture, the effect of pressure on the rate of gasification was studied with maple hardwood and is also shown in Figure 15. Two effects may be present to produce the behavior shown by the 10-psig data. One is that the rate or slope at 10 psig is lower because of the strong dependence of the rate on the partial pressure of steam; the pressures of 100 and 300 psig significantly increase the rate. The second effect is that the initial amount of devolatilization or initial weight loss producing the in-situ char is greater at lower pressures.

The experimental results of gasification of maple hardwood and jack pine chars were analyzed and described with the first order rate expression —

$$\frac{dX_c}{dt} = k\,(1 - X_c) \tag{1}$$

or

$$-\ln\,(1 - X_c) = kt \tag{2}$$

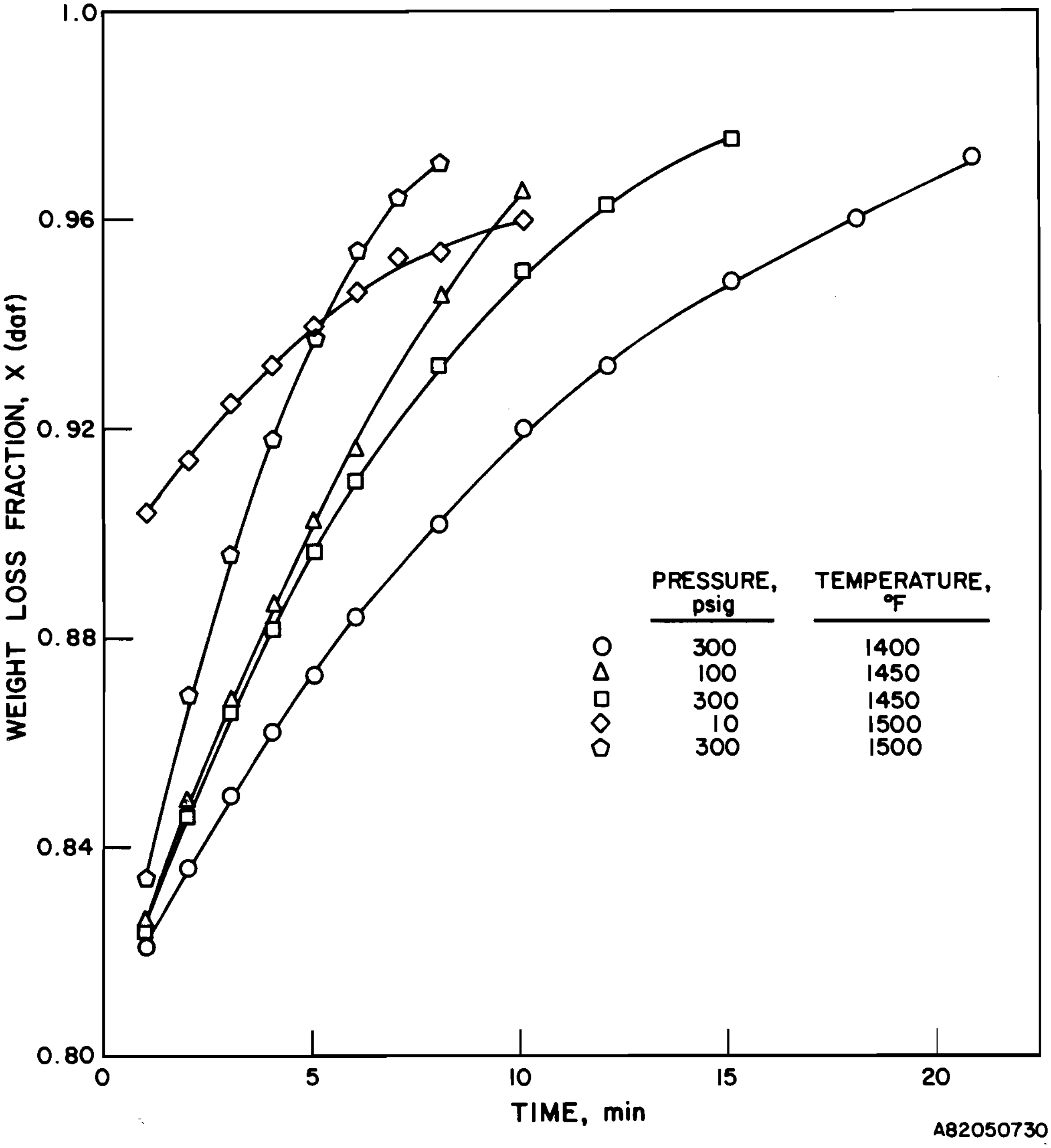


Figure 15. GASIFICATION OF IN-SITU CHAR FROM MAPLE HARDWOOD (-12+16 Mesh) IN 5% H_2 + 45% He + 50% H_2O

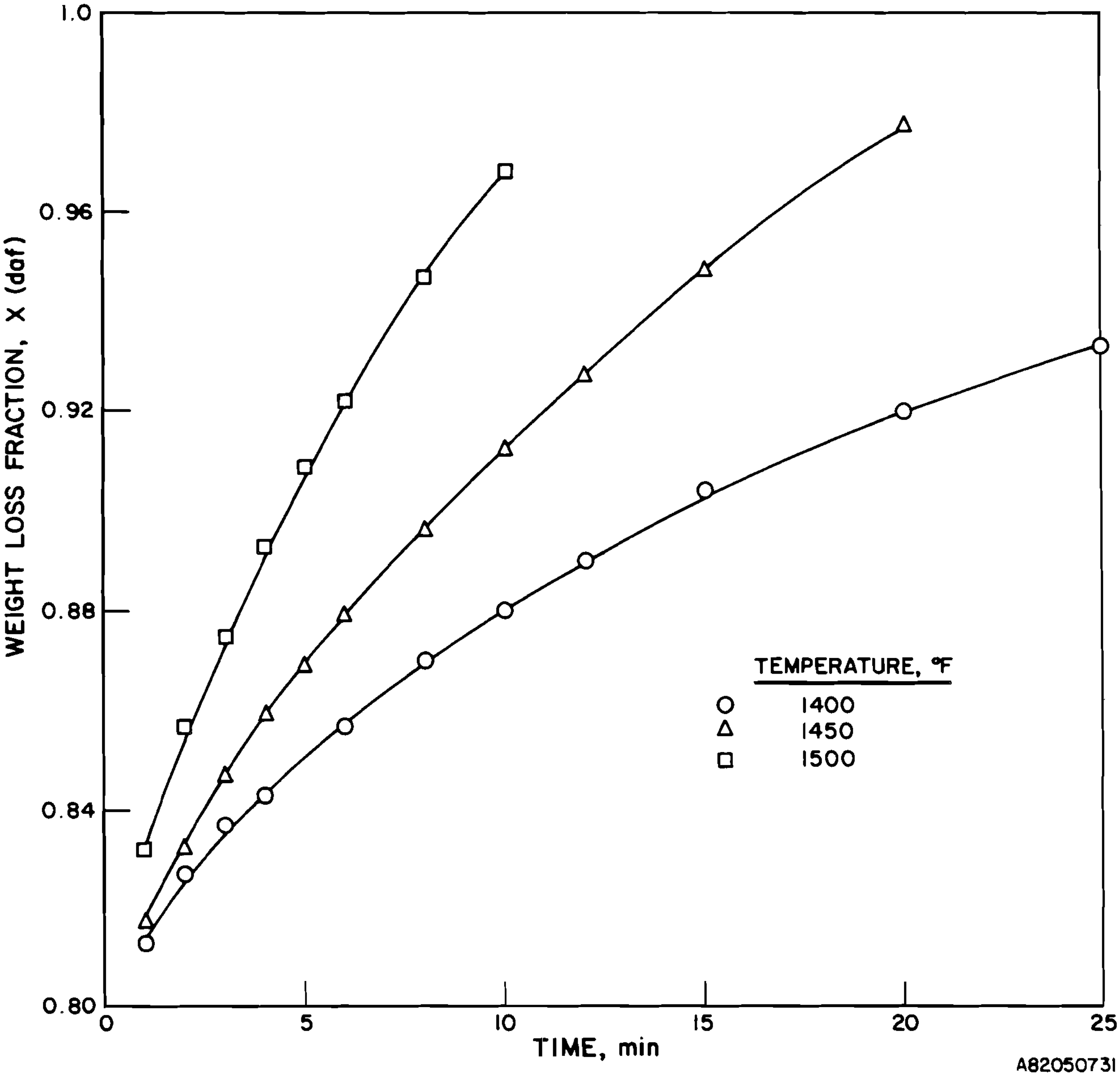


Figure 16. GASIFICATION OF IN-SITU CHAR FROM MAPLE HARDWOOD (-12+16 Mesh) IN 10% H_2 + 40% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPERATURES

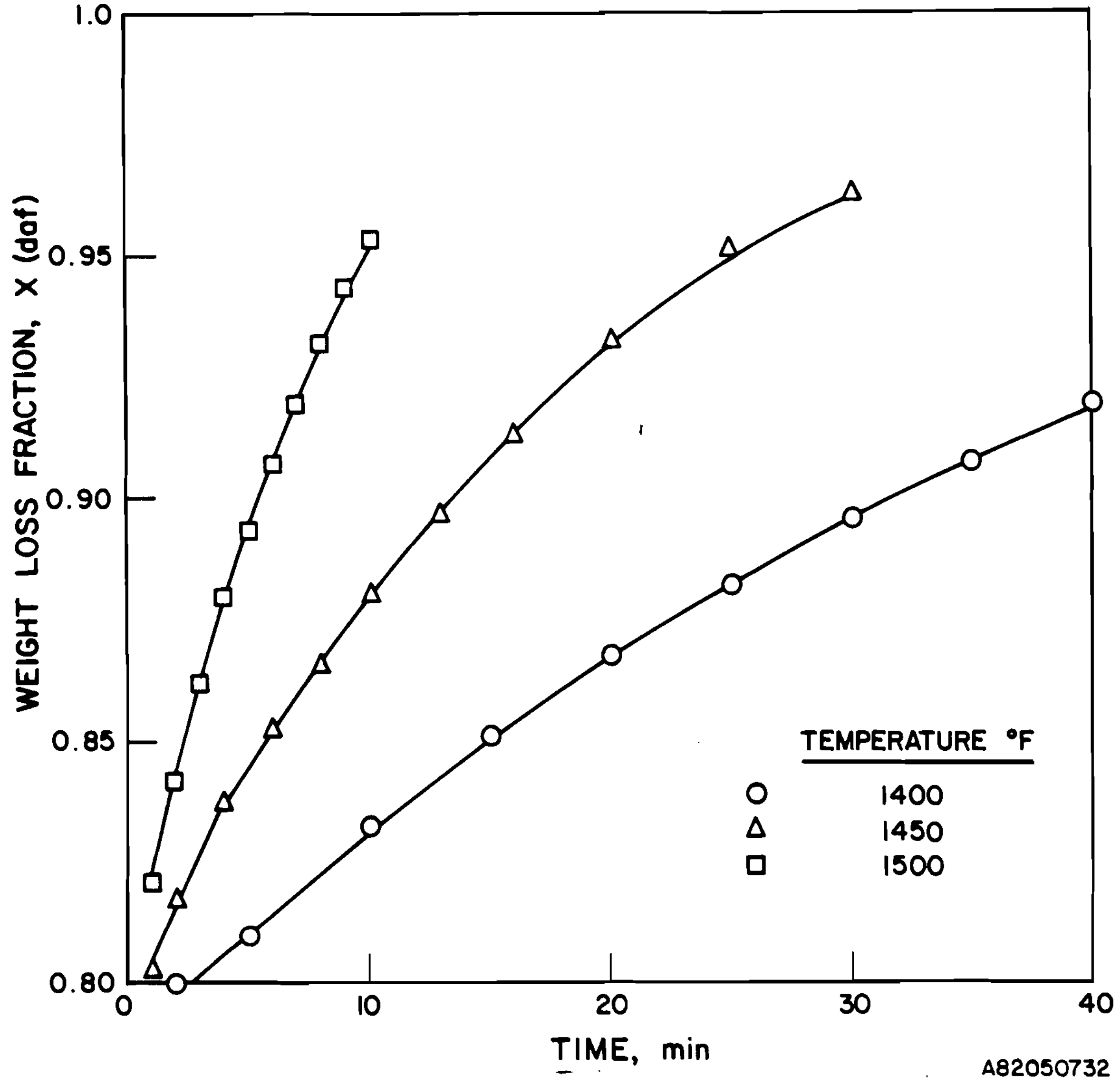


Figure 17. GASIFICATION OF IN-SITU CHAR FROM MAPLE HARDWOOD (-12+16 Mesh) IN 25% H_2 + 25% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPERATURES

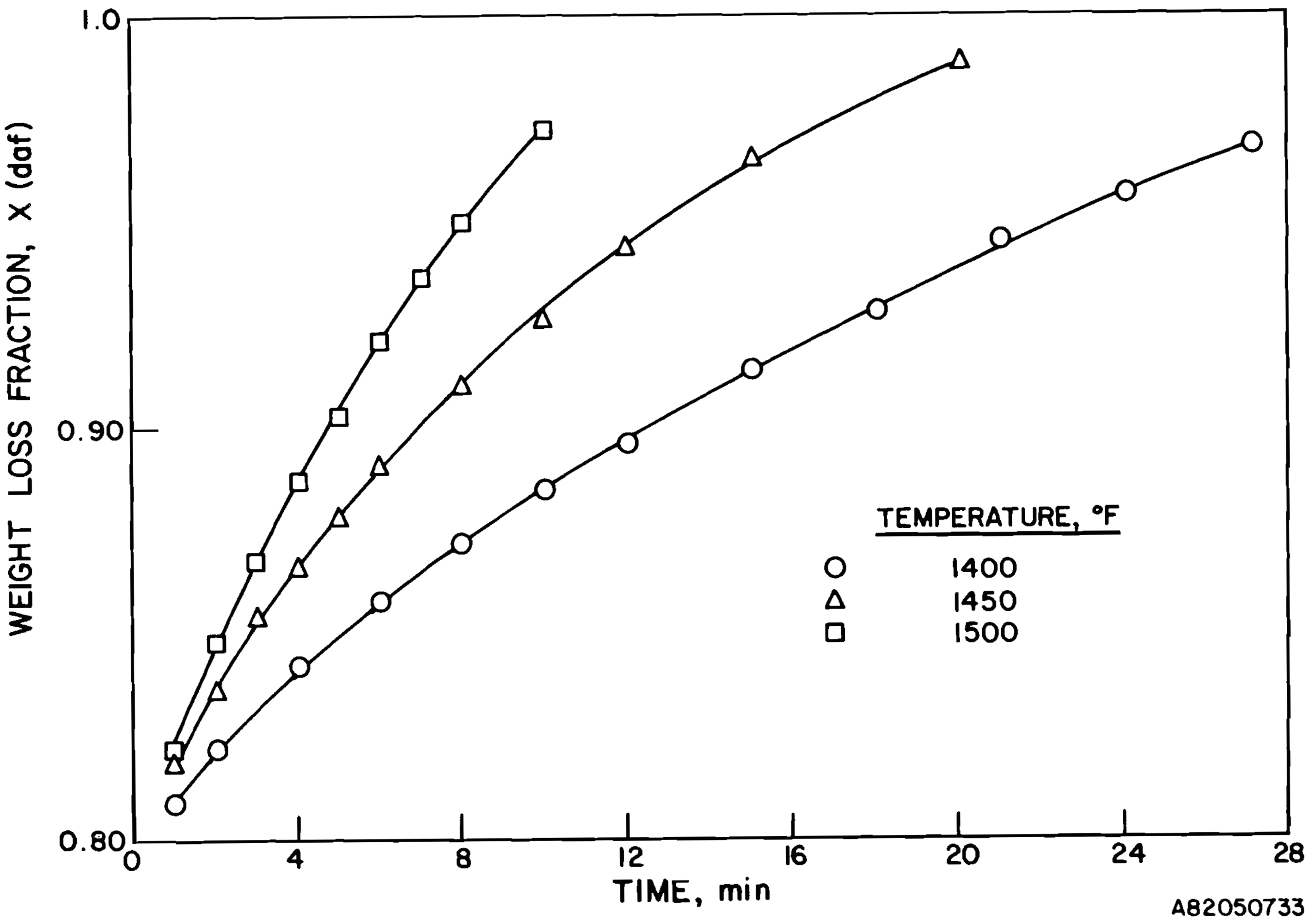


Figure 18. GASIFICATION OF IN-SITU CHAR FROM JACK PINE (-12+16 Mesh) IN 5% H_2 + 45% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPEATURES

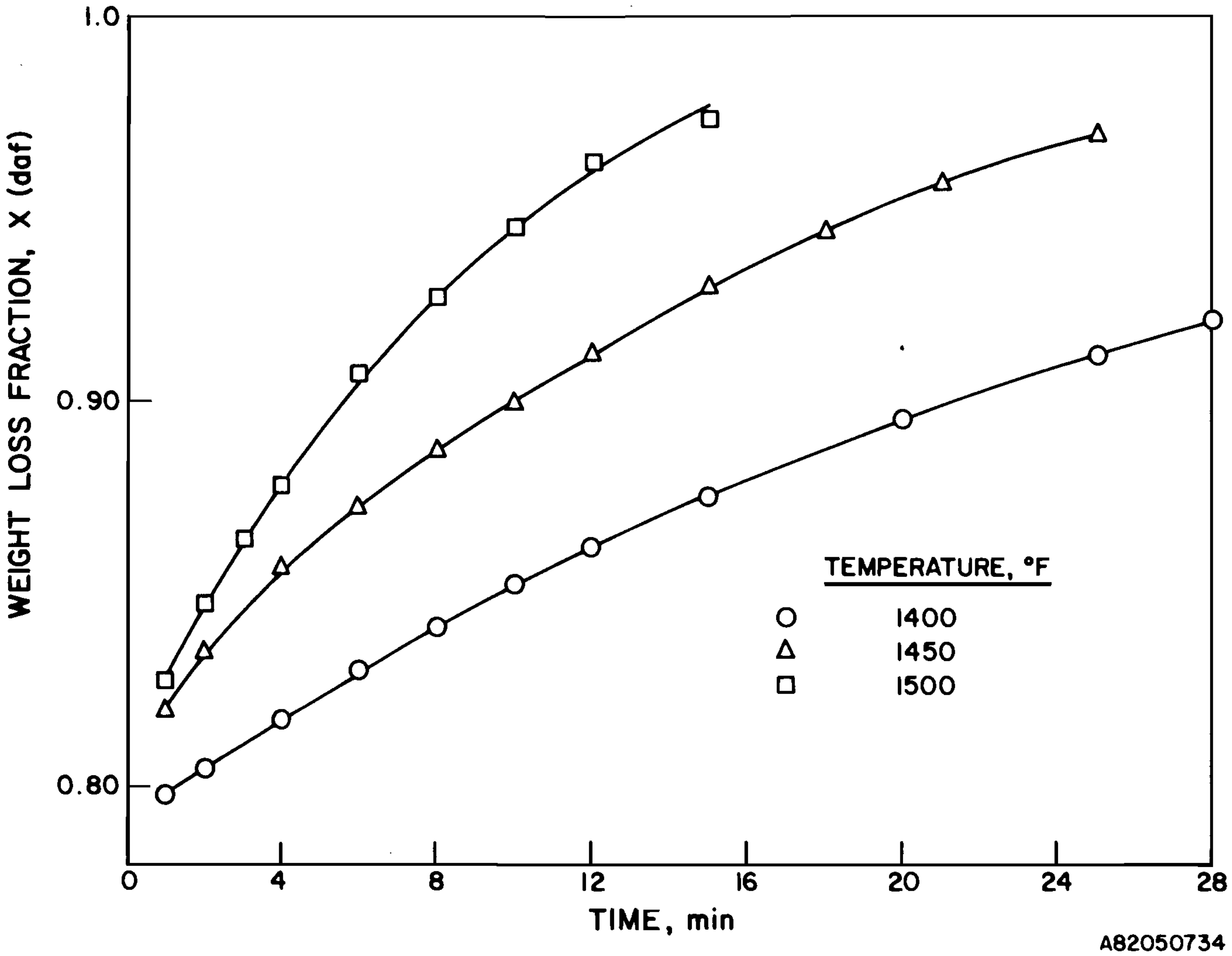


Figure 19. GASIFICATION OF IN-SITU CHAR FROM JACK PINE (-12+18 Mesh) IN 10% H_2 + 40% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPERATURES

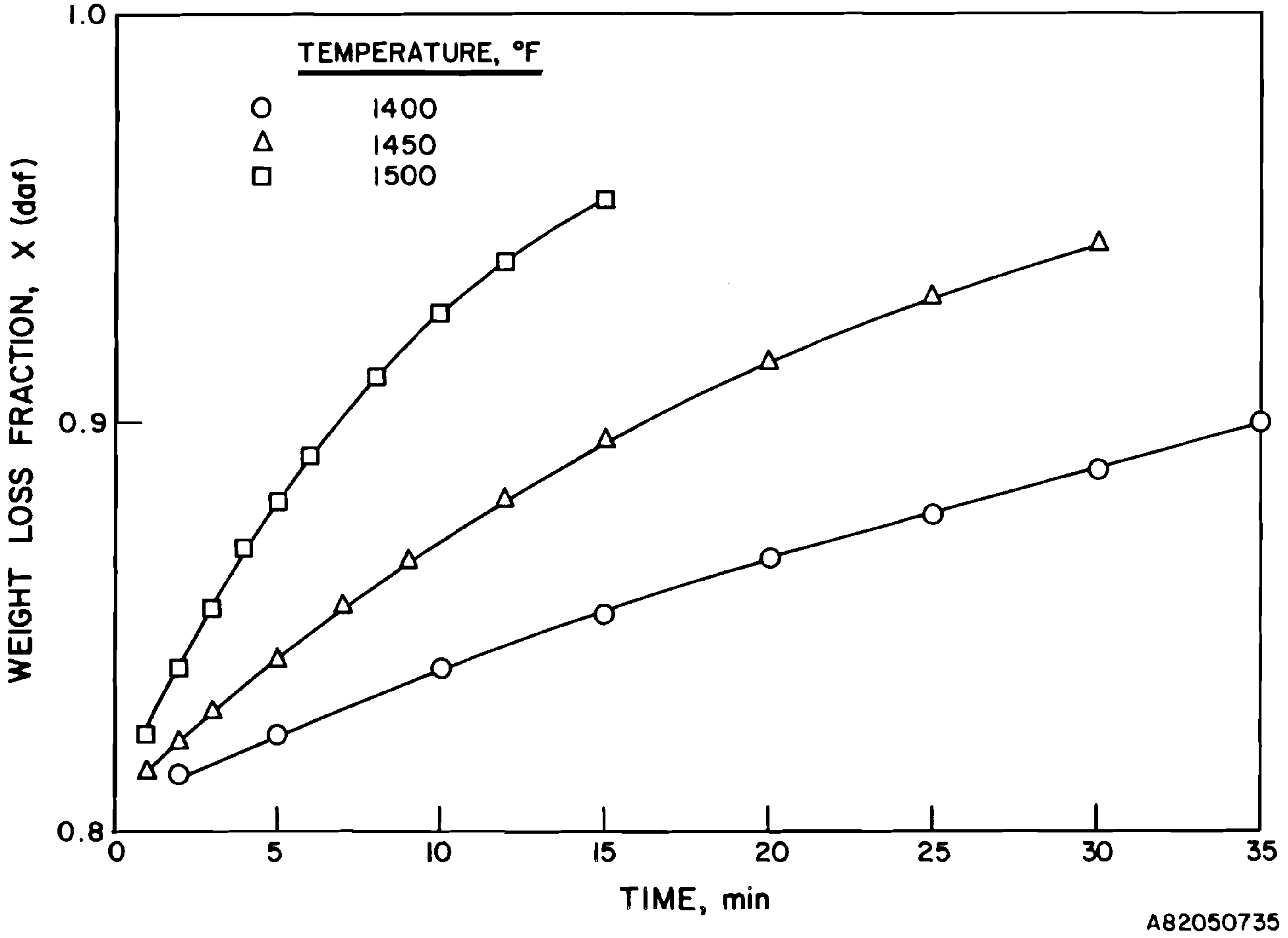


Figure 20. GASIFICATION OF IN-SITU CHAR FROM JACK PINE (-12+16 Mesh) IN 25% H_2 + 25% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPERATURES

where —

X_c = weight loss fraction of char (daf)

t = time, min

k = reaction rate constant, $\min^{-1}$

When starting with a raw wood sample to study "in-situ" char gasification the following definitions were used.

X = total weight loss fraction (daf) of feed

X^* = weight loss of feed due to devolatilization

Therefore, the char carbon fraction is expressed as

$$X_c = (X - X^*)/(1 - X^*) \tag{3}$$

and from Equations 2 and 3

$$-\ln (1 - X) = -\ln (1-X^*) + kt \tag{4}$$

Figure 21 is a plot according to Equation 4 of the typical experimental results shown in Figure 16. The data follow the straight lines, showing that the gasification reactions are nearly first-order. The analyses and conclusions above were similar for all the experimental results presented in Figures 15 through 20.

The values of all the first-order reaction rate constants, k, for maple and jack pine chars are presented in Table 9. The effect of pressure on k was determined with the gas composition 5% H_2 + 45% He + 50% H_2O for maple hardwood. The rest of the tests were conducted at 300 psig.

The Arrhenius equation was used to determine the apparent activation energy of the char gasification process in different gas mixtures:

$$k = A \cdot e^{-E/RT} \tag{5}$$

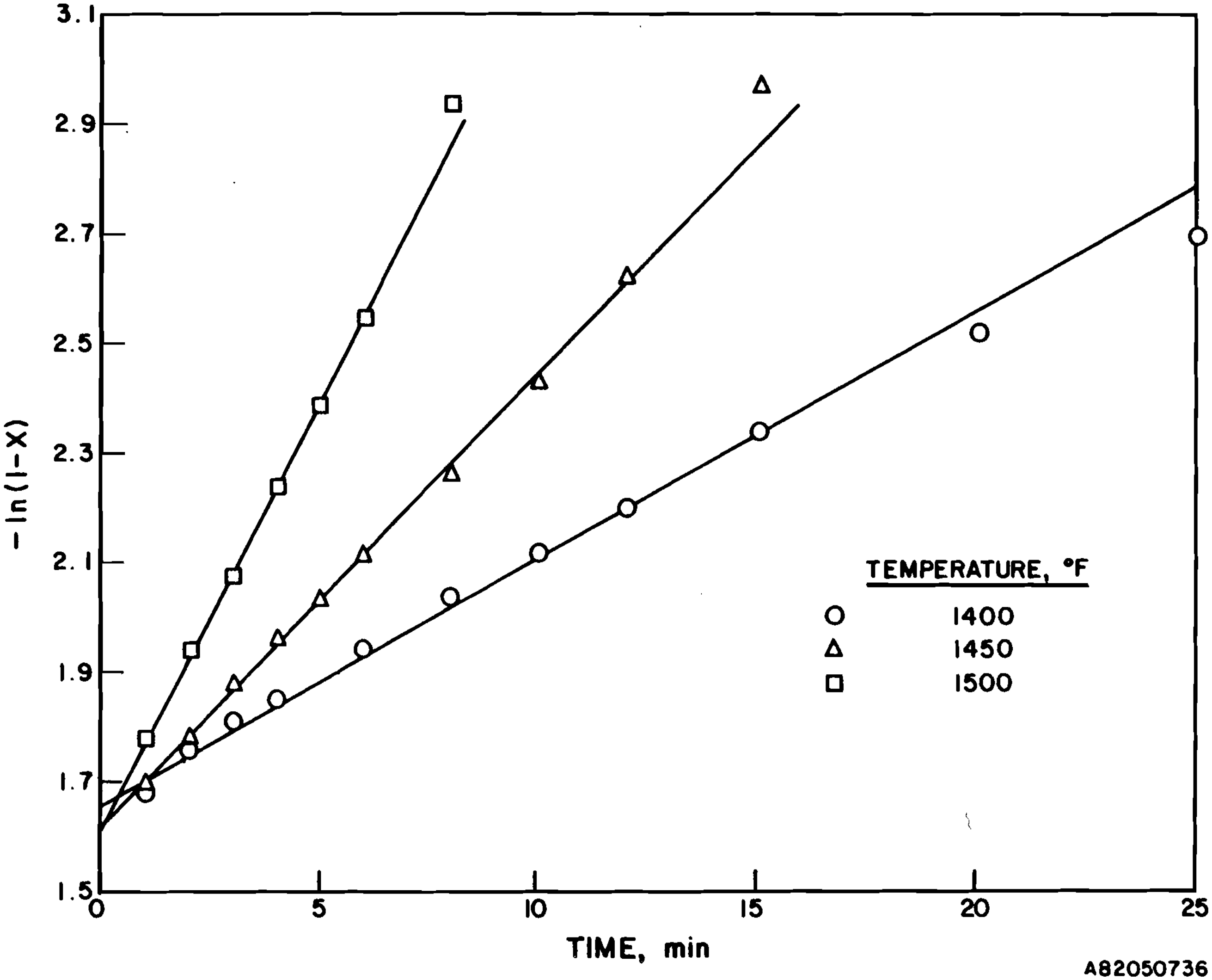
where —

A = preexponential factor

E = apparent activation energy

R = gas constant

T = temperature, °R



A82050736

Figure 21. GASIFICATION OF MAPLE HARDWOOD CHAR (−12+16 Mesh) IN GAS MIXTURE (10% H_2 + 40% He + 50% H_2O) AT A PRESSURE OF 300 psig AND AT DIFFERENT TEMPERATURES — FIRST-ORDER PLOT

Table 9. REACTION RATE CONSTANT FOR THE GASIFICATION OF MAPLE HARDWOOD AND JACK PINE CHARS IN STEAM-HYDROGEN-HELIUM MIXTURES

Temperature, °F	Pressure, psig	Gas Composition 50% H_2O + 5% H_2 + 45% He	 50% H_2O + 10% H_2 + 40% He	 50% H_2O + 25% H_2 + 25% He
		First-Order Rate Constant (k), min^{-1}		
Maple Hardwood				
1400	300	0.086	0.047	0.024
1450	300	0.135	0.084	0.055
1450	100	0.142	--	--
1500	300	0.230	0.161	0.130
1500	10	0.119	--	--
Jack Pine				
1400	300	0.057	0.035	0.018
1450	300	0.101	0.069	0.040
1500	300	0.155	0.123	0.097

Taking the logarithm of Equation 5 yields —

$$\ln k = \ln A - \frac{E}{R} \cdot \frac{1}{T} \tag{6}$$

The data for maple hardwood are plotted according to the Arrhenius equation in Figure 22. Figure 23 is a similar plot for jack pine. The calculated values of E (apparent activation energy) and A (preexponential factor) are given in Table 10. The values obtained from the earlier steam gasification (50% H_2O + 50% N_2) are also included for comparison. The value of k decreases with an increase in hydrogen concentration in this temperature range. At the same time, the apparent activation energy also increases with an increase in hydrogen concentration.

Table 10. APPARENT ACTIVATION ENERGY FOR THE GASIFICATION OF MAPLE HARDWOOD AND JACK PINE CHARS IN STEAM-HYDROGEN-HELIUM MIXTURES

	A, min^{-1}	E, Btu/lb-mol
Gas Composition		
Maple Hardwood		
50% H_2O + 50% N_2	2.56×10^7	72,000
50% H_2O + 5% H_2 + 45% He	2.44×10^7	72,500
50% H_2O + 10% H_2 + 40% He	9.87×10^8	88,500
50% H_2O + 25% H_2 + 25% He	2.14×10^{12}	119,500
Jack Pine		
50% H_2O + 50% N_2	2.14×10^7	72,200
50% H_2O + 5% H_2 + 45% He	3.71×10^7	75,500
50% H_2O + 10% H_2 + 40% He	1.97×10^9	92,000
50% H_2O + 25% H_2 + 25% He	1.42×10^{12}	119,000

Corn Stover Results

A densified corn stover sample received from the University of California-Davis as 1-1/4-inch cubical pellets was ground to obtain a fraction of -12+16 mesh size for gasification tests. The ash content of this particular fraction was 7.75 weight percent, dry basis. As shown in previous characterization tests, the ash content of the total sample is probably higher in this fraction and is also expected to be greater in the smaller size fractions.

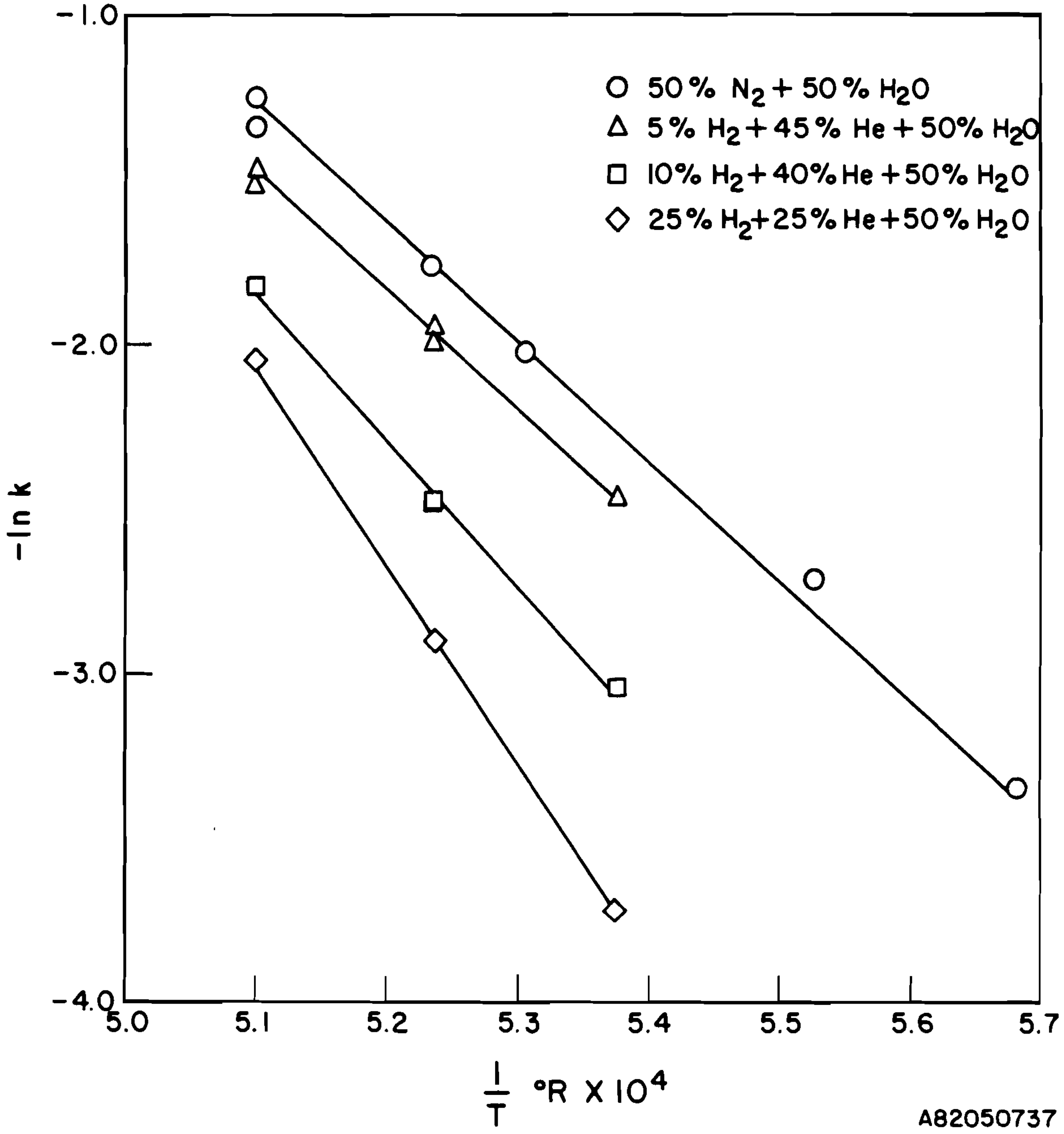


Figure 22. GASIFICATION OF MAPLE HARDWOOD CHAR (-12+16 Mesh) IN DIFFERENT GAS MEDIA — ARRHENIUS PLOT

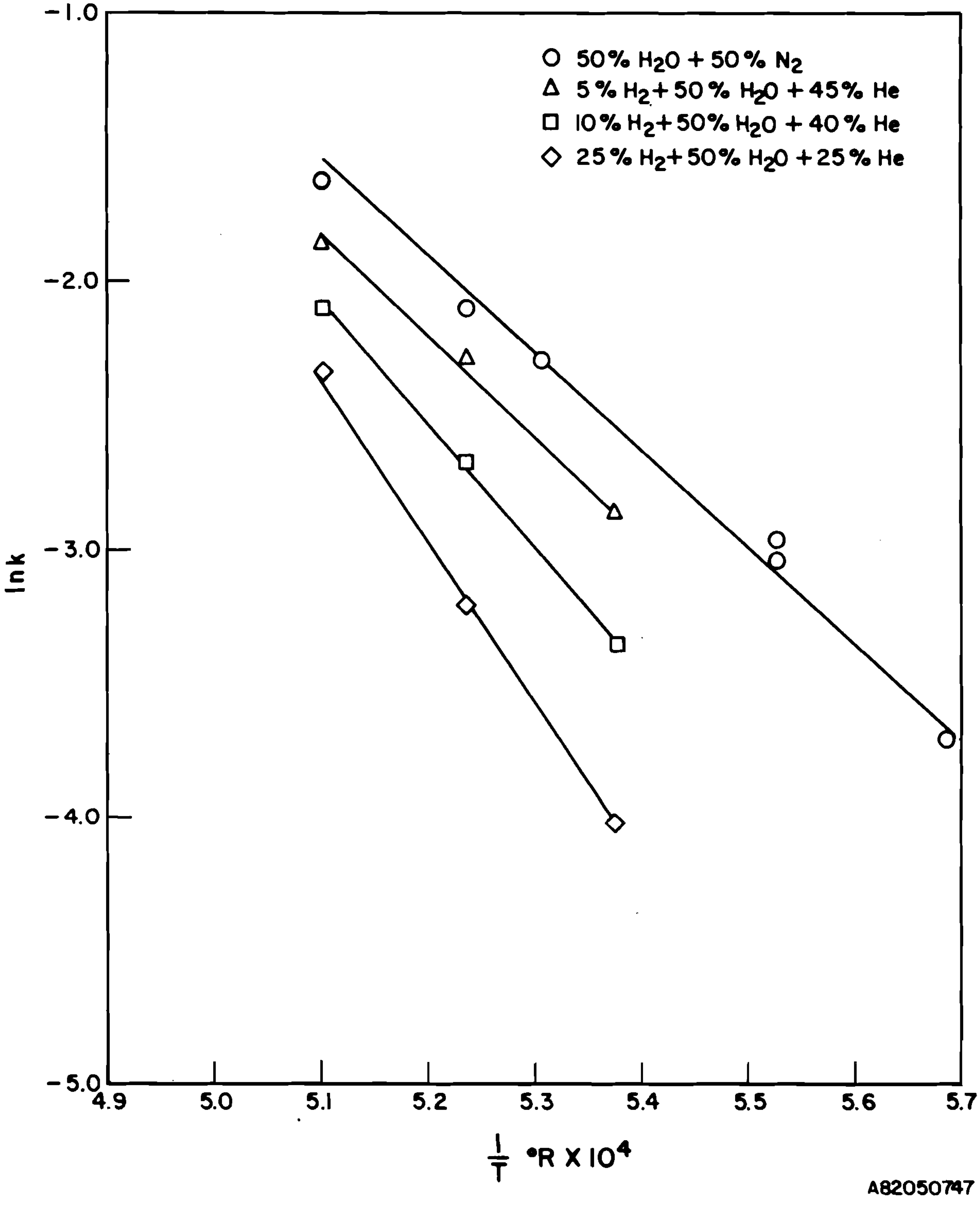


Figure 23. GASIFICATION OF JACK PINE CHAR (−12+16 Mesh) IN DIFFERENT GAS MEDIA — ARRHENIUS PLOT

The gasification experiments were conducted in the temperature range from 1300° to 1700°F at a pressure of 300 psig according to the in-situ procedure described earlier. Three gasification media were used for corn stover char with the following compositions, 1) 50% H_2O and 50% N_2; 2) 50% H_2O, 5% H_2, and 45% He; and 3) 50% H_2O, 10% H_2, and 40% He.

The experimental results for the ground sample of the densified corn stover cubes are presented in Figures 24 through 27 for various temperatures. The weight-loss fractions (daf) are plotted against reaction time in these figures. The gasification characteristics of the in-situ chars from the corn stover sample are markedly different from those of maple and jack pine, as was concluded also from the previous experimentation with the laboratory-prepared or stabilized chars of the biomass materials.

The calculated function $-\ln(1-X)$, when plotted, illustrates how the first-order equation used for the woody materials represents the corn stover data poorly and indicates a different behavior. Figure 28 is a typical plot of $-\ln(1-X)$ versus reaction time, t, for reaction Medium 2. For gasification temperatures 1600° and 1700°F, the experimental points are nearly linear, that is, at 1600°F or higher temperatures, the reaction was nearly first-order in X. The gasification characteristics for the other mixtures with corn stover char are qualitatively similar to that shown in Figure 26.

This initial attempt of the analysis of the corn stover data by a first-order model did not describe the behavior adequately over all times or conversions. The model did not describe the complete gasification range (that is, all values of X). To account for the overall kinetic behavior of densified corn stover, another model was developed, which is similar to that developed for lignite gasification.[7] It is based on the assumption that two types of entities exist in the feed and are gasified sequentially. Let —

X = total feed conversion, dry ash-free basis

X_o = total conversion due to devolatilization

Y = conversion of char.

From these definitions, then —

$$Y = (X - X_o)/(1 - X_o) \qquad (7)$$

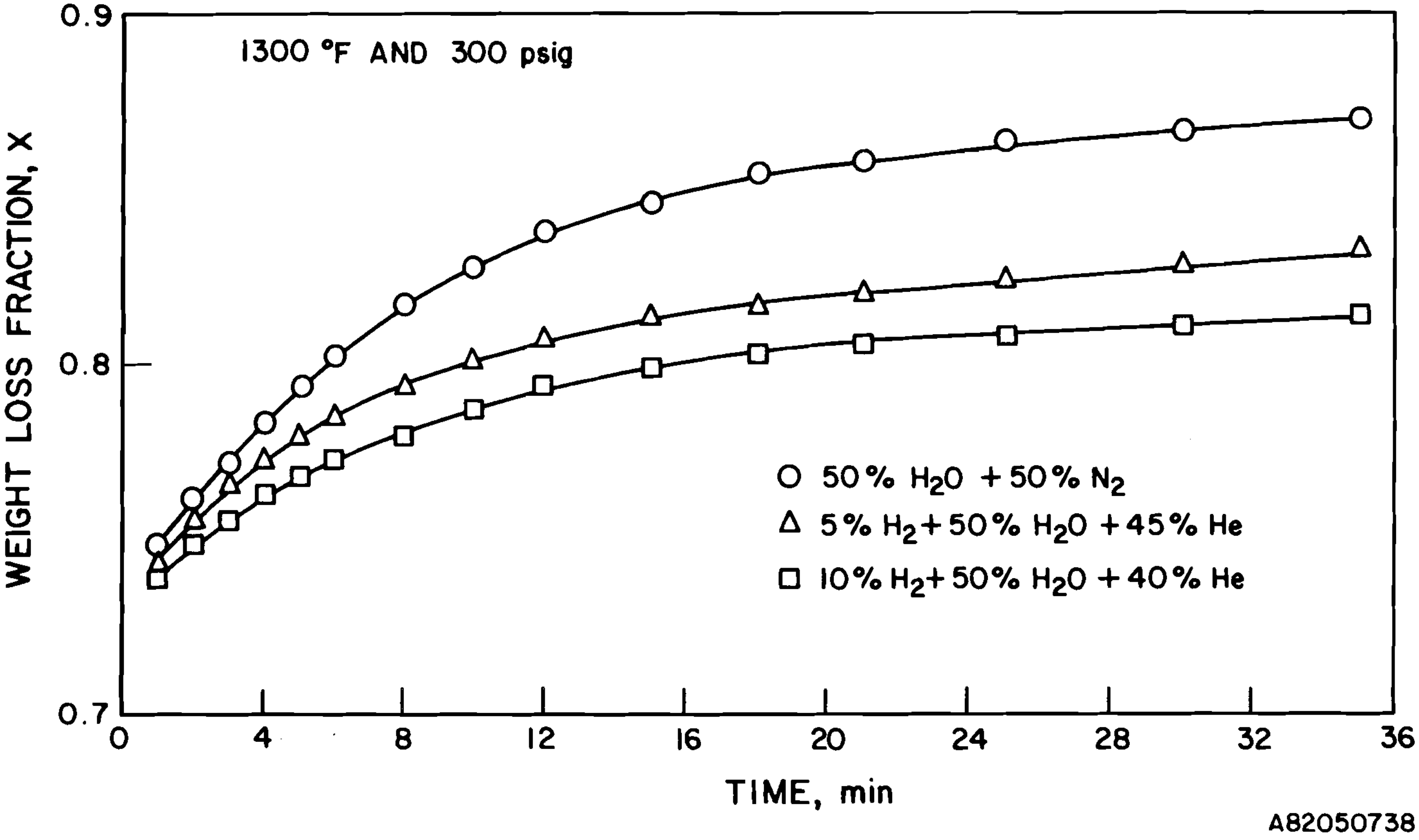


Figure 24. GASIFICATION OF IN-SITU CHAR FROM DENSIFIED CORN STOVER AT 1300° AND AT A PRESSURE OF 300 psig WITH DIFFERENT REACTION GAS MEDIA

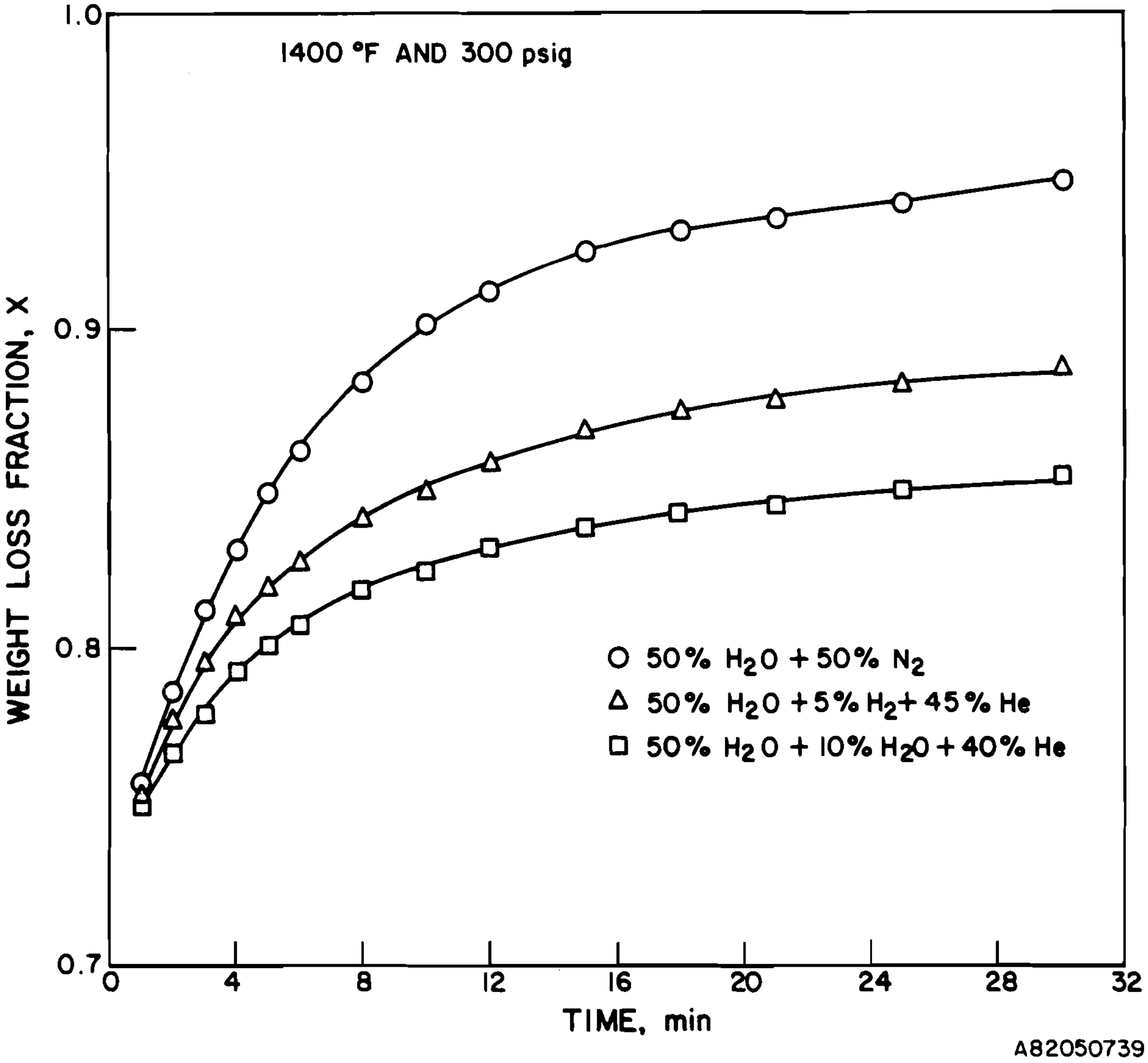


Figure 25. GASIFICATION OF IN-SITU CHAR FROM DENSIFIED CORN STOVER AT 1400°F AND AT A PRESSURE OF 300 psig WITH DIFFERENT REACTION GAS MEDIA

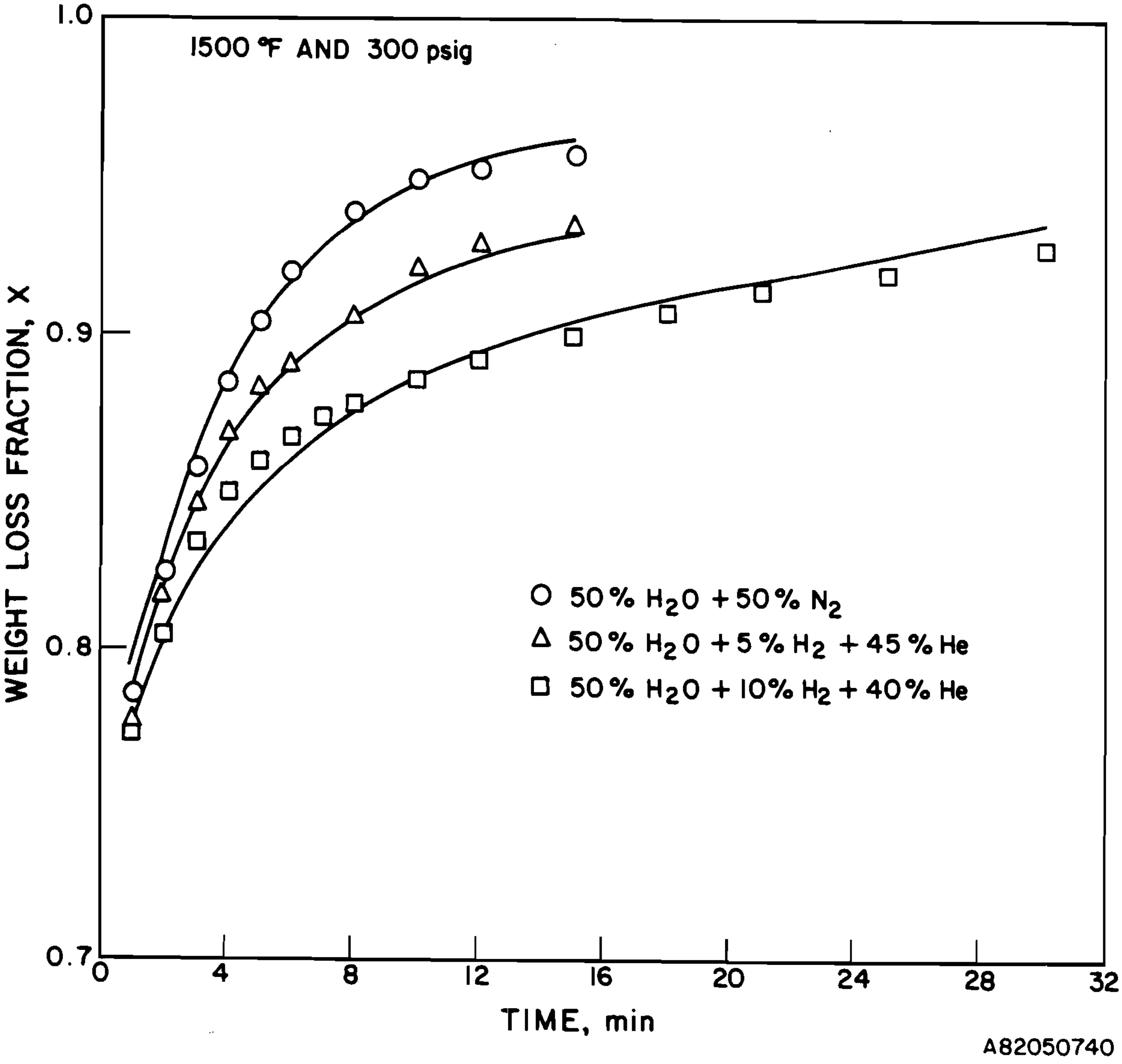
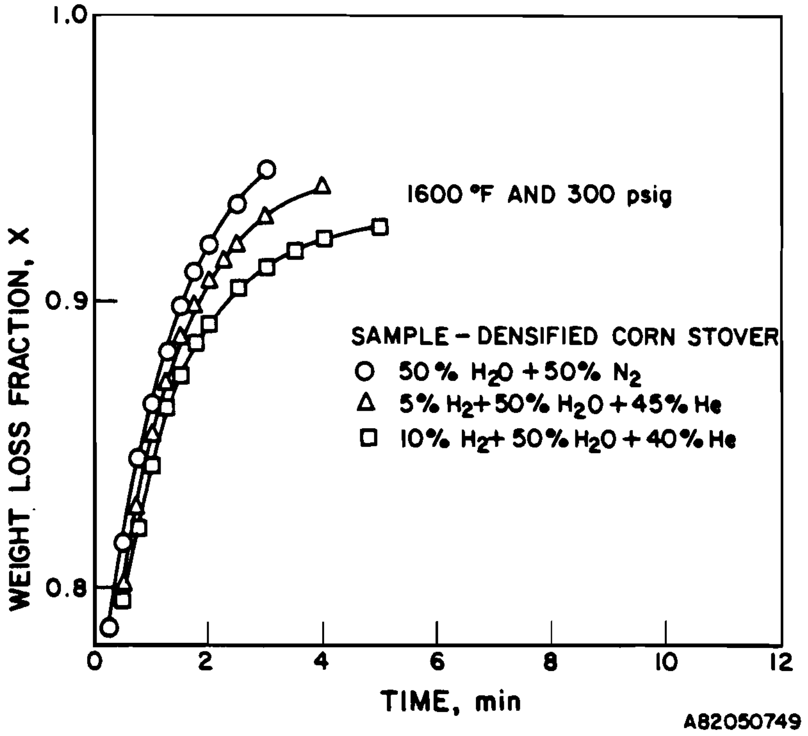


Figure 26. GASIFICATION OF IN-SITU CHAR FROM DENSIFIED CORN STOVER AT 1500°F AND AT A PRESSURE OF 300 psig WITH DIFFERENT REACTION GAS MEDIA



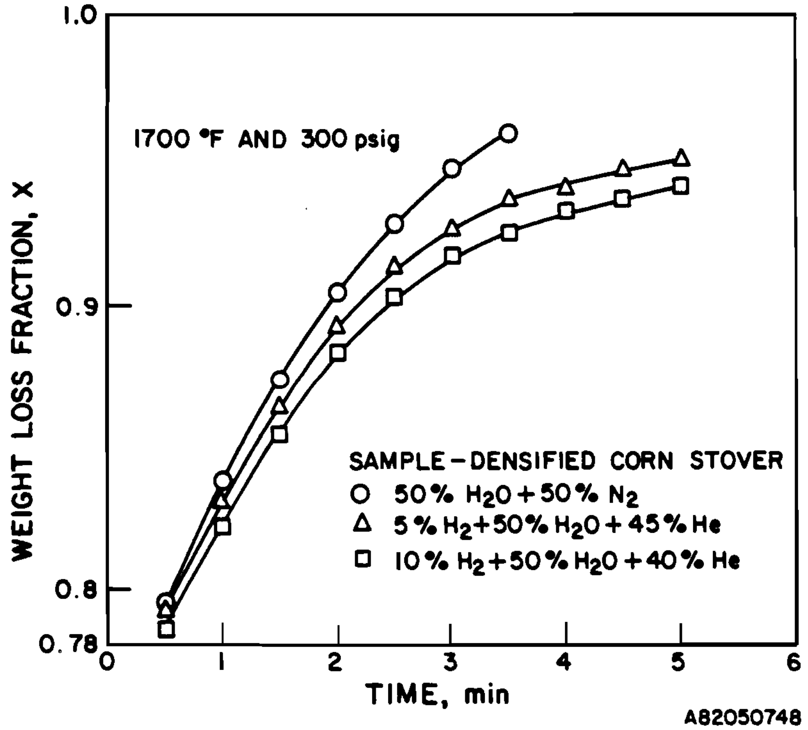


Figure 27. GASIFICATION OF IN-SITU CHAR FROM DENSIFIED CORN STOVER AT 300 psig WITH DIFFERENT REACTION GAS MEDIA

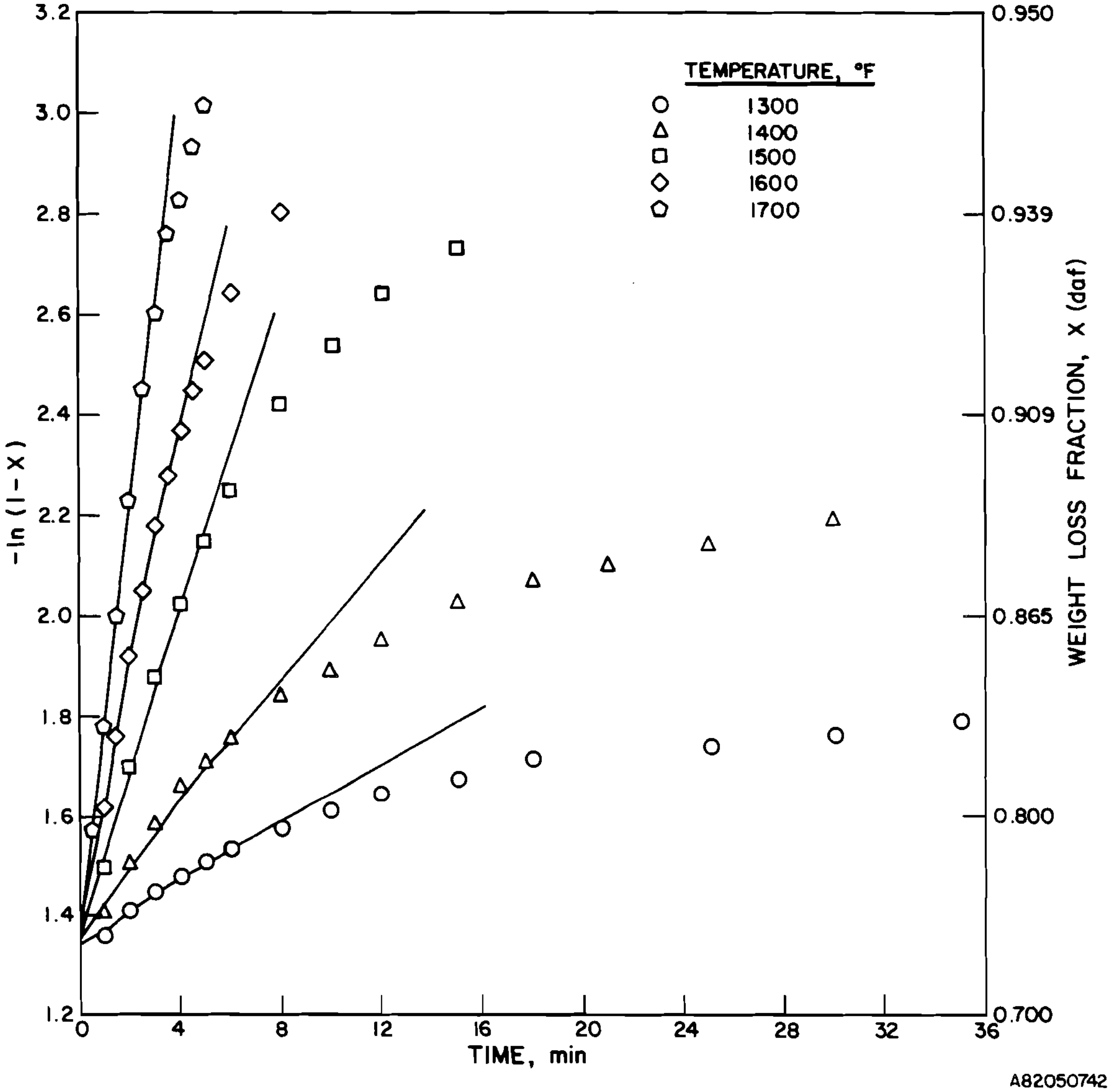


Figure 28. GASIFICATION OF IN-SITU CHAR FROM DENSIFIED CORN STOVER WITH 50% H_2O, 5% H_2, and 45% He AT A PRESSURE OF 300 psig AND AT DIFFERENT TEMPERATURES — LIMITATIONS OF FIRST-ORDER FIT

Hence, the proposed model assumes that the char can gasify by two routes:

$$\text{Char} \xrightarrow{K_2} \text{Gaseous Products} \qquad \text{(Reaction I)}$$

$$\text{Char} \xrightarrow[n^*]{K_1^*} \text{Gaseous Products} \qquad \text{(Reaction II)}$$

Reaction I is uncatalyzed first-order reaction. Reaction II corresponds to a path in which some entity, n^*, catalyzes gasification. The rate of this reaction is K_1^*. The catalytic entity is assumed to be some structural component present in the char rather than some inorganic catalytic materials.

The overall gasification rate of the char is then described by the expressions —

$$dY/dt = (K_2 + K_1^* C_{n*}) (1-Y) \tag{8}$$

where —

C_{n*} = concentration of catalytic entity, n^*, in char

t = time, min.

Additionally, it is assumed that n^* deactivates by a first-order process, consistent with the expression —

$$dC_{n*}/dt = (-K_o^*) C_{n*} \tag{9}$$

where —

K^*_o = rate constant, min^{-1}.

Integrating Equation 9 at constant environmental conditions yields —

$$C_{n*} = C^o_{n*} \exp(-K_o^* t) \tag{10}$$

where —

C^o_{n*} = initial concentration of n^*.

Substituting Equation 10 into Equation 6 and integrating provides —

$$-\ln(1-Y) = K_2 t + \frac{K_1^* C^o_{n*}}{K_o^*} [1 - \exp(-K_o^* t)] \tag{11}$$

From Equation 7 —

$$- \ln (1-Y) = -\ln (1-X_o)/(1-X_o) \tag{12}$$

Therefore —

$$-\ln (1-X) = -\ln (1-X_o) + K_p [1 - \exp (-K_o^* t)] + K_2 t \tag{13}$$

where —

$$K_p = \frac{K_1^* C_{n*}^o}{K_o^*} \tag{14}$$

The experimental results presented in Figures 17 through 24 were analyzed via Equation 13, and the parameters K_p, K_o^* , and K_2 were evaluated for different gasification conditions. The values are given in Table 11. The value of $-\ln (1 - X_o)$ was equal to 1.34 under all experimental conditions, a result similar to that of the first-order approach. The data fit are clearly satisfactory as shown in Figures 29 and 30.

As mentioned earlier, gasification results of stabilized chars (chars prepared by separate devolatilization in nitrogen) of corn stover in a gas mixture of 50% H_2O, 5% H_2, and 45% He were reported previously. The data were reevaluated according to the model represented by Equation 13. As the stabilized char was devolatilized before gasification, the first term on the right-hand side of Equation 13 for the laboratory-prepared char will be zero. The other parameters of Equation 13 were evaluated from the experimental results for the gasification of stabilized chars from corn stover. The values are given in Table 12.

The values of the parameters shown in Table 12 were used to calculate the stabilized char curves shown in Figure 29; the experimental values of X are shown by data points. The fit appears satisfactory. Although Equation 13 is unquestionably empirical, it is useful as a model for estimating the residence time in a reactor for a certain conversion under known conditions.

Comparison of the parameters for gasification of _in-situ_ chars and stabilized chars in Tables 11 and 12 shows that the stabilized chars are less reactive than the _in-situ_ chars. This is graphically illustrated in Figure 30. The conversion for the _in-situ_ char at 1500°F appears to take about 1.5 times longer than for the stabilized chars.

Table 11. THE VALUES OF KINETIC PARAMETERS FOR THE GASIFICATION OF IN-SITU CHARS FROM DENSIFIED CORN STOVER IN DIFFERENT MEDIA

Temperature, °F	Medium 1 (50% H_2O and 50% N_2)			Medium 2 (50% H_2O, 5% H_2, and 45% He)			Medium 3 (50% H_2O, 10% H_2, and 40% He)		
	K_p	K_o^*	K_2	K_p	K_o^*	K_2	K_p	K_o^*	K_2
1300	0.40	0.14	0.0095	0.27	0.15	0.0051	0.18	0.14	0.0060
1400	0.60	0.17	0.0400	0.54	0.19	0.0105	0.35	0.18	0.0094
1500	0.86	0.20	0.0920	0.90	0.23	0.0330	0.66	0.22	0.0250
1600	Equation 13 not applicable			0.90	0.29	0.0850	0.85	0.28	0.0640
1700	Equation 13 not applicable			Equation 13 not applicable			0.90	0.40	0.1500

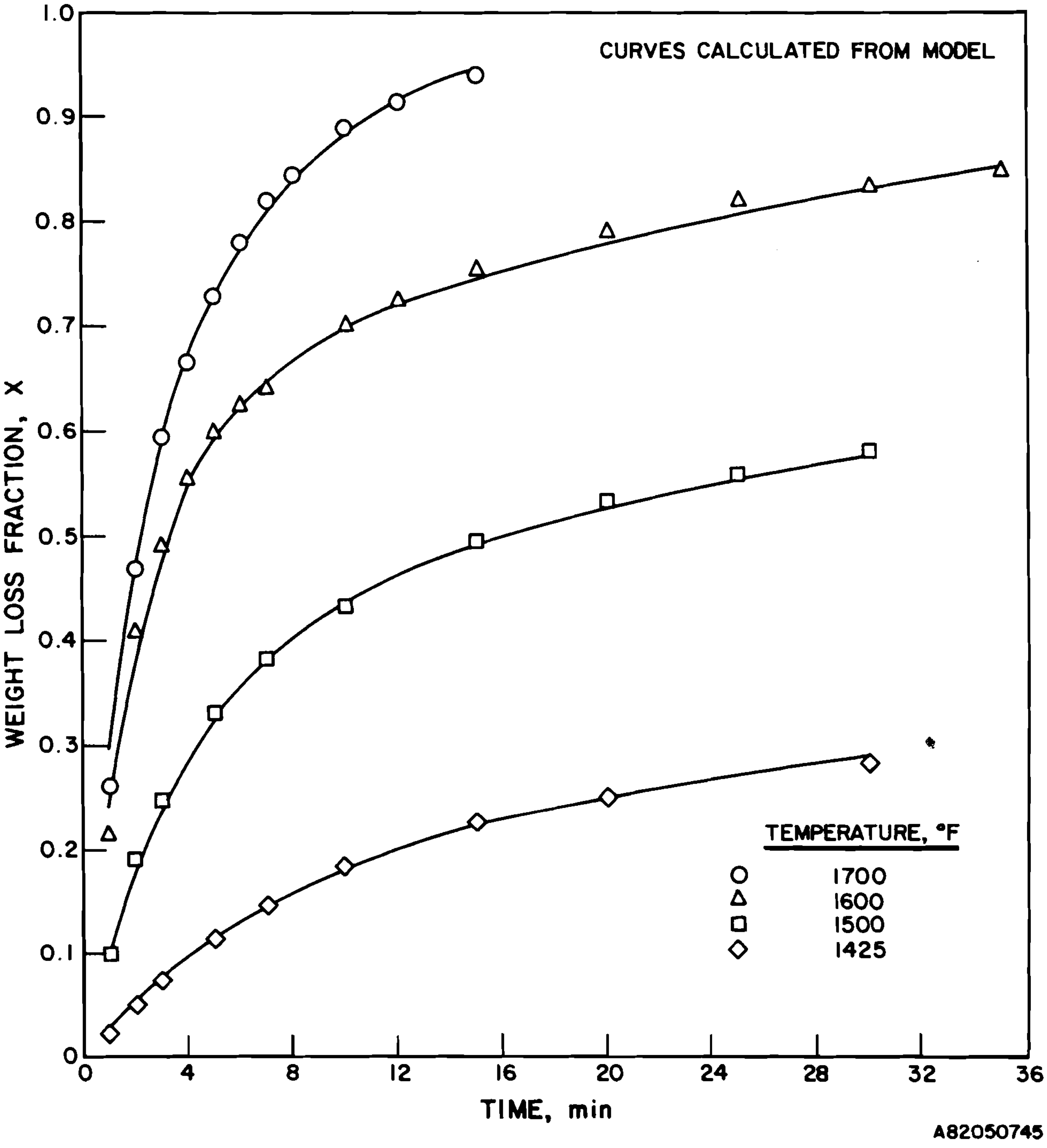


Figure 29. GASIFICATION OF STABILIZED CHAR FROM CORN STOVER WITH 5% H_2 + 45% He + 50% H_2O AT 300 psig AND AT DIFFERENT TEMPERATURES

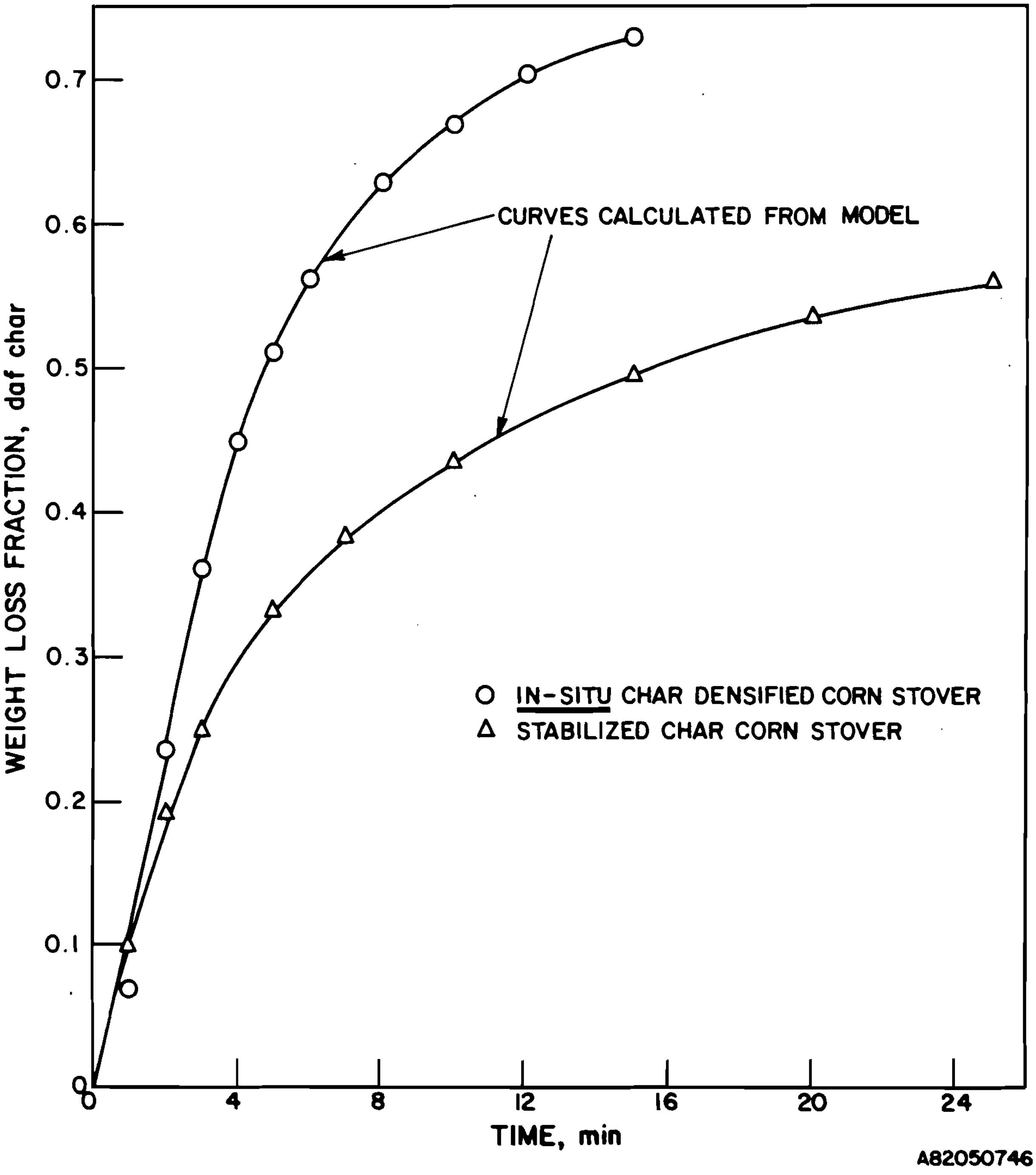


Figure 30. COMPARISON OF THE GASIFICATION OF STABILIZED CHAR FROM CORN STOVER WITH IN-SITU CHAR FROM DENSIFIED CORN STOVER AT 1500°F AND AT A PRESSURE OF 300 psig IN A GAS MIXTURE CONTAINING 5% H_2, 45% He, AND 50% H_2O

Figure 31 provides a comparison of the relative reactivities of the in-situ chars obtained from the three biomass species with that of peat char and of bituminous coal char. The in-situ chars of the biomass species, as is generally known, are much more reactive than the peat char, which in turn is more reactive than the bituminous coal char. In this study the in-situ biomass chars were found to be about 1.5 to 2.5 times more reactive than the stabilized, laboratory-prepared chars.

Table 12. THE VALUES OF THE KINETIC PARAMETERS FOR THE GASIFICATION OF STABILIZED CHARS FROM CORN STOVER IN 50% H_2O, 5% H_2, AND 45% He AT DIFFERENT TEMPERATURES

Temperature, °F	K_p	K_o^*	K_2
1425	0.24	0.12	0.0037
1500	0.54	0.20	0.0107
1600	0.98	0.30	0.0271
1700	0.60	0.40	0.1567

Char Surface-Area Measurements

The surface areas and total open pore volumes of the stabilized, laboratory-prepared chars of maple hardwood were determined. The chars were prepared by devolatilization of maple hardwood (-12+16 mesh) in nitrogen at various temperatures from 1350° to 1700°F.

An Arrhenius plot of the rate of gasification of the maple hardwood chars was linear for gasification temperatures from 1350° up to 1500°F. The linearly extrapolated value of the rate at 1700°F was higher, however, than the experimentally determined value. Table 13 lists the measured surface areas and pore volumes of the chars along with measurements of particle and true densities.

The nitrogen surface area was determined from adsorption of nitrogen at -320°F, using the BET equation. The carbon dioxide surface area was determined from the adsorption of carbon dioxide at 77°F with the Dubinin-Polanzi equation. The total open pore volume was calculated from the mercury density and helium density values of the chars.

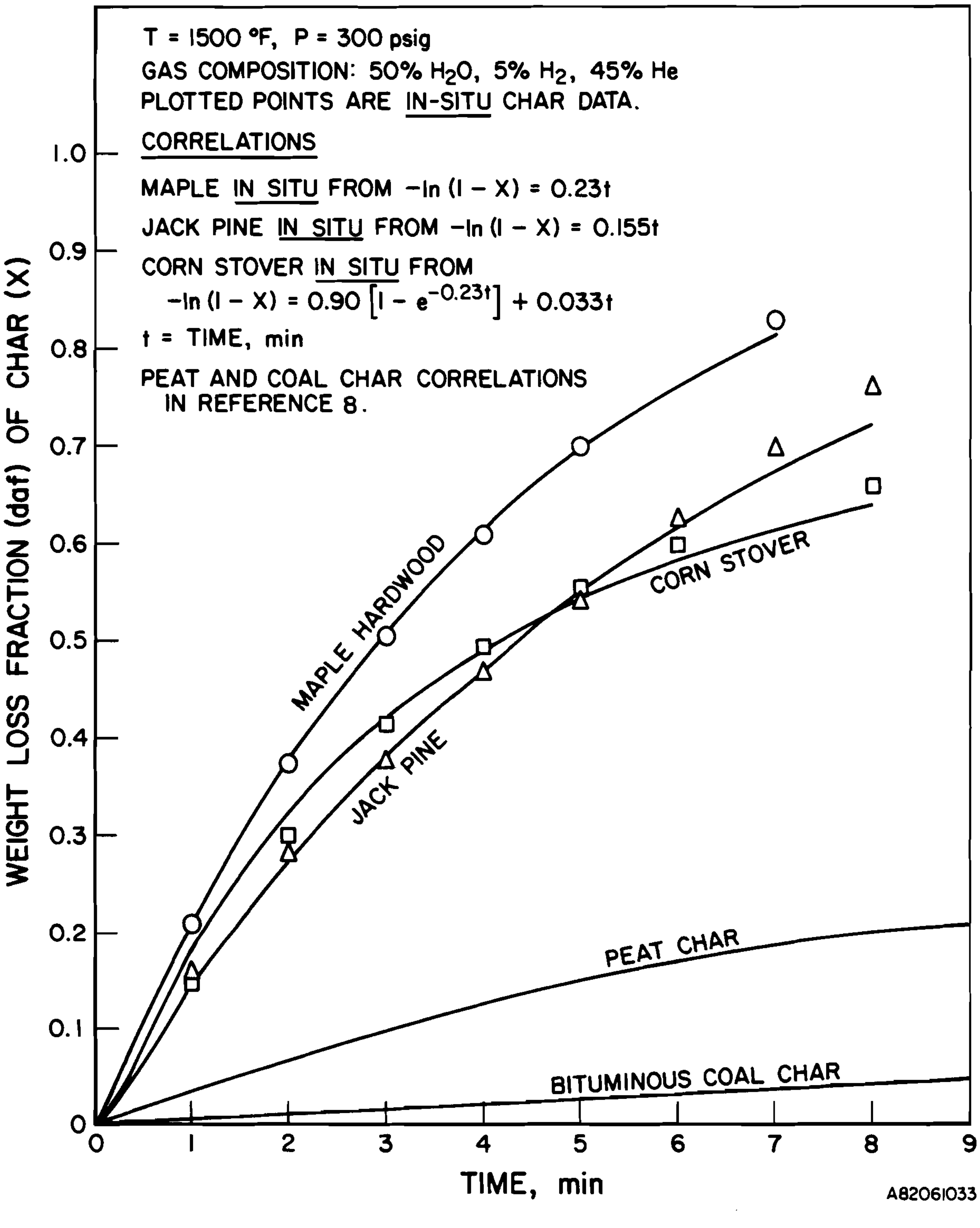


Figure 31. COMPARISON OF THE GASIFICATION RATES OF JACK PINE, MAPLE HARDWOOD, AND CORN STOVER IN-SITU CHARS WITH PEAT AND BITUMINOUS COAL CHARS

Table 13. SURFACE AREAS AND TOTAL OPEN PORE VOLUMES OF MAPLE HARDWOOD (-12+16 Mesh) CHAR

Devolatilization Temperature, °F	Nitrogen Surface Area, m^2/g	Carbon Dioxide Surface Area, m^2/g	Particle Density (by Mercury), g/cm^3	True Density (by Helium), g/cm^3	Total Open Pore Volume, cm^3/g
1200	58.1	676	0.44	1.58	1.64
1350	37.5	693	0.41	1.65	1.83
1425	46.2	640	0.42	1.72	1.80
1500	39.3	606	0.42	1.76	1.81
1600	13.3	680	0.42	1.76	1.81
1700	11.8	398	0.44	1.82	1.72

In general, the nitrogen surface area values are smaller than the carbon dioxide values. Similar differences between the nitrogen and carbon dioxide values have been observed for coals[9] and low-temperature coal chars.[10] It has been hypothesized that the nitrogen molecules at the low-temperature could not diffuse into all the micropores of coal and the low-temperature coal char. Hence, the carbon dioxide surface area, measured at room temperature, can be considered to account for most of the total surface area of the maple hardwoodchars. The nitrogen surface area can be considered to account for the geometric surface area of the particles plus the area of the relatively larger pores. It has been indicated[11] that the intermediate-sized pores (20Å to 40Å in diameter) work as a feeder or distributor for gas transport to the micropores.

As Table 13 shows that for maple hardwood laboratory-prepared chars, the carbon dioxide surface area values remain high up to a devolatilization temperature of 1600°F. The measured value decreases only for the 1700°F char. The change in the nitrogen surface area value was relatively small for the chars prepared at up to 1500°F, beyond which there is a significant decrease in the surface area values. The total open pore volumes of the chars as calculated remain almost unchanged from 1350° to 1700°F.

The results of these surface area determinations indicate that at devolatilization temperatures greater than 1500°F, the accessible surface area of the chars decreases. This structure change could contribute to the lower reactivity observed for the stabilized chars at 1700°F.

Task IV. Process Research Unit Tests

The goal of this task was to design, construct, and operate an adiabatic 11.5-inch-ID steam-oxygen-blown fluidized-bed gasifier as a PRU. The design of the PRU major vessels and other system components was based on the results of the first three program tasks. The unit was designed to operate up to 1800°F and 500 psig with a maximum capacity of 1000 lb/h of biomass. The procurement activities for the construction of the PRU began after DOE authorization was received on December 31, 1981. The major PRU vessels were delivered on-site at the end of June 1982. Other auxiliary equipment was delivered by August 1982.

Construction of the PRU system was completed at the beginning of March 1983, 8 months after delivery of the major system vessels. Shakedown of individual units of the PRU system such as the feed preparation system and the live-bottom feed hopper, and lockhopper slide-gate valve system was done by January 1983. Shakedown of the integrated PRU system began in March 1983.

Description of the Process Research Unit

IGT built the PRU, at IGT's Energy Development Center (EDC) in Chicago. The PRU gasifier capacity is a nominal 12-TPD biomass feed. Figure 32 shows the isometric layout of the PRU equipment as installed in an existing structure, extending over 50 feet in total height. The 11.5-inch-ID, Incoloy 800H balanced pressure reactor liner is surrounded by about 12 inches of fiber insulation in a 3-feet-OD X 24 feet carbon-steel pressure vessel. The 12 inches of bulk fiber insulation in the annular region is sufficient to assure a close approach to adiabatic gasification conditions. The pressure vessel is equipped with two horizontal 6-inch pipe nozzle positions (displaced by 2 feet) for introducing the feed biomass, at a point in the fluidized bed near the oxygen distributor. The gasifier is specifically designed to permit operational flexibility to study the effect of different bed heights and fluidizing-gas distributor positions relative to the feeding location. The total internal height of the gasifier is about 21 feet, with 10 feet for the reaction zone at the bottom and 11 feet for an enlarged 18-inch-diameter solids disengaging zone. The gasifier bottom closure flange has provisions for introducing the fluidization and gasification medium (steam and oxygen or air), a support member for thermocouples and fluidized-bed differential pressure probes and a solids drain. Two fluidizing-gas distributors are provided. One distributor is exclusively for fluidization control below the feed point and is positioned under the steam-oxygen or air distributor. This prevents the formation of a zone of stationary solids near the oxidizing gas distributor, which reduces the exposure of bed solids to possible high temperatures or sintering conditions.

In the PRU system the feed hopper and the associated solids handling equipment are designed for continuous feeding to the pressurized fluidized-bed gasifier. At the top of the continuously pressurized metering feed hopper is a 24-inch-ID by 6-feet-high lockhopper vessel, equipped with quick-opening-and-closing gate valves, with provision for cyclic pressurization and

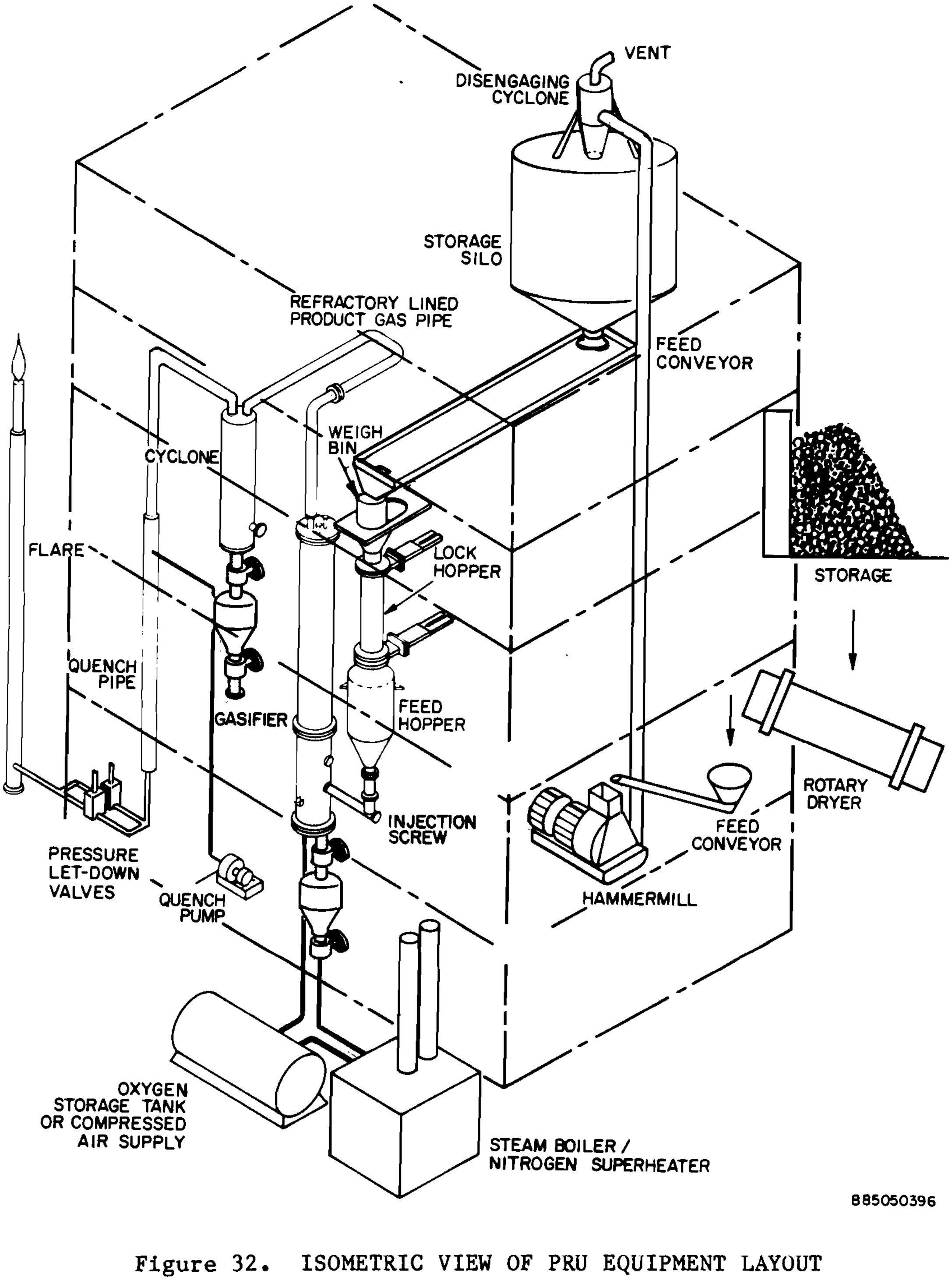


Figure 32. ISOMETRIC VIEW OF PRU EQUIPMENT LAYOUT

depressurization with nitrogen. The opening diameters of the top and bottom gate valves for the tapered lockhopper vessel are 18 inches and 24 inches, respectively. The metering feed hopper is 4 feet in diameter, 9 feet high, and equipped with a multiple-screw live bottom, which meters and discharges the biomass material into the gasifier injector screw feeder. The entire feed system is designed for operating pressures up to 500 psig and it is capable of continuously feeding 1500 lb/h of single screened biomass, with a top size of up to 1.5 inch. Some mechanical design drawings of the PRU are presented in Appendix A.

The piping between the gasifier and the cyclone and between the cyclone and the downstream water spray quench is fabricated from refractory-lined carbon-steel. Partial quenching of the hot product gases after the cyclone to about 800°F avoids liquid condensation, and also permits the use of less expensive unlined carbon-steel pipe to direct the product gases to a metering station and pressure letdown system, before the gases are flared for disposal. The PRU also contains a lockhopper system to load the inert fluidization media initially to the gasifier and on an "as required" basis. More details about the PRU instrumentation and experimental procedures are presented in Appendices B and C, respectively.

Shakedown Testing

The shakedown of the entire PRU system began in March 1983 with a four-step plan of tests. These steps included cold nitrogen pressurization tests; hot nitrogen (700°F) pressure and flow tests; an extended hot nitrogen (1100°F) flow test to dry the refractory linings and begin refractory curing; and a procedure test to heat the gasifier with charcoal and oxygen to 1500°F at 50 psig PRU system pressure.

This series of shakedown tests was successful. Minor leaks and instrumentation problems were corrected during the tests. The gasifier heat-up procedure established that a controlled startup would take about 8 hours. Additional corrections and recalibrations to various valves and instruments were completed after the tests.

During the heat-up test to reaction temperatures, charcoal was combusted with oxygen in the fluidized bed with sand. The gasifier temperature was held at 1500°F until the downstream piping temperatures exceeded 500°F, to prevent downstream condensation of steam or biomass liquids. Hardwood charcoal was first used, but later coconut shell charcoal was ideal for the fluidized-bed combustion to bring the gasifier to operating temperature. Charcoal has a minimum of volatile material, which would condense on the colder downstream system. After the PRU system temperatures stabilized, the hot nitrogen and oxygen fluidizing gas was replaced with steam and oxygen, and dried pine wood was fed at a rate of about 100 lb/h for 2 hours at 1540°F and 61 psig. The transition to wood and steam was very smooth. Several samples of product gas were collected and the product gases were successfully flared.

Overall system operation was successful at 61-psig pressure. Analysis of the product gas by mass spectroscopy showed a typically expected mix of hydrogen, carbon monoxide, methane, carbon dioxide, and some C_2+ gases. On a nitrogen-free basis the Btu content was about 300 Btu/ft^3. No material balances were attempted in these shakedown tests. The adiabatic operation of the well-insulated gasifier was confirmed as the metal skin temperature of the pressure vessel was only a few degrees above ambient temperature.

Following this a program of system-proving tests was initiated to achieve operation of the PRU system at design conditions of temperature, pressure, and feed rates, and also to develop procedures to attain satisfactory material and energy balances.

PRU System Proving Tests

During a system pressurization test at 330 psig, a flange leak at the 24-inch slide-gate valve on the lockhopper vessel was found. Routine flange tightening procedure was followed, but the leak persisted and the opening and closing motion of the slide-gate became erratic with binding. Inspection after depressurization showed that the internal clearances within the slide-gate retracting passage area were insufficient. The cause of the gate pinching and scoring was due to nonparallel cavity construction and raised weld beads that were not ground flush by the valve manufacturer.

The 4000-pound, 24-inch valve was removed from the PRU structure and shipped back to the manufacturer in Portland, Oregon. The defects in construction were repaired and the deeply scored knife gate faces were refinished. The 24-inch slide-gate valve was received from the manufacturer in the last week of April 1983 and reinstalled in the structure. To maintain the slide-gate clearances in the cavity and proper position during operation, seven hard plastic Rulon buttons of various thicknesses were installed to hold the gate in proper alignment to seal the 600-pound slide-gate in its closed position at IGT.

However, in the subsequent 300-psig pressure test the rear or lagging area of the gate would not seal properly with the existing adjustments. Therefore, two high-pressure, low-profile hydraulic jack cylinders were purchased and installed inside the valve's bonnet to push the gate up after its closing stroke. This modification achieved the approximate 0.020-inch upward movement necessary to seal the gate at 300 psig.

In May 1983, the first test (WG-1) was made with gasifier operating conditions at about 1440°F, 200 psig, and 200 lb/h of 9%-moisture maple hardwood. Start-up was smooth and wood charcoal was burned with oxygen with nitrogen as a moderator and fluidizing gas to heat the gasifier and downstream sections to operating temperatures. The charcoal was ignited at a temperature of 550°F instead of the 700°F as in the shakedown operations.

Just prior to achieving steady test temperatures with charcoal combustion and nitrogen fluidization medium in this test, a failure with a lubrication pump for the high-pressure liquid nitrogen pump forced an earlier-than-planned switchover to steam to maintain fluidization of the bed. The liquid nitrogen supply vendor replaced the pump after the run.

The switchover to steam for fluidization upon the loss of nitrogen, was done rapidly and the run proceeded with wood feeding and gasification. However, the fluidized-bed differential pressure sensing probes, which lost their high-pressure nitrogen purges during the abrupt transition to steam, plugged for the duration of the test, hence the state of the fluidized bed was unknown.

The test had lasted a little more than an hour when the bed temperature between the top and bottom regions began to increase and diverge from their normally observed ±20°F tight band. Temperature control of the bed could not be maintained and the test was terminated. Inspection of the bed silica sand material after draining the gasifier through the bottom 3-inch nozzle showed some sintered sand material in the form of very porous friable clumps.

It is possible that the sand bed defluidized for a short period during the emergency switchover to steam and caused a temperature excursion in a near-stagnant bed. After fluidization with steam was established the sintered lumps that formed interfered with fluidization and proper bed mixing.

Also, during this first system test, the 18-inch slide-gate valve began malfunctioning in a similar drag-grab manner that indicated clearance-stroking problems. After the test, the 18-inch valve was removed from the lockhopper and disassembled on-site. Repairs similar to what was done to the 24-inch valve were made by IGT personnel.

The gate cavity clearance, as manufactured, for the 18-inch gate was too tight and the weld fillets in the area were not ground smooth. This time a sheet of 1/8-inch Rulon hard plastic was installed under the gate to maintain gate position rather than plastic buttons as was done in the 24-inch valve. The gate-supporting rails were refurbished and aligned and the valve stroked smoothly and sealed properly.

After the delay caused by the 18-inch valve repair, the PRU system was readied for another test (WG-2). Gasifier operating conditions of 1430°F, 210 psig, and 270 lb/h of maple hardwood were achieved and maintained for about 2 hours. All system components operated well in this test and operational control procedures were learned for the stable, smooth operation of the fluidized-bed gasifier.

The next shakedown test (WG-3) at 300 psig was made in June 1983 with the goal of achieving a 500 lb/h feed rate. After the gasifier heat-up period and after an hour into the approach to steady state at the first feed rate plateau of 270 lb/h, the feed injector screw to the gasifier began binding. This caused the screw drive motor to overload and trip the circuit breaker repeatedly. Consequently, steady-state conditions could not be achieved. The test was stopped to correct the injector screw operation. The cause of the screw binding was found to be a misalignment of the shaft-bearing with the screw-housing, which was corrected by slightly enlarging two of the flange bolt holes to accept pressed-fit body bolts to act as fixed alignment dowels to ensure proper flange mating and alignment after repeated post-test inspections.

All of the other mechanical equipment in the system worked well. The slide-gate valves operated smoothly and the lockhopper feed system cycle time was satisfactory for 6 to 7 cycles/h, which is sufficient to achieve feed rates about 1000 lb/h.

During the pause in the DOE/PNL sponsored program following Test WG-3, pressurized (up to 500 psig) low-Btu gasification tests were conducted for a private sponsor in a 6-inch-ID fluidized-bed gasification system. Following the useful experience of this biomass test program, the DOE/PNL program was resumed to complete the remaining higher feed rate shakedown tests. It was learned that when silica sand is used as inert solids, there is a risk of forming clinkers during gasification at bed temperature between 1500° and 1600°F. Consequently, it was decided to use some form of alumina as the inert solids medium.

In February 1984, two more system proving tests (WG-4 and WG-5) at 300 psig and 1500°F were made to prove the PRU system at high feed rates of 500 and 1000 lb/h. Alumina grit (No. 80 grit) was used as the inert solids in these tests.

The conditions of Test WG-4 held steady in the gasifier at the 500 lb/h feed rate for a half hour until the automatic water quench flow became erratic. The water-spray quench controls the downstream gas temperatures from the exit of the refractory-lined pipe to the entrance to the uninsulated carbon steel piping to the flare. Because the gas temperatures were exceeding 800°F in the carbon steel pipe, the test was stopped. The total gasification time logged was about 2-1/2 hours including the stepwise climb in feed rates at 200 and 375 lb/h.

The cause of the erratic quench flow was found after the test to be simply dislodged rust scale that plugged the 1/16-inch-diameter orifice in the spray nozzle. The lines were cleaned and a strainer was installed in the line.

The PRU system was prepared for Test WG-5, conducted at conditions of 1500°F, 303 psig, and a set feed rate of 1000 lb/h. The duration of the time at this setting was about 1-1/2 hours (96 minutes) following periods of 1 hour each at 250 and 500 lb/h feed rates. The test was stopped after 96 minutes because the high-pressure liquid oxygen pump was unable to be restarted at the oxygen storage and compression pad at EDC. The vendor repaired the pump after the test.

Samples from this test of the bed material, the solids receiver solids, and condensate collected from a raw gas slipstream were sent for analysis. The on-line gas chromatograph measured steady wet-gas compositions, which calculated to be about 350 Btu/SCF on a dry, nitrogen-free basis. The collected liquid sample appeared to be quite clear with some fine carbon black material and some naphthalene.

The wood metering screw feed rate calibration that was originally done at ambient conditions by collecting weighed quantities in a drum appeared to be about 12% higher in the last test than what was fed over the test period according to the weigh bin load cell recordings. The load cell weights over the test period indicated a wood feed rate of 853 lb/h as timed between occurrences of the "empty" condition light from the level sensor in the live-bottom feed hopper.

According to the mid- and three-quarter position settings on the feeder system controls, the PRU system is capable of feeding and gasifying at higher rates. During Test WG-5, the lockhopper loading, pressurization, and depressurization cycle was consistently done within 4 minutes which, if continued automatically, would feed 1900 lb/h. The feed system was calibrated earlier to 1600 lb/h of 10% moisture wood chips.

Tests WG-4 and WG-5 confirmed that the PRU system was capable of operating at the design conditions. Even though the system was able to feed and gasify in excess of 1000 lb/h of biomass at 1800°F and 500 psig, the "centerline" or baseline operating conditions for the parametric testing were selected to be at 750 to 800 lb/h of biomass at 1500°F and 300 psig. The performance trends that were found as a function of primary operating variables identified approaches for system optimization and indicated the need or extent of various upstream or downstream operations for scaled-up processes. The program test matrix covered a range of temperatures and feed rates that were distributed around the centerline conditions in order to determine the effect of operating variables, turndown limiting throughput capabilities, and feedstock types.

The results for Test WG-5 in Table 14 show that the specific feed throughput rate is about 1200 lb/ft^2-h and the specific heat release amounts to 8.5×10^6 Btu/ft^2-h. A review of the system proving test results in this table show a learning and steady improvement in the PRU operating capabilities in terms of increasing temperatures, pressures, feed rates, reduction in steam and oxygen requirements, and an increase in carbon conversion.

Parameter-Variation Tests

IGT began the gasification parameter variation tests with the PRU in March 1984. The PRU tests were conducted at different gasification conditions to develop process optimization information on fluidized-bed gasification of biomass to produce medium-Btu value gas. A total of 22 tests have been conducted in the program. Fourteen of these tests were operated for steady-state data collection periods of approximately 4 hours, sufficient for parameter evaluation, while five tests were conducted for longer duration steady-state periods of up to 3 days. Three tests consisted of less than 4 hours steady-state operation.

These tests produced adiabatic, process-design data on the effect of temperature, steam feed rate, pressure, biomass throughput rate, type of feedstock, fluidized-bed height, and feed moisture content on pressurized oxygen-blown, fluidized-bed gasifier performance. The tests were conducted over the parameter range of 1390° to 1800°F temperatures, 69 to 330 psig pressures, and feed rates up to 1030 lb/h. The steam input rates varied from 0.41 to 1.18 lb/lb wood feed with the wood feed moisture content at approximately 10%. Different tests were made with feed moisture contents from 5% to 27% by weight.

The following is a short summary of the tests conducted in the 11.5-inch I.D. PRU that highlights specific test purposes and describes system modifications and/or repairs. Table 15 presents all of the test conditions and analyzed test results. Gasification trends and the effects of the test parameters are discussed later.

Test GT-1. The first test of the PRU test parameter variation matrix was designed to investigate the effect of temperature on pressurized oxygen blown biomass gasification. Test GT-1 was conducted on March 21, 1984 at a temperature of 1500°F using No. 80 alumina grit as the inert solids in the fluidized bed.

Table 14. SUMMARY OF SYSTEM PROVING TEST RESULTS

Test No.	WG-1	WG-2	WG-3	WG-4	WG-5
Pressure, psia	218	225	159-285	315	318
Temperature, °F	1444	1432	1368	1515	1510
Feed Rate, lb/h	200	270	270	461	853
Steam, lb/lb feed	3.4	2.1	2.6	1.4	0.92
Oxygen, lb/lb feed	0.58	0.29	0.44	0.4	0.3
Product Gas Rate (dry), SCF/h	5493	7668	10,755	15,042	20,065
Product Gas Composition (dry), mol %					
H_2	6.2	13.0	15.9	14.9	21.8
CO	2.9	9.9	8.7	7.9	10.9
CO_2	5.2	19.3	26.9	24.9	29.4
CH_4	3.0	8.8	7.5	8.5	13.2
C_2H_6	0.3	0.8	--	--	0.4
C_2H_4	0.2	0.3	--	--	0.1
C_6+	--	0.2	--	--	0.5
N_2	82.2	47.7	41.0	43.8	23.7
Total	100.0	100.0	100.0	100.0	100.0
Dry, N_2-free Gas, SCF/lb feed	4.9	14.9	23.5	18.3	17.9
GHV, dry N_2-free Gas, Btu/SCF	384	363	264	284	349

171/65058fr-t/RPP

Table 15. SUMMARY OF ANALYZED RESULTS OF PRU GASIFICATION TESTS

	Wisconsin Maple Wood Chips									
Test No.	GT-1	GT-2	GT-4	GT-5	GT-6	GT-8	GT-9	GT-10	GT-11	GT-16
Pressure, psia	323.7	323.7	308.7	308.7	311.7	308.7	314.7	104.7	296.7	314.7
Temperature, °F	1500	1650	1800	1390	1500	1510	1500	1465	1500	1450
Feed Rate, lb/h (wet)	813.4	690.6	731.9	724.3	693.5	750.4	765.9	399.5	1029.7	768.6
Moisture, wt %	8.35	9.50	9.70	10.47	10.72	11.15	12.44	12.08	10.02	7.71
Steam Input, lb/lb feed (wet)	0.79	0.71	0.60	0.77	0.86	0.65	0.50	0.62	0.48	0.74
Oxygen, lb/lb feed (wet)	0.21	0.25	0.34	0.17	0.24	0.22	0.21	0.23	0.20	0.22
Nitrogen, lb/lb feed (wet)	0.52	0.45	0.51	0.42	0.50	0.52	0.21	0.76	0.29	0.44
Product Gas Flow Rate, SCF/h	33,446	27,154	31,218	27,662	31,155	30,371	25,103	17,918	34,407	30,164
Superficial Gas Velocity, ft/s	2.20	1.93	2.49	1.80	2.13	2.11	1.70	3.59	2.47	1.99
Gas Composition, vol %										
H_2	10.58	11.82	13.58	9.62	8.08	9.97	9.81	7.52	10.37	10.52
CO	6.09	6.38	9.92	4.07	5.36	6.63	7.05	7.24	9.39	6.09
CO_2	15.63	17.15	15.49	15.92	13.98	15.04	17.64	11.89	15.61	15.89
CH_4	7.39	7.39	5.29	6.20	5.95	6.78	7.96	4.87	7.30	6.17
C_2H_4	0.10	0	0	0.10	0.08	0.19	0.27	0.45	0.27	0.12
C_2H_6	0.27	0.03	0	0.84	0.45	0.31	0.56	0.37	0.54	0.61
C_3H_8	0	0	0	0.02	0	0	0	0.01	0	0
C_6H_6	0.08	0.29	0	0.21	0.12	0.21	0.44	0.60	0.43	0.34
N_2	17.08	15.42	16.23	14.93	15.17	17.45	8.64	22.85	11.71	15.28
H_2O	42.78	41.52	34.96	48.09	45.44	39.00	40.84	36.06	38.11	44.98
Ar	0	0	4.53	0	5.37	4.42	6.79	8.14	6.27	0
Gross Molecular Weight, lb/lb-mol	22.63	22.78	23.36	22.62	23.59	23.74	24.28	25.04	24.09	22.75
Gas Yield, SCF/lb feed (wet)	41.12	39.32	42.65	38.19	44.92	40.47	32.78	44.85	33.41	39.25
Dry, Inert Free Gas, vol %										
H_2	26.36	27.45	30.67	26.01	23.75	25.48	22.43	22.82	23.62	26.47
CO	15.17	14.82	22.40	11.01	15.76	16.94	16.12	21.97	21.38	15.32
CO_2	38.94	39.83	34.98	43.05	41.09	38.44	40.34	36.08	35.55	39.98
CH_4	18.41	17.16	11.95	16.77	17.49	17.33	18.20	14.78	16.62	15.53
C_2H_4	0.25	0	0	0.27	0.24	0.49	0.62	1.37	0.61	0.30
C_2H_6	0.67	0.07	0	2.27	1.32	0.79	1.28	1.12	1.23	1.53
C_3H_8	0	0	0	0.05	0	0	0	0.03	0	0
C_6H_6	0.20	0.67	0	0.57	0.35	0.54	1.01	1.82	0.98	0.86
Gross Heating Value, Btu/SCF	344.20	337.07	292.61	356.93	345.34	354.64	379.35	405.31	382.19	356.62
Dry, Inert Free Gas Yield, SCF/lb feed (wet)	16.51	16.93	18.89	14.12	15.28	15.84	14.33	14.78	14.67	15.60
Cold Gas Thermal Efficiency, %	75.08	76.15	73.85	68.80	71.31	76.42	74.63	82.17	74.94	75.76
Carbon Conversion to Gas, %	88.2	92.2	94.2	82.3	88.2	90.5	88.5	95.4	87.4	90.2
Carbon Conversion to Gas and Liquids, %	92.0	94.4	94.8	87.2	92.0	92.7	92.0	96.0	91.8	94.4

171/65058fr-t/RPP

Table 15, Cont. SUMMARY OF ANALYZED RESULTS OF PRU GASIFICATION TESTS

	Whole Tree Chips Feedstock											
Test No.	GT-13	GT-14	GT-15	GT-17	T12-1	T12-2	T3D-1a	T3D-1b	T12-3a	T12-3b	T12-4a	T12-4b
	From Pennsylvania				From Wisconsin							
Pressure, psia	323.7	344.7	320.7	320.7	314.7	116.7	323.7	323.7	317.7	317.7	83.7	98.7
Temperature, °F	1520	1510	1520	1530	1530	1500	1538	1562	1672	1413	1509	1516
Feed Rate, lb/h (wet)	742.1	826.9	673.4	684.8	643.9	352.9	427.5	748.0	708.1	708.1	375.4	375.4
Moisture, wt %	9.58	15.02	14.47	26.74	4.94	7.72	10.80	10.80	9.14	9.14	8.98	9.59
Steam Input, lb/lb feed (wet)	0.53	--	0.41	0.46	0.61	0.69	1.18	0.63	0.69	0.68	0.72	0.73
Oxygen, lb/lb feed (wet)	0.23	0.18	0.25	0.33	0.25	0.26	0.26	0.23	0.26	0.18	0.27	0.28
Nitrogen, lb/lb feed (wet)	0.36	0.95	0.87	1.34	0.54	0.91	0.74	0.43	0.41	0.40	0.85	0.93
Product Gas Flow Rate, SCF/h	27,220	27,772	28,271	33,016	24,603	15,693	23,003	27,695	27,472	25,373	16,813	17,439
Superficial Gas Velocity, ft/s	1.81	1.73	1.90	2.23	1.69	2.87	1.55	1.88	2.01	1.63	4.31	3.80
Gas Composition, vol %												
H_2	13.84	5.60	8.14	7.96	12.05	5.90	10.88	12.30	12.69	8.55	7.49	7.38
CO	7.08	7.20	6.89	3.99	8.00	7.72	3.59	5.58	7.22	5.59	7.79	7.59
CO_2	17.28	13.26	12.93	13.42	17.06	11.52	13.86	17.32	17.42	15.72	11.98	11.93
CH_4	6.82	5.83	4.79	3.95	7.37	4.58	4.79	6.56	7.60	6.95	4.32	4.61
C_2H_4	0.01	0.36	0.20	0	0.03	0.65	0.04	0.04	0	0.28	0.65	0.50
C_2H_6	0.51	0.60	0.27	0.09	0.22	0.56	0.17	0.20	0.02	0.90	0.35	0.30
C_3H_8	0	0	0	0	0	0.01	0	0	0	0	0.01	0.01
C_6H_6	0.14	0.84	0.49	0.17	0.27	0.24	0.18	0.81	0.41	0.57	0.47	0.40
N_2	13.16	46.37	28.24	37.53	19.18	27.64	18.63	15.59	14.34	15.13	25.80	27.29
H_2O	35.02	14.53	30.03	32.89	35.82	41.18	47.86	41.60	40.30	46.31	41.14	39.99
Ar	6.14	5.41	8.02	0	0	0	0	0	0	0	0	0
Gross Molecular Weight, lb/lb-mol	23.66	27.59	25.59	24.40	23.27	23.77	22.12	23.04	22.75	23.13	23.58	23.65
Gas Yield, SCF/lb feed (wet)	36.68	33.59	41.98	48.21	38.21	44.47	53.81	37.03	38.80	35.83	44.79	46.45
Dry, Inert Free Gas, vol %												
H_2	30.30	16.62	24.15	26.91	26.78	18.92	32.47	28.73	27.98	22.17	22.66	22.56
CO	15.50	21.37	20.44	13.49	17.78	24.76	10.71	13.03	15.92	14.50	23.56	23.20
CO_2	37.83	39.36	38.36	45.37	37.91	36.95	41.36	40.46	38.40	40.77	36.24	36.46
CH_4	14.93	17.30	14.21	13.35	16.38	14.69	14.29	15.32	16.75	18.02	13.07	14.09
C_2H_4	0.02	1.07	0.59	0	0.07	2.08	0.12	0.09	0	0.73	1.97	1.53
C_2H_6	1.12	1.78	0.80	0.30	0.49	1.80	0.51	0.47	0.04	2.33	1.06	0.92
C_3H_8	0	0	0	0	0	0.03	0	0	0	0	0.03	0.03
C_6H_6	0.31	2.49	1.45	0.57	0.60	0.77	0.54	1.89	0.90	1.48	1.42	1.22
Gross Heating Value, Btu/SCF	331.07	440.15	366.27	292.95	342.21	384.74	315.72	371.16	346.39	409.61	386.05	377.89
Dry, Inert Free Gas Yield, SCF/lb feed (wet)	16.76	11.32	14.15	14.26	17.19	13.87	18.03	15.85	17.60	13.82	14.81	15.20
Cold Gas Thermal Efficiency, %	75.33	71.05	72.71	69.52	74.91	70.26	76.99	79.57	80.72	74.95	75.62	76.89
Carbon Conversion to Gas, %	88.3	86.1	90.2	96.6	90.2	87.4	93.0	93.8	96.2	87.1	91.8	93.3
Carbon Conversion to Gas and Liquids, %	89.9	92.1	94.4	96.6	95.6	92.7	96.1	96.8	98.4	93.8	96.9	98.0

171/65058fr-t/RPP

Test GT-1 was successfully completed with a 4-hour steady-state period at a feed rate of 813.4 lb/h. The heat up and pressurization period went smoothly into the gasification period. Successive 1-hour steps at about 250 and 500 lb/h feed-rates preceded the target feed rate. The test was voluntarily terminated at the end of the 4-hour period. Post run inspection of the unit showed that a significant amount of the inert alumina grit solids were carried overhead to the solids receiver vessel.

Because the carryover was a significant portion of the inert material in the bed, the alumina grit was replaced with slightly larger, but spherical alumina beads for Test GT-2 and used in the remainder of the tests in the program. The properties of the alumina grit and alumina beads are given in Table 16. Using these properties and the following correlation for the minimum fluidization velocity developed at IGT, the minimum fluidization velocity was calculated.

$$u_{mf} = (\mu/\rho_g D_p)\{[(25.25)^2 + 0.0651\ Ar]^{1/2} - 25.25\} \tag{15}$$

where —

Ar = Archimedes Number

$$= D_p^{\ 3}\ \rho_g(\rho_p - \rho_g) \cdot g/\mu^2 \tag{16}$$

The fluidizing-gas properties used in the calculation were for steam at 1000°F and 300 psig.

Test GT-2. The second test in this series on gasification temperature variation (GT-2) was conducted on April 11, 1984 at 300 psig and 1650°F. Test GT-2 was successfully completed at a feed rate of about 700 lb/h. The heat up and pressurization period went smoothly into the gasification period, which also followed successive 1-hour steps at about 250 and 500 lb/h feed rates before reaching the target feed rate. After achieving a 4-hour steady-state period the test was voluntarily terminated.

Test GT-3. Gasification Test GT-3 was attempted on April 25, 1984 at 300 psig and 1400°F. However, during the steady-state period the injector screw stopped, interrupting the wood feed to the gasifier. The test was terminated to fix the injection screw alignment.

Test GT-4. Another gasification test was conducted on May 24, 1984. Test conditions for this test (GT-4) were 1800°F bed temperature at 300 psig

Table 16. PROPERTIES OF GASIFIER INERT SOLIDS

	Alumina Grit (No. 80 grit)	Alumina Beads (40 X 70 mesh)
IGT Sample No.	48925	48926
U.S. Sieve	wt % retained	
40	0.0	0.3
45	0.0	54.4
50	0.0	37.1
60	0.1	7.8
70	13.7	0.3
80	53.1	0.1
100	29.8	0.0
120	3.1	0.0
140	0.1	0.0
170	0.1	0.0
Pan	0.0	0.0
Total	100.0	100.0
Bulk Density, lb/CF	125.3	138.6
Particle Density, lb/CF	306.0	223.0
Calculated Minimum Fluidization Velocity, ft/s for Fluidization Medium of (Steam at 1000°F, 300 psi)	0.2	0.38

with about 700 lb/h feed rate. An inert tracer gas injection system was installed for periodic checking of the product gas flow measurements. Argon was chosen as the inert gas. The argon input flow rate was regulated to result in a 5% concentration in the raw gas downstream from the gasifier. A 5% argon concentration was able to override the low background argon (about 0.1%) normally contained in the feed oxygen. The argon was metered for a 1-hour period during the steady gasification period at the feed injection screw's nitrogen purge position. The nitrogen purge was shut off during this period so as to not inject an additional amount of cold gas into the gasifier. The feed hopper purge nitrogen, however, was always maintained.

Test GT-5. On June 13, 1984 Test GT-5 was conducted with nominal test conditions of 1390°F, 300 psig, and at a wood feed rate of about 720 lb/h. An improved sampling system was installed prior to Test GT-5 to obtain a large isokinetic raw-gas sample for measuring solids carryover and liquids production rates. The sampling system was designed to operate for 1 hour during the steady 4-hour period and to withdraw a sample at a rate of approximately 1% of the total flow from the gasifier. The solids are first removed with a hot sintered metal filter, then the stream is cooled and the liquids are condensed first in a water-cooled condenser then by an ice bath-trap condenser. The condensate-free raw gas is then metered and vented. The collection of a large volume of condensate provided a representative sample that contributed to better off-line chemical analysis and consequently to improved elemental and material balances. The measured steam condensate rate also obtained was useful in validating the undecomposed steam concentration in the raw gas as determined by the on-line wet-gas chromatograph. A more detailed description of this isokinetic sampling system is presented in Appendix D.

Test GT-6. Test GT-6 was conducted on June 28th at 1500°F, 300 psig, and about 700 lb/h feed rate.

During the 4-hour steady-state operation period in Test GT-6, the heat-sensitive vessel paint showed an isolated hot spot, of about a 12-inch diameter near the top of the gasifier pressure vessel. The skin temperature in this spot ranged from 250° to 500°F. To complete the 4-hour steady-state operation and collect the required data, the hot spot was controlled with water cooling.

To correct this insulation breach between the liner and pressure vessel the reactor top head was removed for inspection as part of the post run activities of Test GT-6. The top 4 feet of the bulk fiber insulation in the annular region of the pressure vessel, enclosing the hot spot, was removed and repacked. The numerous pressurizations and depressurizations over the previous tests could have caused a slumping of the insulation.

Test GT-7. After the insulation was repacked, gasification Test GT-7 was conducted on July 20, 1984. The nominal test conditions were 1500°F, 300 psig, and 700 lb/h of maple wood feed. The purpose of this test was to reduce the steam-to-wood ratio to about 0.6 as part of the overall test plan. During the steady-state operation, the steam boiler went off-line when the feedwater control on the boiler malfunctioned and interrupted the flow of makeup water to the boiler. Even though the boiler was brought back on-line within minutes, the fluidizing-gas distributor ring, with flow interrupted, became plugged with the fluidized-bed inert solids. Consequently, it was impossible to resume fluidization, and the test was terminated.

During this test, different hot spot regions, about 5 feet from the top, appeared at a lower elevation opposite to the first hot spot area. The shell temperature was again controlled by a small water spray to complete the test, but to correct the problem for continued testing, the annular insulation region was emptied and repacked uniformly down to about 6 feet from the gasifier top.

Test GT-8. After a general check-out of the PRU, gasification Test GT-8 was conducted on August 2, 1984. Nominal test conditions were 1500°F, 300 psig, and 750 lb/h of maple hardwood feed. The purpose of this test, similar to that of the aborted test, GT-7, was to reduce the steam-to-wood ratio to complement the previous steam-to-wood ratio tests. The heat-up and pressurization period went smoothly into the gasification period, which followed a stepwise wood feed rate of about 300 lb/h before reaching the target feed rate of about 750 lb/h. The test was voluntarily terminated at the end of a 2.5-hour steady-state period when the feed supply was depleted from the 20-ton overhead storage silo.

During this test the gasifier shell hot spots described earlier appeared again, indicating that a persistent flow of product gas was bypassing through the insulation area. After the run, the gasifier top head was removed and the insulation in the annular area was removed and inspected. It was eventually repacked to a depth of 12 feet from the top. (The overall length of the upper gasifier shell is 16 feet.)

However, upon further examination, by separating the upper and lower reactor vessel sections, it was found that part of the product gas was bypassing from the slip-joint area between the two reactor sections. This was caused by a failure in a seal weld of the semitorroidal bellows that isolate the insulation section from the fluidization zone and also isolate the lower and upper sections of the reactor vessel. The bellows had flexed and the weld to the reactor liner gave way. The gasifier construction drawings for the balanced pressure liner is shown in Appendix A.

The procedure selected for repairing the upper bellows involved concentrically cutting the bellows about 4 inches away from the 11.75-inch-OD liner and inserting a short, space-filling cylinder and disc set about the liner as a transition piece between the bellows and liner, providing an accessible welding area. The welding of the thin-gauge semitorroidal bellows to the installed transition repair piece was done by using an inert gas-multiple-pass arc welding technique.

During the time of this repair procedure, a new outlet pipe flange set was installed in the 8-inch-ID refractory-lined product-gas pipe, as part of the same welding job order. With this extra flange in place, only a short length of product-gas pipe has to be removed to permit easy access to the top of the reactor for maintenance and inspection. New instruments were also added to prevent inadvertent overpressurization of each of the annular insulation areas with respect to the liner.

Also, in July 1984, a new component was added to the PRU system to improve the method of loading the inert fluidized-bed solids into the gasifier. A lockhopper system was fabricated with components on-site at IGT. This vessel is now charged with inert solids for the test and pressurized to the system pressure. The solids are discharged from the vessel through one of the unused sight-port nozzles installed on the feed hopper. The solids flow directly down the wood chute to the injection screw without contacting the metering screws. This system simplified the loading procedure, which previously had required the opening, closing, and sealing of the 24-bolt, 24-inch manway on the feed hopper.

Test GT-9. The conditions for Test GT-9, conducted on October 11, 1984, were 1500°F and 300 psig with a feed rate of 765 lb/h. The test achieved a low steam-feed rate of 0.5 lb steam/lb feed. The operation of Test GT-9 also confirmed the successful repair of the bellows seal arrangement for isolation of the two bulk fiber insulation zones from the gasification zone. The gasifier pressure vessel skin temperatures remained at about 110°F during the test, with no hot spots appearing on the top section of the gasifier. The start-up procedure was also modified to protect the bellows isolation seal by slowly pressurizing the PRU before beginning the heat-up.

Test GT-10. Test GT-10 was operated at a gasifier bed temperature of 1465°F and a system pressure of 100 psig to investigate the effect of lower system pressure on gasifier performance. The feed rate of maple wood was reduced to 400 lb/h to maintain the correct superficial gas velocity.

Test GT-11. After the system turnaround period, Test GT-11 was conducted on November 8, 1984. Conditions for this test were a gasifier bed temperature of 1500°F and a gasifier bed pressure of 300 psig. Test GT-11 achieved the highest wood feed rate of the program. The wood feed rate was increased in a stepwise fashion to about 1030 lb/h. The test was conducted at this feed rate for a steady-state period of 4-1/2 hours, with a period of approximately 1/2 hour of reduced feed rate when the supply of wood feed in the storage silo was depleted and additional wood chips had to be crushed to continue the test at the higher feed rate. No operational difficulties were encountered when the operation was resumed following the interruption in the wood feed rate. After a 4-hour steady-state period at a feed rate of 1030 lb/h was achieved, Test GT-11 was voluntarily terminated. Up to this point all tests were conducted with maple wood chips.

Test GT-12. Test GT-12 was the first gasification test conducted with Pennsylvania whole tree chips at a feed rate of 750 lb/h at 1500°F and 300 psig. The operation of the PRU system went smoothly with this material. The operation differed from that with the maple feedstock only in that the lower bulk density of the whole tree chips required a lower lockhopper-charge weight in the feeding cycle. The product gas composition indicated by the on-line gas chromatograph was similar to the past maple feedstock gasification tests.

Test GT-12 had to be stopped after about 2-1/2 hours into the steady operating period when a 0.5-inch-OD tubing-to-pipe cap seal weld failed on the product gas particulate and condensate sampling probe. The leak opening was located upstream of the first shutoff valve and could not be isolated. A new sampling probe was constructed with thicker wall tubing to make heavier welds in the area, and it was installed for the next test.

Test GT-13. Test GT-13 was conducted on December 13, 1984. Conditions for this test were similar to those for the aborted Test GT-12. The gasifier was operated at 300 psig and a bed temperature of 1520°F with a feed rate of 740 lb/h of whole tree chips. Test GT-13 was the first successful test using Pennsylvania whole tree chips as feed material. No operational difficulties were encountered during the approximately 4-hour steady-state period. After this period, the test was voluntarily terminated.

During the earlier system proving tests, a leak occurred in the slide-gate valves of the lockhopper feeding system as was described previously. The early repairs or modifications were not completely successful as the leak at the 24-inch valve flange to the lockhopper flange persisted throughout the initial parametric variation testing. The leak, however, was measurable and the leaking gas was also feed hopper makeup nitrogen. The problem persisted because the slide-gate valve's flange thickness was designed by the valve manufacturer for 500 psig cold water pressure code. These flanges, therefore, were only about half the thickness required by the ASME-ANSI pressure code by which the PRU system was designed. This fact and the valve's horizontal installation position rather than the manufacturer's normal vertical installation positions contributed to a poor seal integrity in this new valve application. Thicker flanges and substantial slide-gate support provisions were necessary to improve the operational reliability of these valves. An improved valve design was made by Thomas R. Miles Design Consulting Engineers in Portland, Oregon. The original manufacturer did not indicate that they were willing to improve and build the new valves.

During January 1985, the improved-design 18- and 24-inch-diameter-opening replacement slide-gate valves for the feed system lockhopper were installed. The existing slide-gate valves from the Fabrivalve Co. were removed and stored aside. Physical modifications to the system were straightforward in fitting the valves in place and rearranging the electrical and pneumatic system components and interlocking safety functions.

Many design features were incorporated on these valves to make field servicing simple. After installation, the valves were disassembled to install the ring-type seals of the slide-gate. This operation, with a practiced crew and with in-place hoisting could be completed in 1 day for both valves. This was a major improvement in comparison to the previous valves, which required over 1 week for a similar seal replacement operation.

In addition, the valves were test-cycled, before delivery to IGT, for 350 cycles. The original Fabrivalve Co. valves had to be repaired and modified after 50 cycles. After the last test in this program, the new valves had 1500 cycles of operation with no sealing difficulties.

A pressure test of the new valves and feed system indicated that no leaks were present at the gate seals or at the flange areas. The new valves operated satisfactorily during the remainder of the tests. The opening and closing strokes and the gate's "lift-to-seal" mechanism operated silently and smoothly compared to the original valve's "bump-nose" lifting. This performance attests to the operational improvements provided by the substantial rail-support and alignment provisions for the sliding gate. The gate "lift-to-seal" mechanism also prohibits rubbing wear on the elastomer seal ring, which was severely galled in the original valves. A mechanical gate stroke counter was installed to monitor the performance of the valves.

Test GT-14. Test GT-14 was conducted on February 14, 1985 to investigate gasifier operation without external steam addition other than that from the moisture content of the whole tree chip feed and the chemically produced water in the gasifier. Steam produced from the 15% moisture in the wood feed and from chemically produced water accounted for a steam-to-wood ratio of 0.23 lb/lb. For this test, the normally used steam was replaced with nitrogen to maintain a minimum fluidization velocity near the oxygen distributor and the feed location. The nitrogen was preheated to about 900°F before entering the gasifier distributor ring and nozzle. No operational difficulties were encountered using nitrogen gas as the fluidizing medium.

Test GT-15. Test GT-15 using the whole tree chips as feed material, was begun on February 28, 1985 and completed on March 1, 1985. For Test GT-15, the PRU steam flow-control system was modified to permit nitrogen to mix with steam at the entrance to the gasifier. This allowed a lower steam-to-wood ratio of 0.41 lb/lb. With the existing steam supply system it was not possible to superheat both nitrogen and steam; therefore, cold nitrogen was added to steam, reducing the incoming fluidizing-gas temperature to 640°F from the normal operating temperature of about 800°F. Consequently, to obtain a gasifier bed temperature of 1500°F, the oxygen flow was increased to compensate for the mixture of cooler incoming fluidizing steam and nitrogen. During Test GT-15, steady-state operation was maintained for a period of 3-1/2 hours before the test was terminated due to a leak in the low-pressure piping downstream of the pressure letdown valves.

Test GT-16. Maple wood chips were used as feed material for Test GT-16 with the purpose to investigate the gasification process with a lower fluidized-bed height and compare to the previous tests. The gasifier was operated at 1450°F and 300 psig with a wood feed rate of 770 lb/h. The fluidized-bed height-to-diameter ratio (L/D) was between 3 and 4 compared with the previous maple wood feed tests with a ratio of about 6. The wood feed and, consequently, the oxygen flow were interrupted in the middle of this test for a brief period in order to repair a bearing on the wood-feed drag conveyor supplying wood to the weigh bin. The gasifier continued to operate smoothly after this quick repair, and the test was voluntarily terminated after a cumulative steady-state operation of 4 hours.

Test GT-17. Test GT-17 was conducted on March 29, 1985 using 27% moisture content whole tree chip feed material. Conditions for this test were 1530°F and 306 psig. Some conveying equipment difficulties were encountered in handling the higher moisture content feed, but these were overcome by reducing each charge of wood to the weigh bin. Longer sliver-type wood pieces present in the feed at this moisture level helped to lock together clumps of feed and restrict the flow.

After Test GT-17, work began on the modifications to the PRU equipment and piping for the extended duration gasification tests for up to 1 week. In preparation for the modifications to the PRU, certain equipment was cleared from the work area, pipe insulation was removed, and cuts were made in the product gas pipe sections.

An internal cyclone was fabricated and installed in the solids receiver vessel to continuously collect the carryover solids. A char collection lockhopper vessel was fabricated and installed under the solids receiver vessel to periodically discharge the collected char during the long-term gasification tests. Special high-temperature service ball valves were installed between the lockhopper and the cyclone. New control instrumentation with safety interlocks was installed in the control room for the lockhopper vessel.

The 8-inch-OD product gas pipe was repacked with refractory at each new weld joint with cast, mitred joints to assure the thermal insulation integrity. A new thermocouple supporting lance for the fluidized-bed temperatures was made with the thermocouples now placed inside the lance to protect against long-term test erosion. The oxygen nozzle and steam distributing ring were raised about 18 inches to reduce the gasification zone under the feed location.

Explosion-proof motors for the hammermill, pneumatic lift fan, and the feed drag conveyor were installed, which permitted simultaneous operation in the building during gasification tests. New feed level sensors that do not require periodic calibration were installed in the lockhopper and the live-bottom feed hopper. The new feed hopper level sensor was a vast improvement over the original sensor. It consisted of a vertical probe that continuously indicated the level in the hopper, rather than, as before, indicating just an empty condition.

Test T12-1. The first test of the long-term test series (T12-1) was completed on June 20, 1985. The test logged 10.5 hours of steady-state operation at 1530°F, 300 psig, and 640 lb/h feed rate. The feed material for this test and the other long-term duration tests was whole tree chips obtained from Wisconsin instead of Pennsylvania. The new material fed well in general, except that a couple of hours elapsed before the feed rate stabilized at 640 lb/h. The lower charging/feeding rate could have been due to the possibility of air-segregation of particles first loaded into the storage silo as they free-fell down about 30 feet from the top filling port of the silo.

During the test the cyclone operated satisfactorily at process temperature and pressure. The cyclone lockhopper discharge system worked well on a 1/2-hour emptying cycle. The discharged solids were blown into a large existing vessel outside the PRU building. The flare plume was visually clean, free of the occasional puffs of dark dust that occurred before the cyclone was installed.

The test was terminated after 10.5 hours of operation because of a rapid loss of fluidized-bed gasifier thermocouples. The test was terminated to avoid the possibility of excessive temperatures occurring in the gasifier. Post-run inspection of the gasifier showed that the gasifier bed thermocouple lance, a 3/4-inch SS pipe, was severed about 2 feet above the steam-oxygen nozzle. Some agglomerates of char were retrieved from the gasifier vessel that could have diverted a sand-blast jet to the lance. The longest bed differential pressure probe was also cut at a 45 degree angle. The lance cutoff could have also interfered with the incoming feed, blocking the mixing, and caused the clumping of the feed.

Test T12-2. The lance was repaired and reinforced and a successful gasification test at 1500°F and 102 psig (T12-2) was made on July 18 and 19, 1985. This second test of the long-term PRU test series logged 20 hours of steady-state operation, surpassing the 12 hour test goal.

The feed material again was whole tree chips obtained from Wisconsin. The test was conducted at a pressure of 102 psig because internal wear degraded the feedwater pump supply pressure to the boiler. The pump could only produce 350 psig, which was insufficient to supply steam to the flow measurement orifices required for operation at 300 psig system pressure. A new pump was installed for the 3-day steady-state period test that was conducted in August. In preparation of the PRU system for the 3 day test, all lines, filters, and instrument taps were cleaned and all mechanical equipment was lubricated.

Test 3D-1. The 3-day steady-state operation period was conducted at 1550°F and 309 psig during the week of August 12, 1985. The test covered two periods with different feed rates; 430 and 750-lb/h. The test began with the lower feed rate to allow the entire PRU and piping system to come to thermal equilibrium with the ambient conditions. A minor problem was corrected during the lower feed rate period without shutting down the gasifier. The difficulty was that dust accumulation in the 18-inch slide-gate valve bonnet prevented the gate from being fully opened by about 5 inches. This incomplete retraction of the slide-gate promoted bridging of part of the drop charge from the weigh bin to the lockhopper, and the balance of each charge had to be manually assisted. Overall, the PRU performed well in this extended period. Valuable additional information was provided on long duration process operation, such as the possible breakthrough observation of minor or very low concentration process components, the equilibration of vessel temperature gradients to establish a true process heat balance, and long-term equipment operation handling dust and tar containing streams.

Tests T12-3 and T12-4. The last two tests of the program were conducted in September and October of 1985 with each test consisting of two different process parameter set points. Test T12-3 was conducted on September 18 and 19. The gasification period was maintained for 12 hours at 303 psig pressure, but within this period two gasification test temperatures of 1413° and 1672°F were studied. Each steady period was maintained for about 4 hours. Test T12-4 was conducted on October 9 and 10 at 69 psig and 1510°F. Again, two gasification periods with different operational set points were conducted in this test. The first gasification period was operated with a fluidized-bed L/D ratio of 3 to 4. Additional inert bed material was then added after the first period to increase the fluidized-bed L/D ratio to about 5 to 6.

Task V. Data Review for Scale-Up Tests

The following sections present the gasification test reslts, analysis, effect of various parameters, and information relative to process scale-up. The gasification and process performance data in this analysis were obtained from PRU test operations conducted over steady gasification periods of up to 3 days and from the process parameter variation tests of 4- and 12- hour steady-state periods. The startup and shutdown phases of the PRU operation were each done slowly in 8-hour periods before and after the gasification periods and are mainly pertinent for the operation of the PRU. The adiabatic process data from the PRU system is detailed in the following section and is necessary to identify the optimum process conditions for a proposed scaled-up application.

Figure 33 presents the chronological history of key inputs and fluidized-bed temperature for the 3-day steady duration PRU gasification test. No differences in performance were evident between the shorter steady gasification test periods and the 3-day test, indicating that the heat and material balances from the shorter tests reflect the true, adiabatic process. The normal feed rates of up to 1000 lb biomass per hour and the normal fluidized-bed volumes used in the tests results in approximately 15 bed turnovers of material per hour. Hence, a steady-state test of about 4 hours duration is in a well-defined steady state regime.

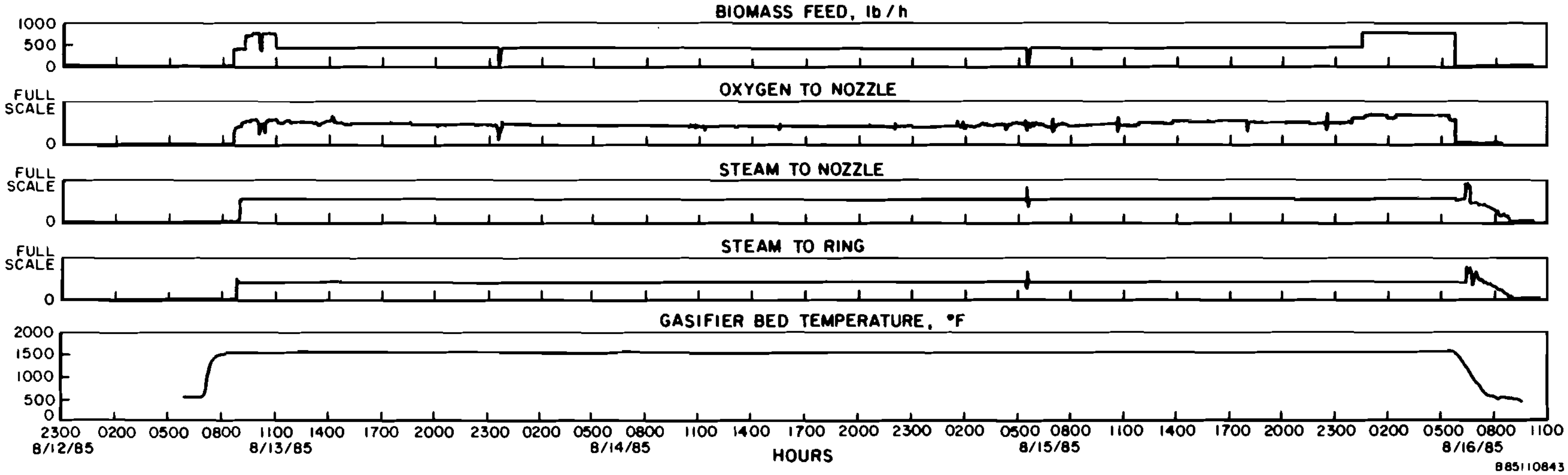


Figure 33. CHRONOLOGY OF SELECTED PROCESS CONTROL PARAMETERS DURING TEST T3D-1

Table 15 summarizes the results from the 19 tests that achieved steady-state operation periods of 4 hours or more. Material and energy balances for each individual test are presented in Appendix E. Corrections were made to the raw data to establish 100% elemental and material balances before correlating the data for process evaluation purposes. Appendix F lists the properties of entrained solids for each test. The size analysis of the entrained solids show that none of the inert solids are carried over with the raw gases. Hence, the PRU operation resulted in the discharge of feed ash containing some unconverted carbon, with the product gas stream.

Tests GT-1 through GT-11 and GT-16 were conducted using maple wood chips from northern Wisconsin as feed material. Whole tree chips from Pennsylvania were used as feed material for Tests GT-13, GT-14, GT-15, and GT-17. Whole tree chips were also used as feed material for the subsequent long duration tests except that this feed material was obtained from Wisconsin. Representative samples of the prepared wood feed were analyzed for their physical and chemical properties. The proximate analysis, ultimate analysis, bulk density, and gross heating value of typical samples of maple wood chips and whole tree chips are given in Table 17.

Effect of Temperature

The first tests that were conducted obtained data on the effect of temperature on gasifier performance. The gasifier was operated at a pressure of 300 psig and temperatures ranging from 1390° to 1800°F.

The results from these tests are plotted in Figures 34 through 37 and show the effect of temperature on process performance. The temperature value used in these plots is an average of at least four thermocouples inside the fluidized bed at various heights covering a fluidized-bed height of up of to 74 inches above the oxygen distributor. In these tests the measured differences in temperature between these thermocouples was from 45° to 90°F. An additional 12 thermocouples are tack welded to the outside of the PRU fluidized-bed liner.

Figure 34 shows the oxygen required to achieve average fluidized-bed gasification temperatures ranging from 1390° to 1800°F at about 300 psig. The oxygen values reported here for these tests are given per pound of feed dried to 10% moisture level. Oxygen demand at a given temperature increases as the

Table 17. TYPICAL WOOD FEED PROPERTIES

	Maple Wood[*]	Whole Tree Chips[**] From Pennsylvania	Whole Tree Chips[†] From Wisconsin
Proximate Analysis, wt %			
Moisture	12.26	10.89	7.72
Volatile Matter	73.94	73.53	77.07
Ash	0.43	0.84	0.75
Fixed Carbon (By Diff.)	13.37	14.74	14.46
Total	100.00	100.00	100.00
Ultimate Analysis, wt %			
Ash	0.50	0.94	0.82
Carbon	49.54	48.51	48.40
Hydrogen	6.11	6.17	6.31
Sulfur	0.02	0.04	0.03
Nitrogen	0.10	0.12	0.21
Oxygen (By Diff.)	43.73	44.22	44.23
Total	100.00	100.00	100.00
Bulk Density, lb/ft^3	16.6	14.7	10.7
Gross Heating Value, Btu/lb	8306	8210	8228
Ash Fusion Temperature, °F	>2700	>2700	>2700

[*] Average of two samples (Tests GT-9 and GT-10).

[**] Average of two samples (Tests GT-12 and GT-13).

[†] Average of two samples (Test T12-2).

ESTIMATED SPECIE COMPOSITION OF TEST FEEDSTOCKS

Feedstock	Estimated Specie Composition, vol %
Maple Wood	100% maple pulpwood
Whole Tree Chips from Pennsylvania	90% red oak, balance chestnut, aspen, black birch
Whole Tree Chips from Wisconsin	34% maple, 33.5% oak, 19.6% birch, 12.9% pine and brush

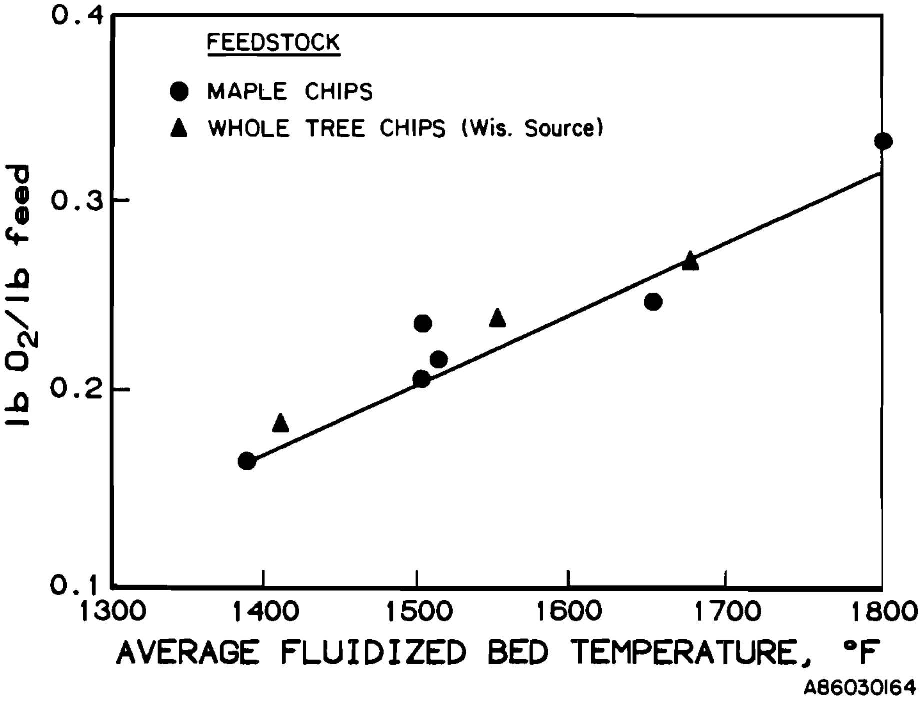


Figure 34. OXYGEN REQUIRED AS A FUNCTION OF GASIFICATION TEMPERATURE (Maple Feed: Tests GT-1 Through GT-8 and Wisconsin Whole Tree Chips: Tests T12-3a, T12-3b, T3D-1b)

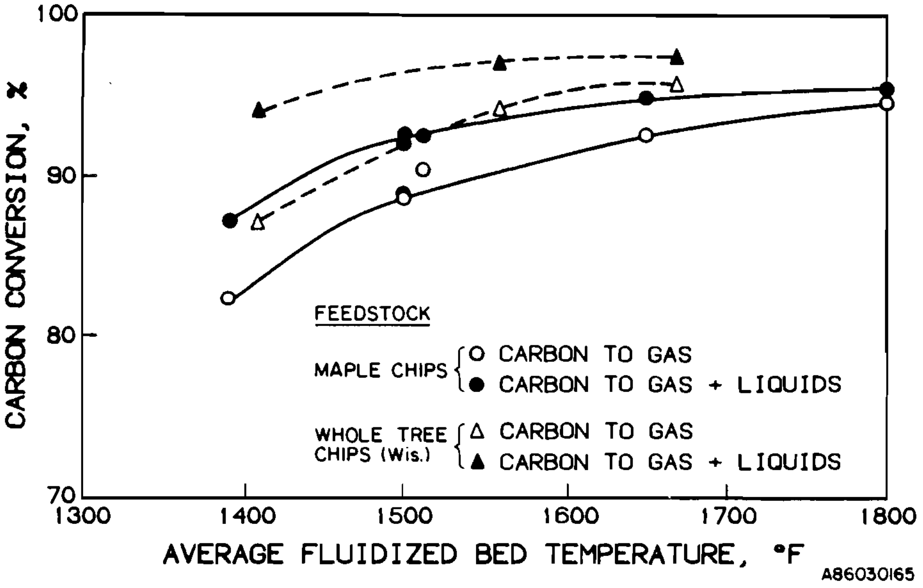


Figure 35. FEED CARBON CONVERSION AS A FUNCTION OF GASIFICATION TEMPERATURE (Maple Feed: Tests GT-1 Through GT-8 and Wisconsin Whole Tree Chips: Tests T12-3a, T12-3b, T3D-1b)

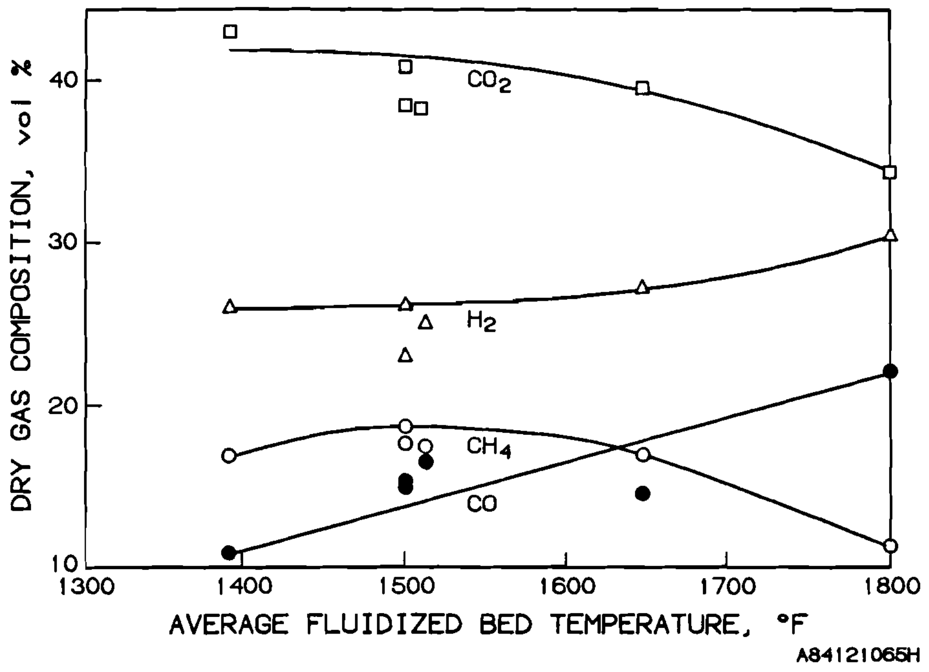


Figure 36. PRODUCT GAS COMPOSITION AS A FUNCTION OF GASIFICATION TEMPERATURE (Maple Feed: Gasification Tests GT-1 through GT-8)

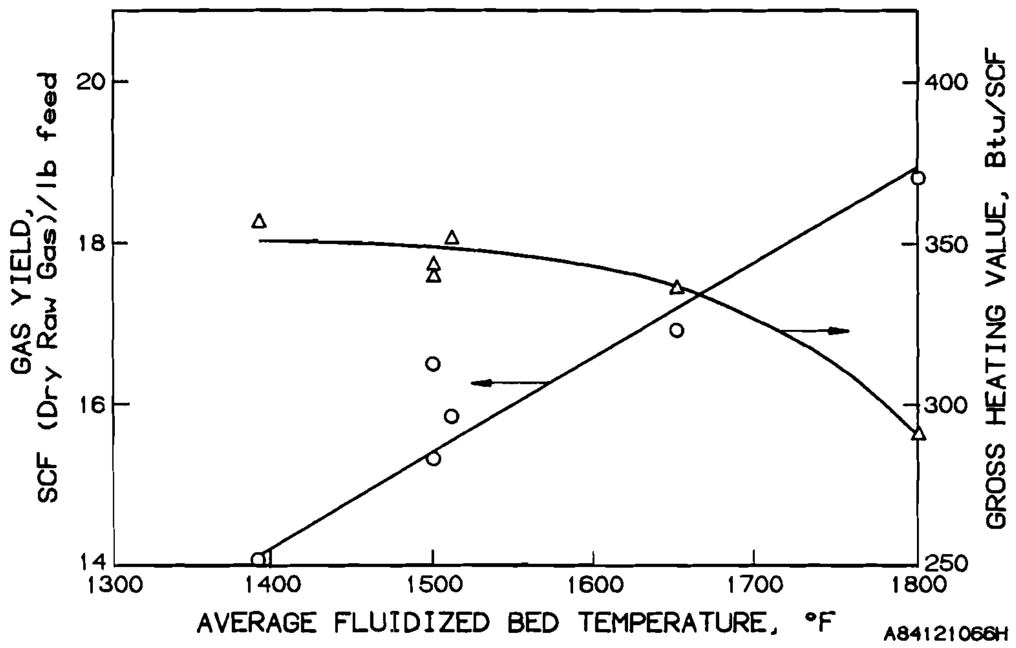


Figure 37. GAS YIELD AND HEATING VALUE AS A FUNCTION OF TEMPERATURE (Maple Feed: Gasification Tests GT-1 Through GT-8)

feed moisture content increases (see Tests GT-13, GT-14, GT-15, and GT-17 in Table 15), so the representative level of 10% feed moisture was chosen in the gasification tests as any commercial process would operate at a moisture level somewhat above bone dry.

The measured oxygen requirement varies from 0.17 lb oxygen/lb feed for the test at 1390°F to 0.34 lb oxygen/lb feed for the highest temperature test at 1800°F. For the gasification tests with maple hard wood at 1500°F and 300 psig, the oxygen required was in the range of 0.21 to 0.24 lb/lb of approximately 10% moisture feed. Gasification of Pennsylvania whole tree chips at the same operating conditions required 0.23 to 0.25 lb oxygen/lb feed and the Wisconsin whole tree chips required 0.23 to 0.27 lb oxygen/lb feed. It is possible that the higher bark content in the whole tree chips, compared to the pulpwood quality maple chips, may be the reason for the slightly higher oxygen requirement.

As expected, carbon conversion in the gasification process increases with increasing fluidized-bed temperature as shown in Figure 35. The total carbon conversions for all the tests, at 1500°F and 300 psig, is in the range of 92% to 96%, except Test GT-13, which has a measured carbon conversion of 89.9%. In this one case, the oils and tar yields measured were unusually low, and a 2% increase in the measured oil yield value (typical of other tests) would raise the total carbon conversion to the same level.

The carbon utilization could be further improved by recycling the elutriated carbon to the high-temperature region of the gasifier. Figure 35 also shows the amount of condensibles produced decreases with increasing temperature. The oils and tar yields for all the tests at 1500°F and 300 psig, for the three feedstocks, are in the range of 1.8 to 2.2 lb/100 lb feed. These condensible organics would contribute heating value to the fuel gases in applications where noncondensing conditions could be maintained between the gasifier and the combustor. In processes where the condensibles would have to be separated, the oils and tars could be gasified by recycling to the high-temperature gasification zone.

The effect of gasification temperature on gas composition is shown in Figure 36. In the temperature range of 1390° to 1800°F, the methane content reaches a maximum at about 1500°F and is reduced at higher temperatures. The hydrogen concentration increases with temperature; the observed hydrogen is produced during biomass devolatilization, steam-char gasification, and the reforming of light and heavy hydrocarbons. Superimposed on these reactions is the water-gas shift reaction, which further alters the overall gas composition. As expected, carbon monoxide increases steadily with temperature, whereas temperature has an inverse effect on carbon dioxide.

The gas yields and their gross heating values are shown as a function of temperature in Figure 37. The results conform with the anticipated trends of increased gas yields coupled with decreasing heating value as the gasification temperature is raised. The reforming of light hydrocarbons, such as methane and ethane, above 1500°F is the reason for the reduction in the fuel gas heating value. The heating value is about 350 Btu/SCF at 1500°F, which is considered a good quality medium-Btu gas.

Effect of Steam Feed Rate

With maple wood chips, Tests GT-1, GT-6, GT-8, and GT-9 were conducted at different steam-to-wood ratios ranging from 0.50 to 0.86 lb steam/lb biomass feed. For the analyzed results for these tests it is observed that steam feed rate has very little effect on gas composition as shown in Figure 38. The small variations in the concentrations of CO_2, H_2, CH_4, and CO can be attributed to the small differences in pressure and temperature that may alter the extent of the water-gas shift reaction and reforming of hydrocarbons. The biomass carbon conversion is also not affected by the amount of steam input. The total carbon conversion is 92% for three of the tests and 92.7% for the other test. The results also show, as expected, that additional steam input contributes only to the undecomposed steam content in the product gas and does not affect the relative content of other gaseous constituents. This is, however, slightly different for the whole tree chip feedstocks from Pennsylvania and Wisconsin, which show some variations as indicated in Figures 39 and 40. The gas composition is at most slightly affected by steam input amounts; however, the character of the oils and tars from these tests is significantly affected as is shown later.

Effect of Operating Pressure

Test GT-10 was operated at 90 psig to investigate the effect of system pressure on gasifier performance, using maple wood chips as feed material. Results from this test were compared with Test GT-8 conducted at 300 psig

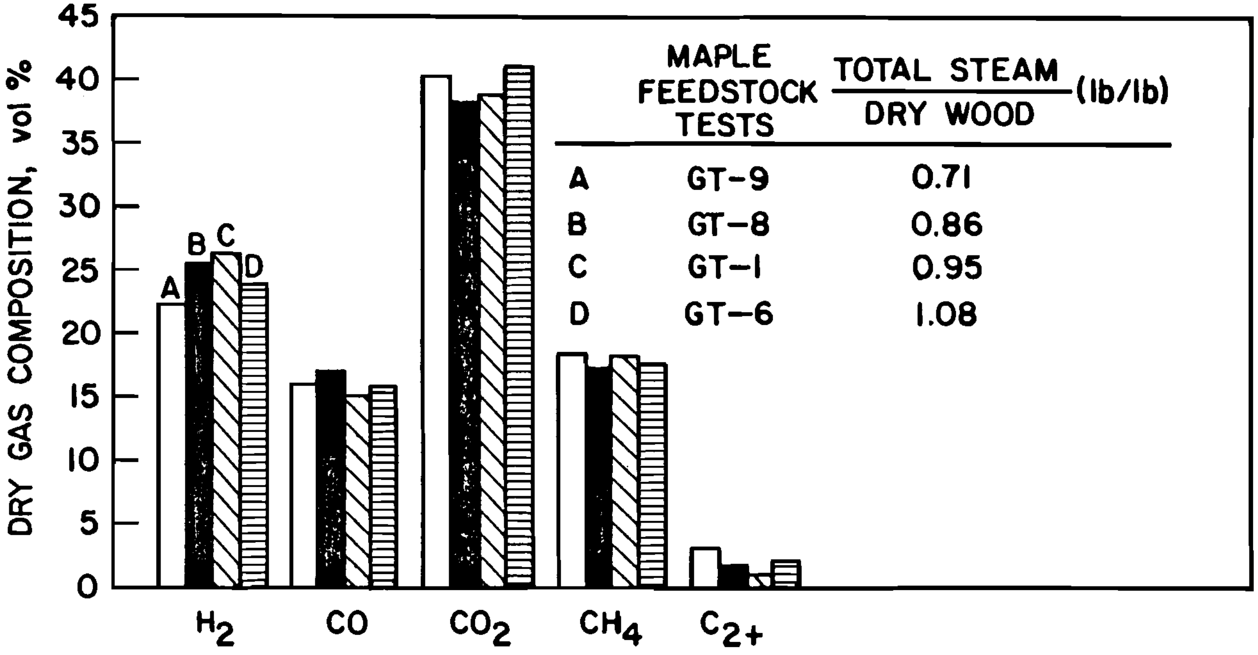


Figure 38. EFFECT OF STEAM ON PRODUCT GAS COMPOSITION
(Maple Feed)

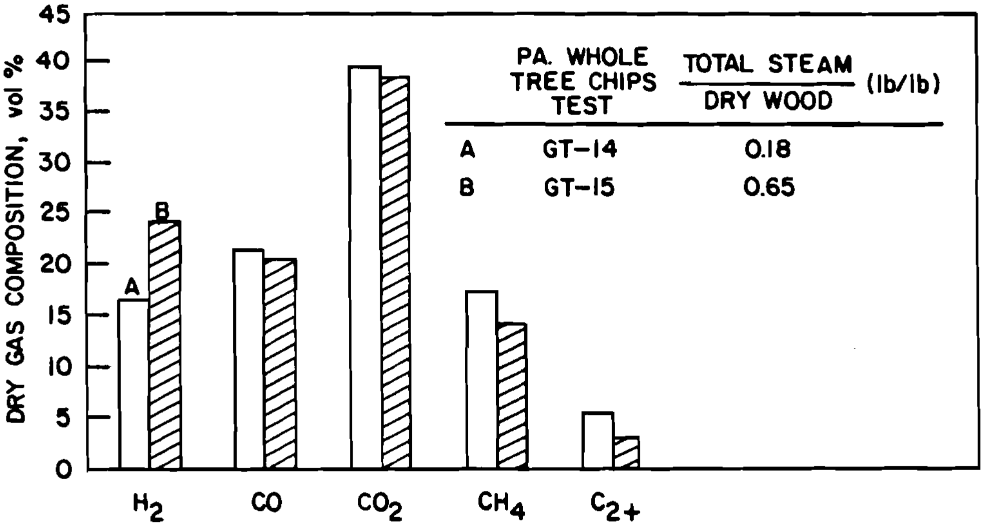


Figure 39. EFFECT OF STEAM ON PRODUCT GAS COMPOSITION (Whole Tree Chips From Pennsylvania)

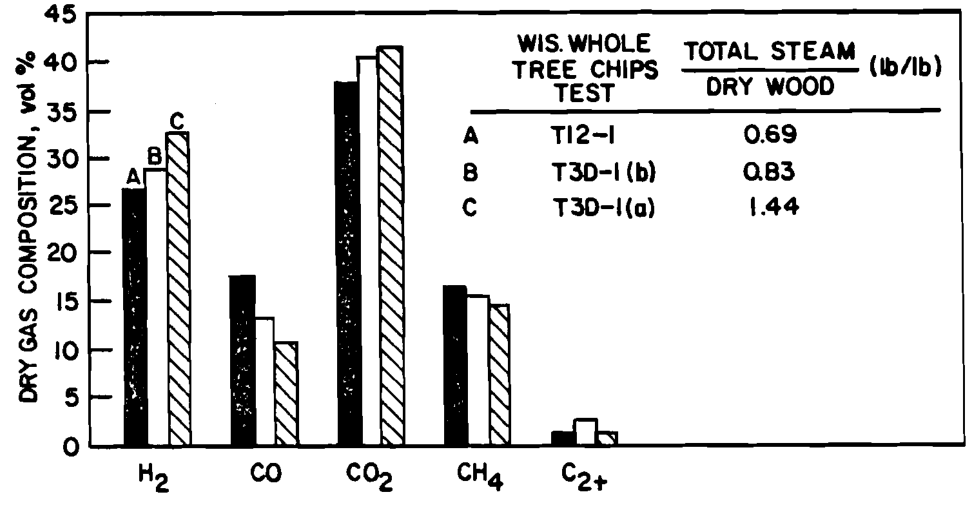


Figure 40. EFFECT OF STEAM ON PRODUCT GAS COMPOSITION (Whole Tree Chips From Wisconsin)

because of the similar steam and oxygen feed rates relative to the biomass feed rate. For the low-pressure case, in order to maintain the proper superficial gas velocity in the gasifier, the throughput rate was decreased by about 50% in comparison to Test GT-8. Under the conditions of different through-put rates at different pressures, the comparison shows that the low-pressure gasification test resulted in a higher carbon conversion to gas and a lower production of oils and tars. A comparison of the gas composition shows that the concentration of the major gaseous components is nearly the same, except for the anticipated lower methane yield at the lower pressure. The apparent higher hydrocarbons content in the product gas for Test GT-10 explains the higher heating value and consequently the higher cold-gas thermal efficiency in comparison to Test GT-8.

A comparison of Tests T12-1 and T12-2 with the 12 hour steady-state gasification periods conducted at 300 psig and 102 psig, respectively, with Wisconsin whole tree chips shows that the low-pressure test resulted in slightly lower carbon conversion. However, the methane content is lower and higher concentration of higher hydrocarbons are observed in the low-pressure Test T12-2 in comparison to the high-pressure Test T12-1. Because of the high concentration of the higher hydrocarbons, the low-pressure gasification test resulted in a higher dry inert-free heating value gas compared to the latter. But, due to the lower carbon conversion and gas yield, the cold-gas thermal efficiency for the low-pressure test is lower than that of the high-pressure test.

Effect of Feed Rate

The operating conditions for Test GT-11 were 1500°F and 300 psig at a maple wood feed rate of 1030 lb/h. The wood feed rate was increased in a stepwise manner to 1030 lb/h, which was the PRU design capacity, and maintained at this feed rate for a steady-state period of 4-1/2 hours before the test was voluntarily terminated.

A comparison of the results from Tests GT-9 and GT-11 in Table 15, shows the effect of the variation in feed rates. The oxygen requirement, total carbon conversion, product gas heating value, calculated cold gas thermal efficiency, and gas yield per pound of biomass feed are roughly the same for both tests. The only apparent difference is in the product gas composition. The higher feed rate test shows higher carbon monoxide and lower carbon dioxide concentrations, which could be simply a function of the extent of the water-gas shift reaction occurring within the gasification system. Similar carbon conversions and cold-gas thermal efficiencies show that the PRU did not approach its limiting throughput rate at the 1030 lb/h value.

Effect of Feedstock Type and Role of Steam

Test GT-13 was the first test using whole tree chips as feed material. No operational difficulties were encountered during the approximately 4-hour steady-state period with this waste feedstock.

Test GT-14 was conducted to investigate gasifier operation with no external steam addition other than that from the moisture content of the whole-tree-chip feed and the chemically produced water. Steam produced from the 15% moisture in the wood feed and from chemically produced water accounted for a steam-to-wood ratio of 0.23 lb/lb. For this test, the steam normally used was replaced with nitrogen to maintain a minimum fluidization velocity near the oxygen distributor and the feed location. The nitrogen was heated to about 900°F before entering the gasifier distributor ring and nozzle. No operational difficulties were encountered using nitrogen gas as the fluidizing medium.

For Test GT-15, the PRU steam flow control system was modified to permit nitrogen to mix with steam at the entrance to the gasifier. This provided a steam-to-wood ratio of 0.41 lb/lb for this test. With the existing system it is not possible to superheat both nitrogen and steam; therefore, cold nitrogen was added to steam, reducing the fluidizing-gas temperature to 640°F from the normal operating temperature of about 800° to 850°F. To obtain a gasifier bed temperature of 1500°F, increased oxygen flow was required to compensate for the mixture of cooler fluidizing steam and nitrogen.

A comparison of the dry gas compositions from Tests GT-14 and GT-15 in Figure 39 shows a higher carbon monoxide content and a lower hydrogen concentration in Test GT-14. This difference can be attributed to the low steam-to-wood ratio in Test GT-14, which could alter the extent of the water-gas shift equilibrium reaction. Less of the higher hydrocarbons were observed in Test GT-15, suggesting their possible reforming in the presence of excess steam.

Effect of Bed Height

The purpose of Test GT-16 was to investigate the effect of bed height on process performance. The fluidized-bed L/D was kept between 3 and 4 compared with previous maple wood feed tests with a ratio of about 6. Results from Test GT-16 were compared with those from Tests GT-1 and GT-8. All three tests were conducted with otherwise similar operating conditions using maple wood chips as feed material. The results indicate that Test GT-16 produced a lower methane concentration coupled with higher concentrations of ethane and C_6+ hydrocarbons. This could be attributed to the lower gas residence time in the inert solids fluidized-bed reactor section allowing less time for reforming of hydrocarbons.

Effect of Moisture

Comparing Test GT-17 with a higher feed moisture to Test GT-15 with a lower feed moisture, but otherwise similar operating conditions, there is also a significant difference in the product gas concentrations of CO and CO_2 in addition to the obvious increase in oxygen demand for the higher moisture content feed material. The higher moisture feed produces a product gas with a higher concentration of CO_2 and a lower concentration of CO when compared with the test with a lower moisture content feed material. This can be explained by the higher demand for combustion for drying biomass inside the gasifier, and the simultaneously occurring water-gas shift reaction in which there is more water available to convert CO to CO_2 and H_2. A comparison of the measured raw gas composition with the calculated equilibrium gas composition shows that the gas composition is closer to equilibrium in the higher feed moisture content test. The high moisture feed test also resulted in little or no oils and tars compared to the nearly 2% oils and tars measured in Test GT-15. It is not clear whether the higher oxygen demand for the high moisture feed, extended the combustion zone within the gasifier to the extent that the devolatilized oils and tars were selectively combusted as they were formed or whether there were slight measurement errors. The lower product gas heating value can be attributed to the lower amounts of higher hydrocarbons produced from the higher moisture feed material.

Environmental Aspects

Some of the by-products of biomass gasification will require treatment or removal before they can be discharged to the environment. These include ammonia, phenols and other organic acids, benzene, and polyaromatic hydrocarbons and potentially, sulfur-containing gases. Due to the low sulfur content (0.02 to 0.04 weight percent) of the feedstock, the formation of sulfur compounds is well within all foreseeable standards. Small amounts (0 to 150 ppm) of COS were occasionally found in the product gas sample bombs, but no H_2S has been detected to date.

Ammonia, phenol, cresols, acetic acid, methanol, and other water-soluble heterocyclic organic compounds were found in the aqueous phase of the gasifier condensate. Due to the presence of ammonia, the pH of the condensate was generally around 8.0, and it was well-buffered, which is favorable for biological wastewater treatment processes which are sensitive to pH. The levels of all water-soluble organic species in the condensate are indicated by total organic carbon (TOC). It was found that TOC in the aqueous effluent declines with increasing gasification temperature; this is shown in Figure 41.

An oil phase is also present in the gasifier condensate. This has been extensively analyzed by GC/MS, and the results are tabulated in Table 18. Oil components were predominantly aromatic hydrocarbons, with naphthalene and benzene as the most abundant species. In contrast to coal-derived oils, no aliphatic hydrocarbons were identified, although some could be present in the unidentified portions, which comprised 3% to 11% of the total oil. Oxygenated species accounted for 0.4% to 7.5% of the oil collected and included phenols, naphthols, and furans. Nitrogen- and sulfur-containing oil components were very low, which is to be expected from the low sulfur and nitrogen content of the feed.

Polyaromatic hydrocarbons (PAH) are organic compounds containing two or more fused benzene rings. Two- and three-ring hydrocarbons, such as naphthalene and phenanthrene, do not pose any special environmental hazards. Compounds with four or more condensed rings, however, generally include hazardous substances such as fluoranthene, chrysene, and benz(a)pyrene. In this section, PAH will refer to the latter class of compounds, those with more than three fused rings. Although higher temperatures tend to favor the condensation reactions that produce these substances, the data show that the

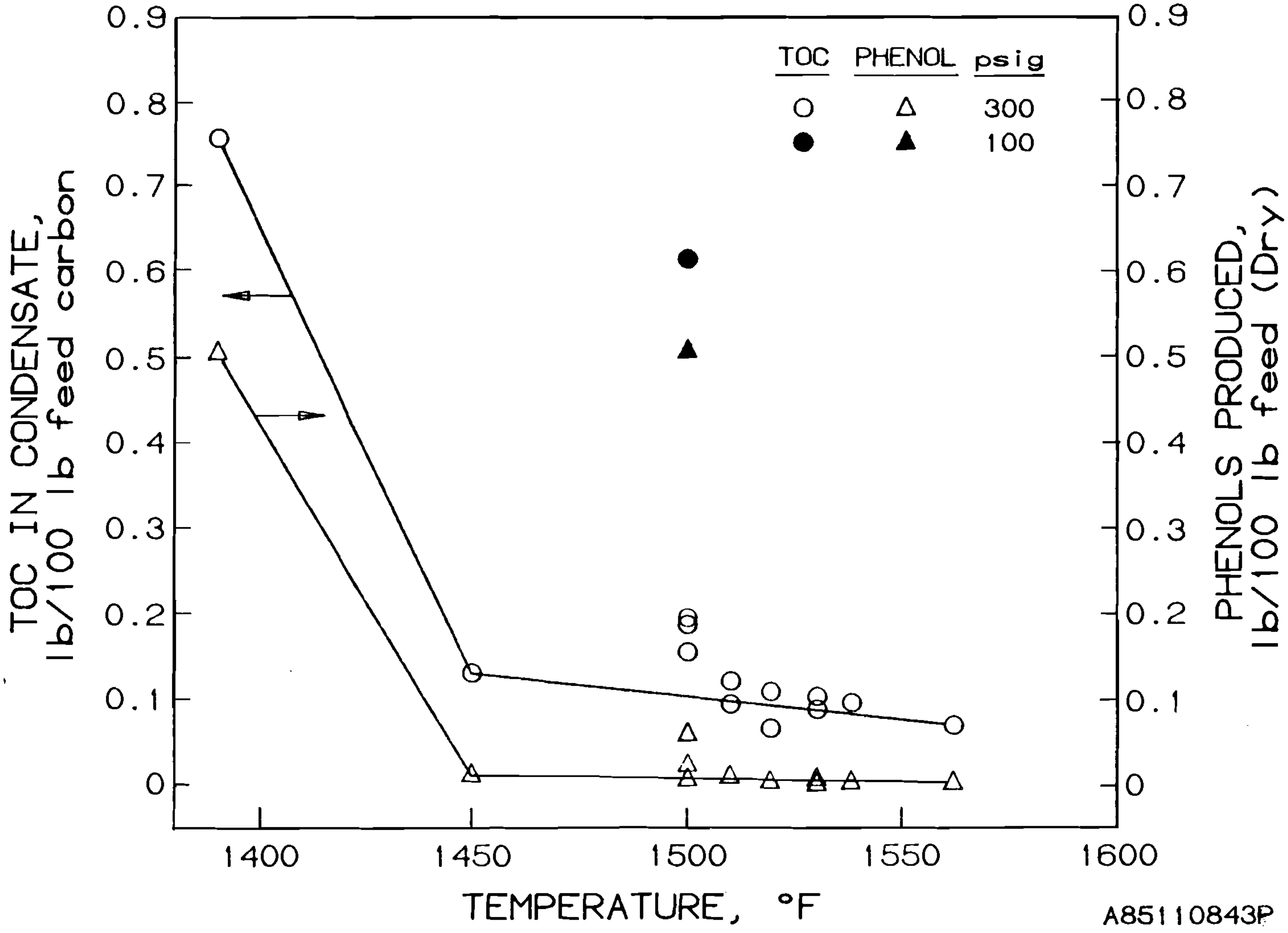


Figure 41. PRODUCTION OF PHENOLS AND TOTAL ORGANIC CARBON IN CONDENSATE AS A FUNCTION OF GASIFICATION TEMPERATURE

Table 18. COMPOSITION OF OILS FOUND IN PRODUCT GAS IN PRU GASIFICATION TESTS

Test No.	GT-5	GT-6	GT-8	GT-9	GT-10	GT-11	GT-13	GT-14	GT-15
Temperature, °F	1390	1500	1510	1500	1465	1500	1520	1510	1520
Oil Yield, lb/100 lb biomass*	2.84	2.18	1.33	1.83	0.34	2.33	1.66	3.00	2.26
Products, wt % in Oils									
One-Ring Hydrocarbons	28.6	30.6	24.4	40.8	15.0	39.9	8.4	31.2	26.8
Benzene	8.9	24.9	20.1	36.2	4.1	34.9	6.1	23.7	23.9
Toluene and Xylenes	12.1	2.9	2.3	2.1	2.9	2.3	0.7	4.7	1.2
Others	7.6	2.8	2.0	2.6	8.0	2.7	1.6	2.9	1.7
Two-Ring Hydrocarbons	28.8	39.0	39.5	33.5	40.4	29.7	54.5	32.2	36.5
Naphthalene	17.6	32.2	32.1	28.4	26.5	24.5	48.7	25.7	30.3
Methylnaphthalene	4.5	0.9	0.8	0.6	3.0	0.6	0.6	1.2	0.6
Others	6.7	5.9	6.6	4.5	11.0	4.5	5.3	5.4	5.6
Three-Ring Hydrocarbons	14.0	10.8	13.2	9.1	20.3	10.3	12.3	11.6	11.7
Fluorene	3.5	2.8	2.6	2.2	4.3	2.2	3.2	2.2	2.3
Phenanthrene and Anthracene	5.8	7.0	8.6	5.9	11.8	6.6	7.9	7.5	7.9
Others	4.7	1.8	2.0	1.0	4.3	1.5	1.3	1.9	1.5
Four-Ring Hydrocarbons	9.6	9.7	13.3	8.2	13.2	10.7	10.1	10.8	12.6
Five-Ring Hydrocarbons	2.2	2.2	2.6	2.4	2.5	3.1	4.1	4.4	4.7
Higher Aromatic Hydrocarbons	0.0	0.8	1.4	1.8	1.0	1.9	1.6	2.4	2.6
Total Hydrocarbons	83.2	93.1	94.4	95.8	92.4	95.6	91.1	92.6	94.8
O-Containing Compounds	7.5	1.1	0.9	0.7	3.5	1.0	0.5	1.9	0.4
Phenol and Cresols	3.2	0.1	0.04	0.1	0.4	0.1	0.0	0.9	0.04
Benzofurans and Dibenzofurans	3.7	1.0	0.6	0.5	2.4	0.7	0.004	1.0	0.4
Others	0.6	0.0	0.3	0.1	0.7	0.2	0.1	0.02	0.03
N-Containing Compounds	0.7	0.4	0.3	0.4	0.5	0.5	0.4	0.9	0.7
S-Containing Compounds	0.2	0.1	0.02	0.02	0.04	0.02	0.2	0.0	0.01
Total Heterocyclic Compounds	8.4	1.6	1.2	1.1	4.0	1.5	1.1	2.8	1.1
Unidentified Compounds	8.4	5.3	4.4	3.1	3.6	3.0	7.8	4.6	4.1

* Dry Basis.

Table 18, Cont. COMPOSITION OF OILS FOUND IN PRODUCT GAS IN PRU GASIFICATION TESTS

Test No.	GT-16	T12-1	T12-2	T3D-1a	T3D-1b	T12-3a	T12-3b	T12-4a	T12-4b
Temperature, °F	1450	1530	1500	1538	1562	1672	1413	1509	1516
Oil Yield, lb/100 lb biomass*	1.96	3.16	3.32	1.65	1.93	1.12	3.51	2.69	2.48
Products, wt % in Oils									
One-Ring Hydrocarbons	31.5	18.2	23.5	21.8	26.0	17.2	38.8	15.1	11.9
Benzene	26.1	14.9	9.0	19.5	23.2	15.6	27.5	6.6	6.7
Toluene and Xylenes	2.0	1.0	7.1	0.8	1.2	0.6	6.6	2.2	1.1
Others	3.4	2.3	7.4	1.5	1.6	1.0	4.6	6.2	4.1
Two-Ring Hydrocarbons	33.8	38.3	39.0	46.9	39.5	35.9	35.8	41.8	42.3
Naphthalene	28.5	31.9	27.0	41.1	33.4	32.7	27.9	30.2	32.4
Methylnaphthalene	0.6	0.4	3.9	0.6	0.9	0.5	1.9	2.2	1.5
Others	4.7	6.0	8.1	5.2	5.1	2.8	6.0	9.4	8.4
Three-Ring Hydrocarbons	9.2	16.6	12.5	12.1	12.8	11.6	9.8	16.0	14.9
Fluorene	2.3	2.3	2.7	2.6	2.5	1.3	3.0	3.6	2.9
Phenanthrene and Anthracene	5.8	9.7	7.3	8.2	8.4	7.9	4.9	8.9	8.9
Others	1.1	4.6	2.5	1.3	1.9	2.4	1.9	3.6	3.1
Four-Ring Hydrocarbons	8.2	13.4	7.3	10.9	11.3	17.1	5.3	10.6	12.6
Five-Ring Hydrocarbons	3.4	4.9	3.0	3.1	3.3	6.8	1.2	4.1	5.1
Higher Aromatic Hydrocarbons	2.0	2.6	0.8	1.1	1.7	5.7	1.0	2.8	3.0
Total Hydrocarbons	88.0	94.0	86.1	95.9	94.6	94.2	91.9	90.4	89.8
O-Containing Compounds	0.6	0.6	2.6	0.3	0.3	0.1	2.5	2.8	2.0
Phenol and Cresols	0.04	0.02	1.0	0.0	0.0	0.0	1.0	0.3	0.1
Benzofurans and Dibenzofurans	0.5	0.3	1.6	0.3	0.3	0.1	1.5	2.3	1.8
Others	0.01	0.3	0.0	0.0	0.0	0.0	0.0	0.2	0.1
N-Containing Compounds	1.3	0.8	1.4	0.08	0.7	0.3	0.8	0.8	1.1
S-Containing Compounds	0.02	0.3	0.03	0.0	0.1	0.0	0.0	0.02	0.2
Total Heterocyclic Compounds	1.9	1.7	4.0	0.4	1.1	0.4	3.3	3.6	3.3
Unidentified Compounds	10.1	4.3	9.9	3.7	4.3	5.4	4.9	6.0	6.9

* Dry Basis.

171/65058fr-t/RPP

overall yield of oils and tars in the PRU decreased considerably at the higher temperatures, so that the net environmental burden may actually be less. This can be seen graphically in Figure 42, which compares Tests GT-5 and GT-8.

It is apparent from the data shown in Table 18 and Figure 42 that higher operating temperatures, in addition to reducing the oil yield, also cause a sharp decline in the relative concentrations of heterocyclic and alkyl-substituted hydrocarbons in favor of unsubstituted aromatic hydrocarbons. Referring back to Figure 41, it is seen that the overall yield of phenols, which is distributed between the aqueous and organic phases of condensate, declines by 97% to 99% when the gasification temperature is increased to 1510°F from 1390°F.

There is also a relationship between the amount of steam present in the gasifier (steam input plus biomass feed moisture) and the nature of organic liquids produced. Figure 43 shows that the concentration of oxygenated oil components, as well as the overall phenols yield, declines as the steam-to-wood ratio is increased. Although more data points are needed in the range of 0.2 to 0.5 steam-to-wood ratio (lb/lb) to confirm this, it appears that the yield of oxygen-containing oils (phenols in particular) reaches a steady minimum at a value of about 0.7 lb steam/lb wood. The overall oil yield, however, seems to depend more on other factors, such as temperature, pressure, and feed material. Just as the results in Figure 42 showed the dependency of oil yield on gasifier temperature, results in Figures 44 and 45 show how pressure and feed type affect the yield and composition of organic liquids found in the effluent. The production of all organic types except highly condensed aromatics (PAH) was much higher at the lower pressure. The overall yield of oil decreased with increased pressure as well. Most strikingly, the yield of phenols decreased by a factor of 67 with the increase in pressure from 102 to 300 psig, and the yield of water-soluble organics, excluding phenols, likewise declined by a factor of about 7. The results in Figure 45 show that the relative proportions of liquid product types did not change as much with varying feed material, although the total organic liquid yield did. Whole tree chips, with a higher content of bark, leaves, and other non-wood pulp components, did produce more oils than the maple wood chips.

There was a complete absence of oils in the condensate from Test GT-17. This test was performed with wetter (26.7% moisture) wood. The reason for the

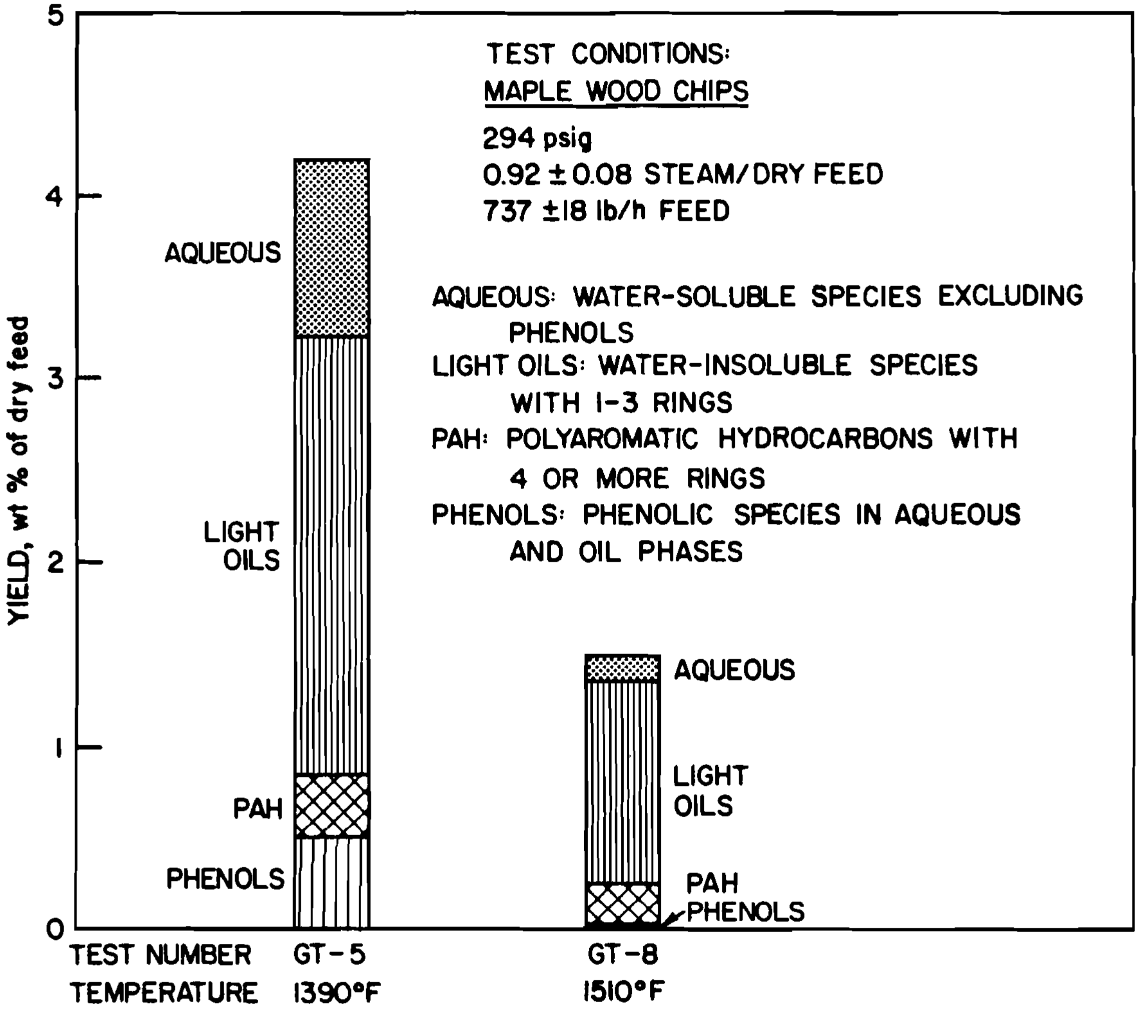


Figure 42. ORGANIC LIQUID YIELD AS A FUNCTION OF TEMPERATURE FOR TESTS GT-5 AND GT-8

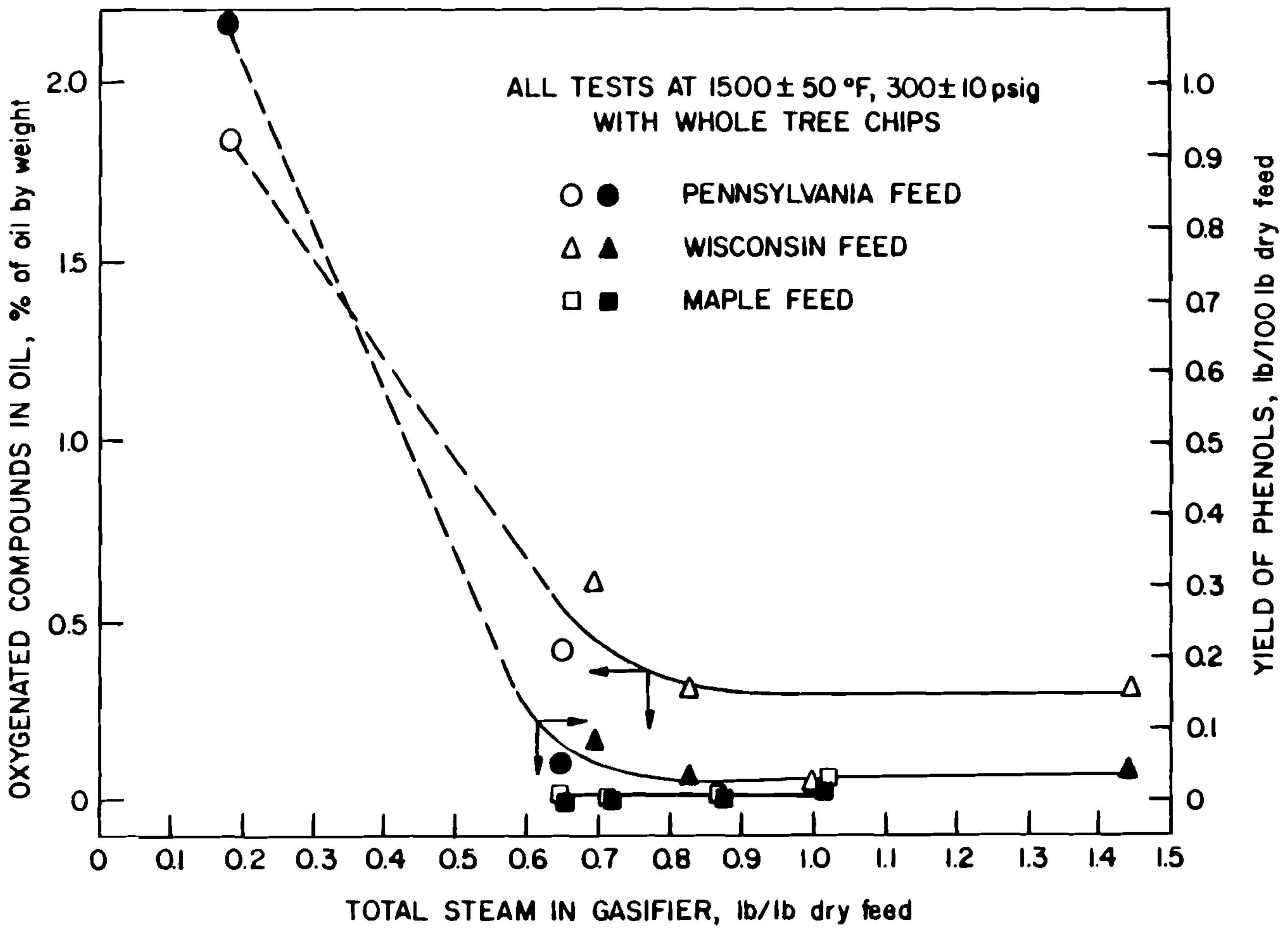


Figure 43. EFFECT OF STEAM ON ORGANIC EFFLUENT

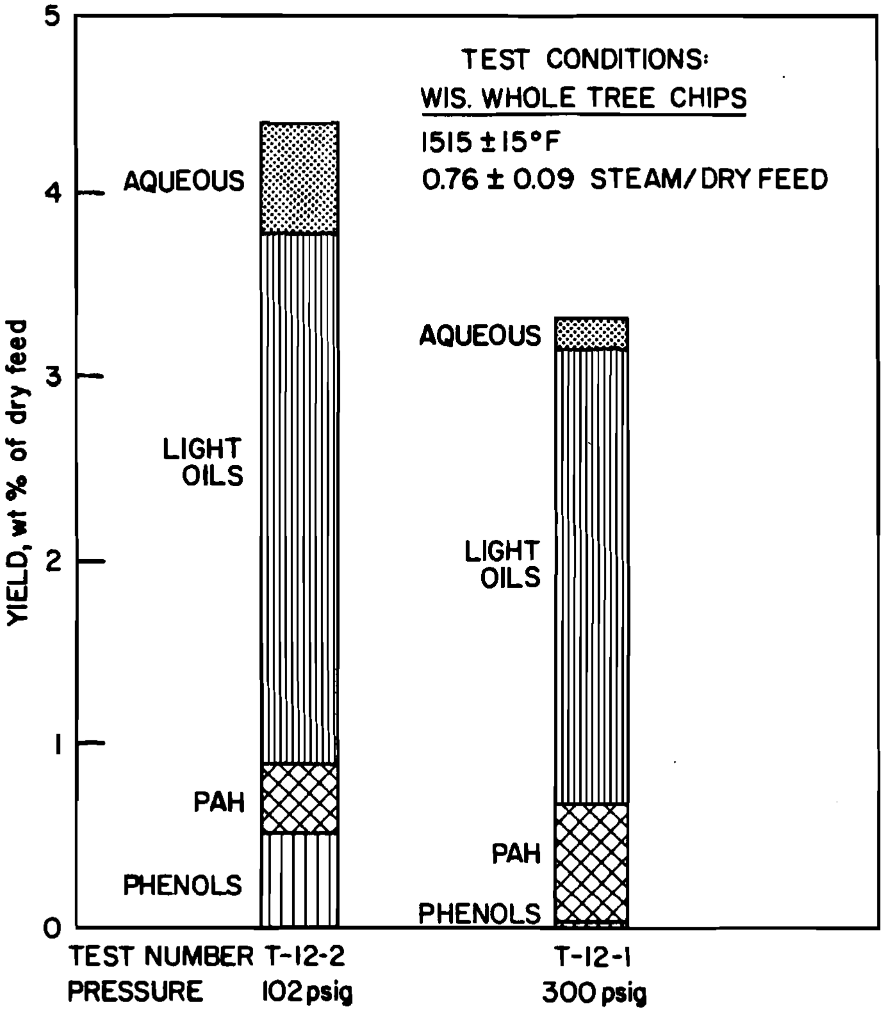


Figure 44. OIL YIELD AS A FUNCTION OF GASIFIER PRESSURE FOR TESTS T12-1 AND T12-2

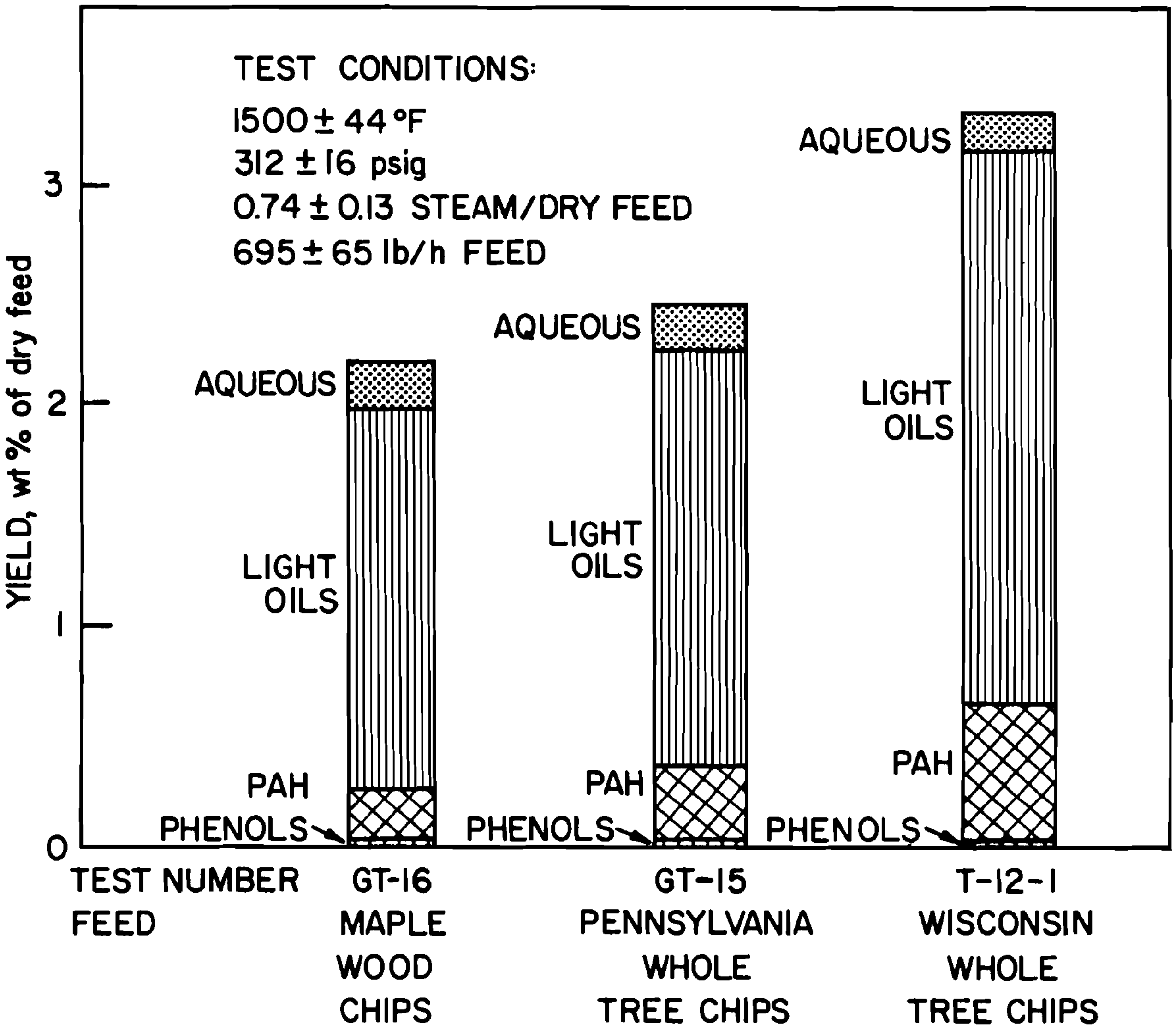


Figure 45. OIL YIELD AS A FUNCTION OF FEEDSTOCK FOR TESTS GT-15, GT-16, AND T12-1

absence of oils is not clear, although it may be related to the high heat demand required to drive water from the incoming feed. A higher oxygen rate was required for combustion to supply this heat, and the combustion of oils as well as some gaseous hydrocarbons may have occurred.

In conclusion, the analyzed data indicate that the production of organic liquid by-products can be minimized by increased temperature and pressure, but may also be somewhat related to feed type. From an environmental standpoint, conditions that favor lower concentrations of oxygenated, water-soluble components, particularly phenols, are desirable. These include higher temperature and pressure, and a steam-to-wood ratio above a minimum value which is in the neighborhood of 0.6 to 0.7 lb/lb. Dealkylation and dehydroxylation reactions, which bring about the decomposition of such undesirable by-products are favored by high hydrogen partial pressure and high temperature. Hydrogen in this case is supplied by the decomposition of steam through water-gas shift and steam-carbon reactions, as well as direct reactions of steam with organic liquid species in the gasifier.

CONCLUSIONS

The Institute of Gas Technology (IGT) has conducted a pressurized, fluidized-bed biomass gasification process development program from laboratory-scale, bench-scale, and PRU process and equipment design phases to the construction and operation of a large-scale 12-TPD PRU system. The program culminated with the successful operation of the PRU over a range of process condition parameters and a successful 3-day steady-state operation of the pressurized fluidized-bed gasifier and auxiliary equipment.

The PRU support research and PRU tests were conducted with woody biomass, maple wood chips, and whole tree chips (a mixture of hard and soft wood species). A pressurized isokinetic probe, designed and constructed at IGT, coupled with a successfully operating wet-gas chromatograph significantly improved the data acquisition and analysis capability.

Test results (up to 3 days of steady-state operation) have shown that pressurized, fluidized-bed gasification at 300 psig, 1500°F, and feed rates up to 1030 lb/h of whole tree chips is a simple operation. Material and energy balances showed that the total carbon conversion is about 95% in the long-duration tests; this could be further increased by recycling the entrained char to the high-temperature region of the gasifier. The oxygen requirement at 1500°F was about 0.22 lb/lb of feed material. Over the temperature range of 1400° to 1800°F in the parameter-variation tests, the dry gas yield ranged from 14 to 19 SCF/lb feed, and the gross calorific value of the fuel gas ranged from about 340 to 290 Btu/SCF, respectively. The cold gas thermal efficiency at 1500°F and 300 psig operation was about 75%.

Analyzed data of the small oil and tar fraction indicated that its production is dependent upon feedstock type and can be reduced by increased gasification temperature and pressure. The new information obtained in this program on the oil and tar fraction is important environmentally and impacts upon the scope and duty of process cleaning equipment.

ACKNOWLEDGMENTS

Contributions by Dr. G. R. Rose and Dr. R. F. Zabransky on biomass devolitilization and Dr. S. P. Nandi on char gasification are gratefully acknowledged. Dr. T. M. Knowlton and his staff assisted in the fluidization cold flow modeling studies. Mr. Gregory Kosowski's efforts in the construction and early operation of the PRU were vital to the success of this program. IGT acknowledges the helpful guidance provided by Mr. Mark Gerber and Mr. Gary Schiefelbein of PNL and Mr. Simon Friedrich of U.S. DOE.

REFERENCES CITED

1. Institute of Gas Technology, "Development of Hydroconversion of Biomass to Synthetic Fuels," Final Technical Progress Report, DOE Contract No. DE-AC02-80CS83004, 1981.

2. Kosowski, G. M., Rose, G. R., Nandi, S. P. Singh, S. P., Onischak, M., Zabransky, R. F. and Babu, S. P., "Development of Biomass Gasification to Produce Substitute Fuels," Progress Report to the Thirteenth Biomass Thermochemical Conversion Contractors' Meeting, Arlington, VA., October 1981.

3. Kosowski, G. M., Rose, G. R., Nandi, S. P., Singh, S. P., Onischak, M., Zabransky, R. F. and Babu, S. P., "Development of Biomass Gasification to Produce Substitute Fuels," Project 65058 Technical Progress Report for the period September 15 through December 15, 1981, Institute of Gas Technology, Chicago, March 1982.

4. Engström, S. and Lindman, N., "A New Synthesis Gas Process for Biomass and Peat," in Symposium Papers, Energy From Biomass and Wastes V, Sponsored by Institute of Gas Technology, in Orlando, Florida, January 1981.

5. Waldheim, L. and Rensfelt, E., "Methanol From Wood and Peat in Sweden," in Proceedings of Biomass-to-Methanol Specialists' Workshop, Solar Energy Research Institute, Golden, Colorado, March 3-5, 1982.

6. Sakoda, A., Sadakata, M., Koya, T., Furusawa, T. and Kunii, D., "Gasification of Biomass in a Fluidized Bed," Chem. Eng. J. 22, 221-27 (1981).

7. Nandi, S. P. and Johnson, J., "Relation of Coal Properties to Gasification Reactivity and the Effect of Alkali Metal Catalysts on the Kinetics of Coal Gasification," Final Report GRI-78/0048, National Technical Information Service, Springfield, Virginia, November 1980.

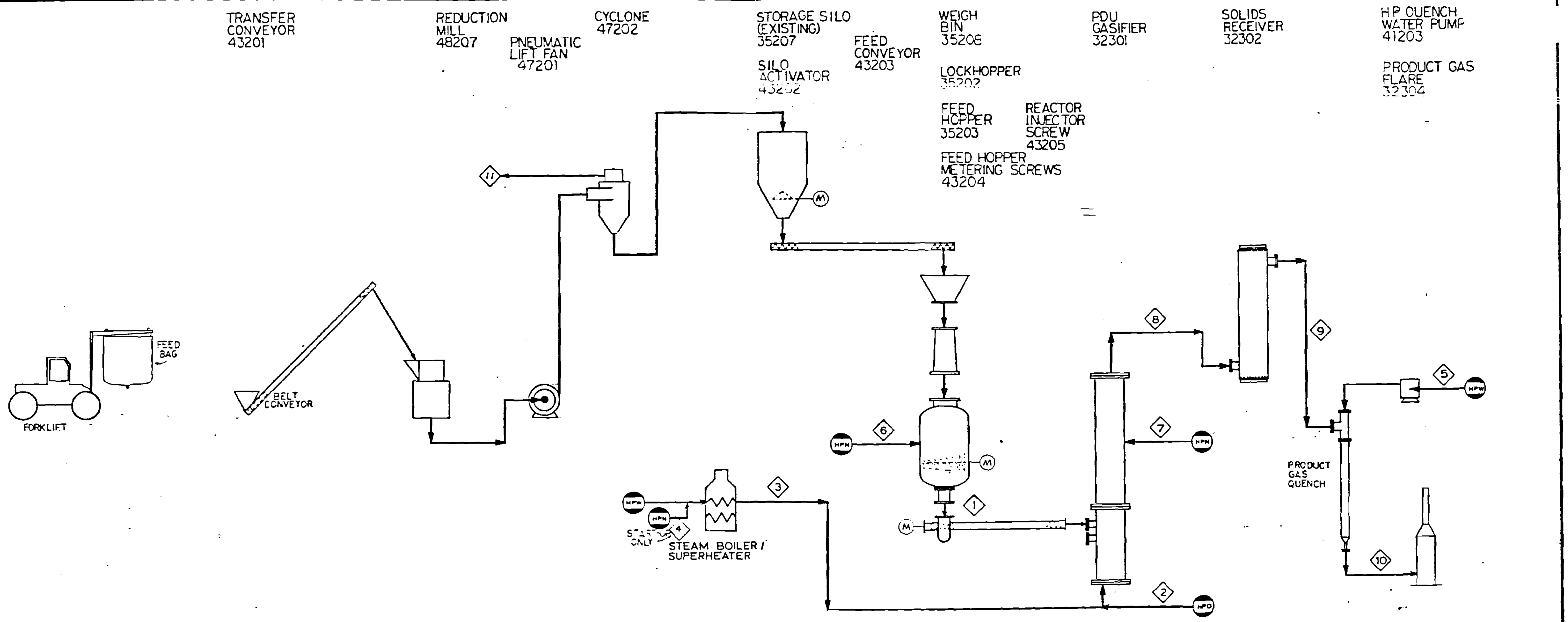
8. Institute of Gas Technology, "Experimental Program for the Development of Peat Gasification," Interim Report No. 2, DOE Contract No. E(49-18)-2649, 1977.

9. Gran, H. S., Nandi, S. P. and Walker, Jr., P. L., "Nature of Porosity in American Coals," Fuel 51, 272 (1972).

10. Roy, T. N. and Nandi, S. P., "Pore Structure of Low Temperature Chars," Fuel 49, 346 (1970).

11. Dubinin, M. M., "Porous Structure and Adsorption Properties of Active Carbons," in Chemistry and Physics of Carbon, Vol. 2, 51-120, New York: Marcel Dekker, Inc., 1966.

APPENDIX A.
Mechanical Design Drawings of the Process Research Unit Test System



MATERIAL BALANCE IN LBS/HR (BASIS - MAPLE CHIPS W/ 10% MOISTURE)

STREAM / MATERIAL	① RAW FEED	② FEED OXYGEN	③ FEED STEAM	④ PRE-HEAT NITROGEN	⑤ QUENCH WATER	⑥ PURGE NITROGEN	⑦ PURGE NITROGEN	◇	◇	◇	◇
WOOD, CHAR, ASH LBS/HR	900										
N_2 (NITROGEN)				505		148	77				
CO (CARBON MONOXIDE)											
CO_2 (CARBON DIOXIDE)											
H_2 (HYDROGEN)											
H_2O (WATER-STEAM/LIQ.)	100		405		523						
O_2 (OXYGEN)		170									
TOTAL LBS./HR	1000	170	405	505	523	148	77				
TOTAL DRY GAS LB. MOL./HR		5.3		18.0		5.3	2.8				
TOTAL WET GAS LB. MOL./HR			22.5								
TOTAL GAS A.C.F.M.		1.5	16.9	14.0		1.5	0.8				
TEMPERATURE °F	70	70	1000	1000	70	70	70				
PRESSURE P.S.I.G.		325	325	325	325	310	310				
DENSITY LBS./FT3	15	1.9	0.4	0.6	62.4	1.6	1.6				
MOLECULAR WEIGHT		32.0	18.0	28.0	18.0	28.0	28.0				

STREAM / MATERIAL	⑧ RAW PRODUCT	⑨ CLEANED PRODUCT	⑩ COOLED PRODUCT	⑪ TRANSPORT AIR	◇	◇	◇	◇	◇	◇	◇
WOOD, CHAR, ASH LBS./HR	27.3										
N_2 (NITROGEN)	225	225	225	42.0							
CO (CARBON MONOXIDE)	199.9	199.9	199.9								
CO_2 (CARBON DIOXIDE)	691.2	691.2	691.2								
H_2 (HYDROGEN)	22.2	22.2	22.2								
H_2O (WATER-STEAM/LIQ.)	441.2	441.2	964.2								
CH_4	110.9	110.9	110.9								
C_2H_4; C_2H_6, C_6H_6 OR $C_{10}H_8$	81.8	81.8	81.8								
H_2S	0.5	0.5	0.5								
O_2				11.0							
TOTAL LBS./HR	1800	1773	2296	53.0							
TOTAL DRY GAS LB. MOL./HR	50.8	50.8	50.8	1.8							
TOTAL WET GAS LB. MOL./HR	75.4	75.4	104.4								
TOTAL GAS A.C.F.M.	83.8	77.7	71.5	11.5							
TEMPERATURE °F	1500	1300	650	70							
PRESSURE P.S.I.G.	300	290	275	14.7							
DENSITY LBS./FT3	0.4	0.4	0.5	0.07							
MOLECULAR WEIGHT	23.5	23.5	22.0	29.0							

LEGEND:

HPO HIGH PRESSURE OXYGEN

HPW HIGH PRESSURE WATER

HPN HIGH PRESSURE NITROGEN

◇ STREAM DESIGNATION

NO	REVISION	BY	CK	DATE
1	REVISE FLOW DIAGRAM AND MATERIAL BALANCE VALUES			4-28-82

TOLERANCES (EXCEPT AS NOTED) REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

DES	KOSOWSKI	12-7-81
DR	JOZEF	12-31-81
CK		
APP		
MATERIAL	—	
SCALE		

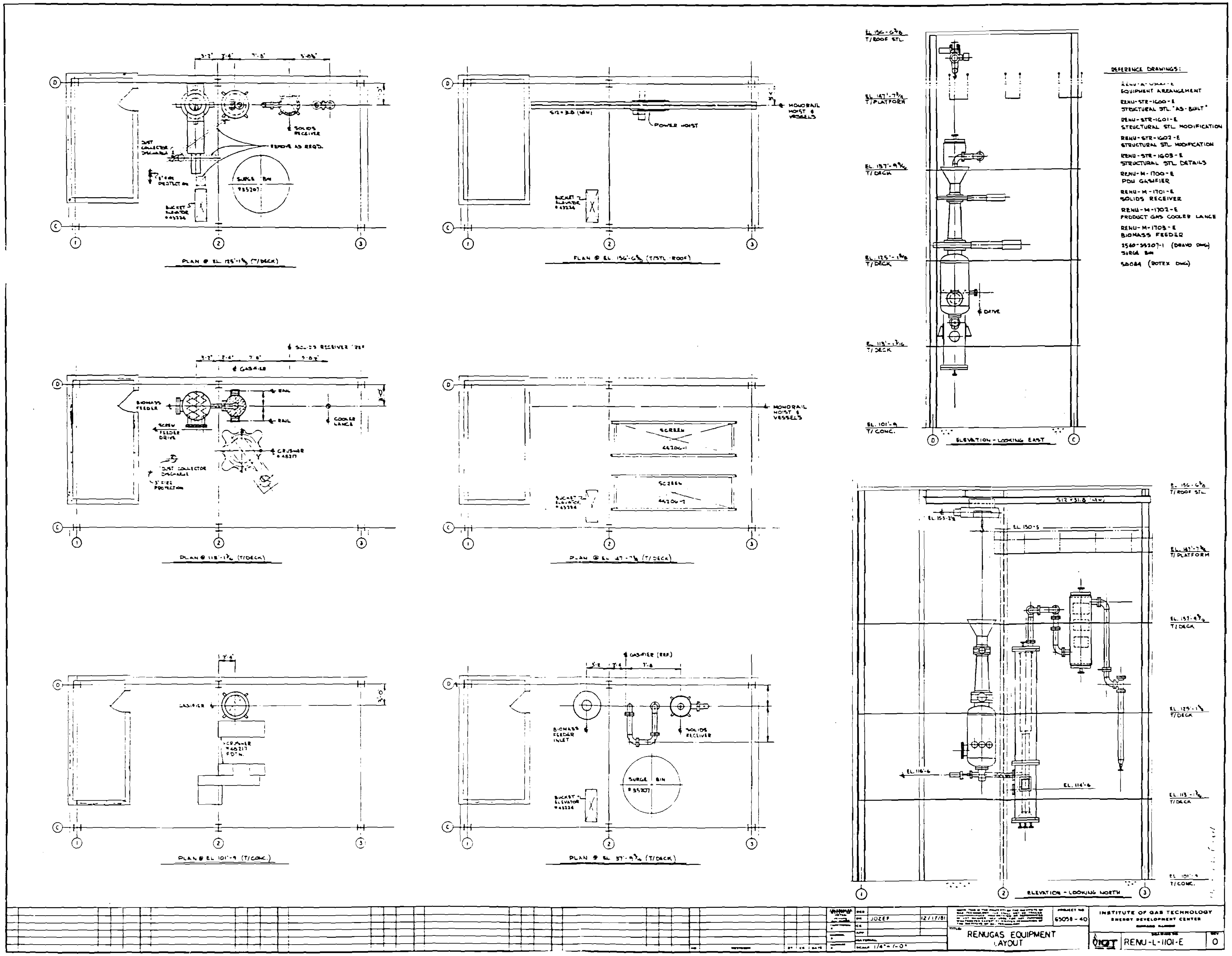
NOTE: THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY AND SHALL NOT BE TRACED, PHOTOGRAPHED, PHOTOSTATED OR REPRODUCED IN ANY MANNER NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

PROJECT NO 65058-40

TITLE: RENUGAS PROCESS FLOW DIAGRAM

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER
CHICAGO, ILLINOIS

IGT DRAWING NO RENU-F-0400-D REV 1



REFERENCE DRAWINGS:

RENU-A-[illegible]-E
EQUIPMENT ARRANGEMENT

RENU-STR-1600-E
STRUCTURAL STL. "AS-BUILT"

RENU-STR-1601-E
STRUCTURAL STL. MODIFICATION

RENU-STR-1602-E
STRUCTURAL STL. MODIFICATION

RENU-STR-1603-E
STRUCTURAL STL. DETAILS

RENU-M-1700-E
PDU GASIFIER

RENU-M-1701-E
SOLIDS RECEIVER

RENU-M-1702-E
PRODUCT GAS COOLER LANCE

RENU-M-1703-E
BIOMASS FEEDER

2540-35207-1 (DRAVO DWG)
SURGE BIN

58084 (ROTEX DWG)

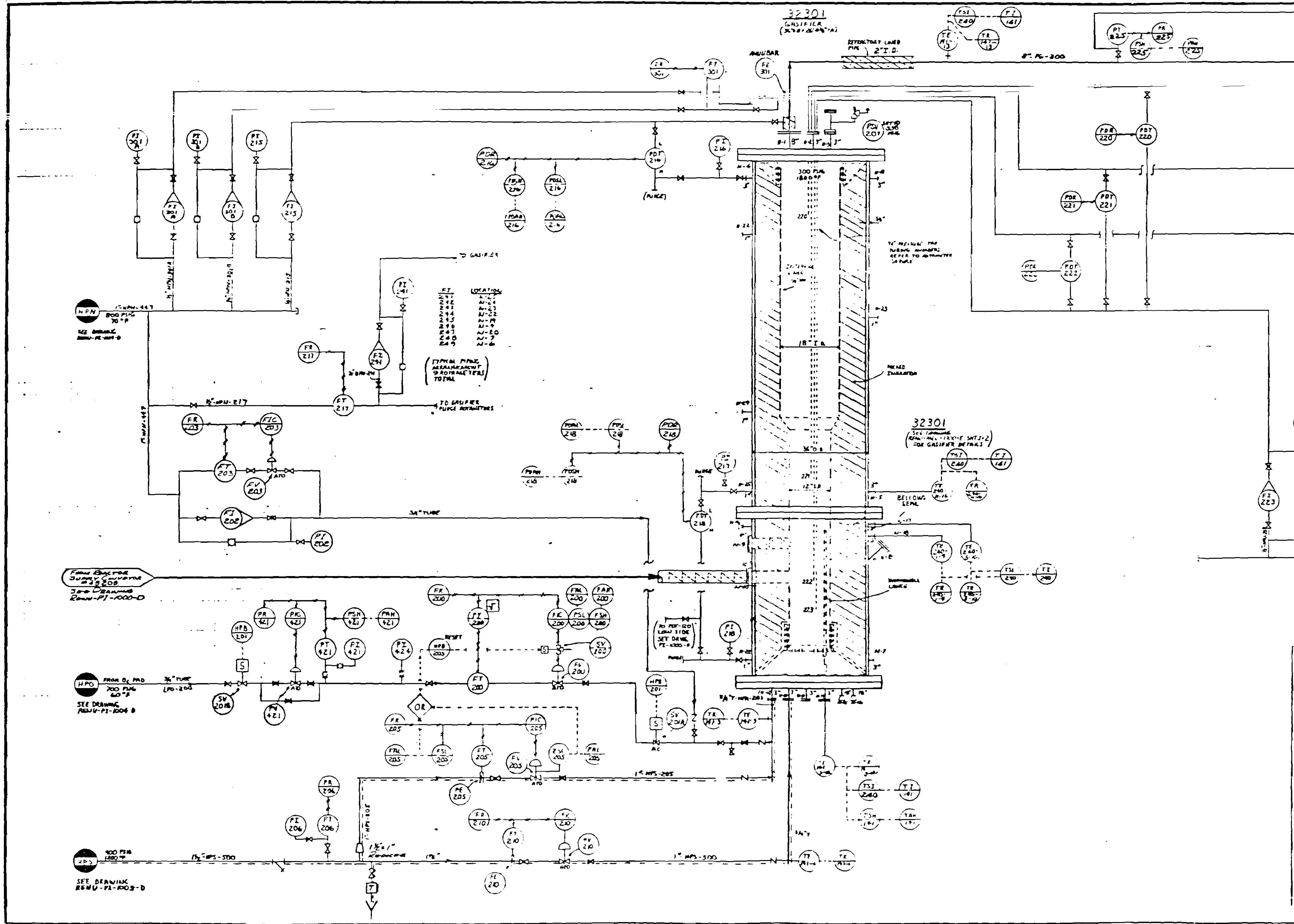
DR	JOZEF	12/17/81
CK		
APP		
SCALE	1/4" = 1'-0"	

PROJECT NO 65058 - 40

TITLE: RENUGAS EQUIPMENT
LAYOUT

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER

IGT RENU-L-1101-E REV 0



NOTES:

1. SEE IGT DRAWING RENU-I-1300-D FOR TE PLACEMENT ON GASIFIER INTERNAL LINER

NO	REVISION	BY	CK	DATE
6	DELETE SOP 219. REVISE ΔP TAPS	GK	GK	4-84
5	ADDED [illegible] HPS-500, ADDED TSI [illegible]	ZPL	JJW	11/4/82
4	[illegible]	SJW	SJW	[illegible]
3	ADDED PV-421, PSV-203 + PSV-214, ADDED [illegible]	SJW	JJW	7/29/82
2	ADDED LINE NO AND GENERAL REVISIONS	SJW	JR	6/28/82
1	REDRAWN + GENERAL REVISIONS	JJW	SJW	4-30-82

TOLERANCES EXCEPT AS NOTED:
REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

DES	KOSOWSKI	12-12-81
DR	J.J. AGUIRRE	1-13-82
CK		
APP		
MATERIAL		
SCALE		

NOTE: THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY AND SHALL NOT BE TRACED, PHOTOGRAPHED, PHOTOSTATED OR REPRODUCED IN ANY MANNER NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

PROJECT NO
65058-40

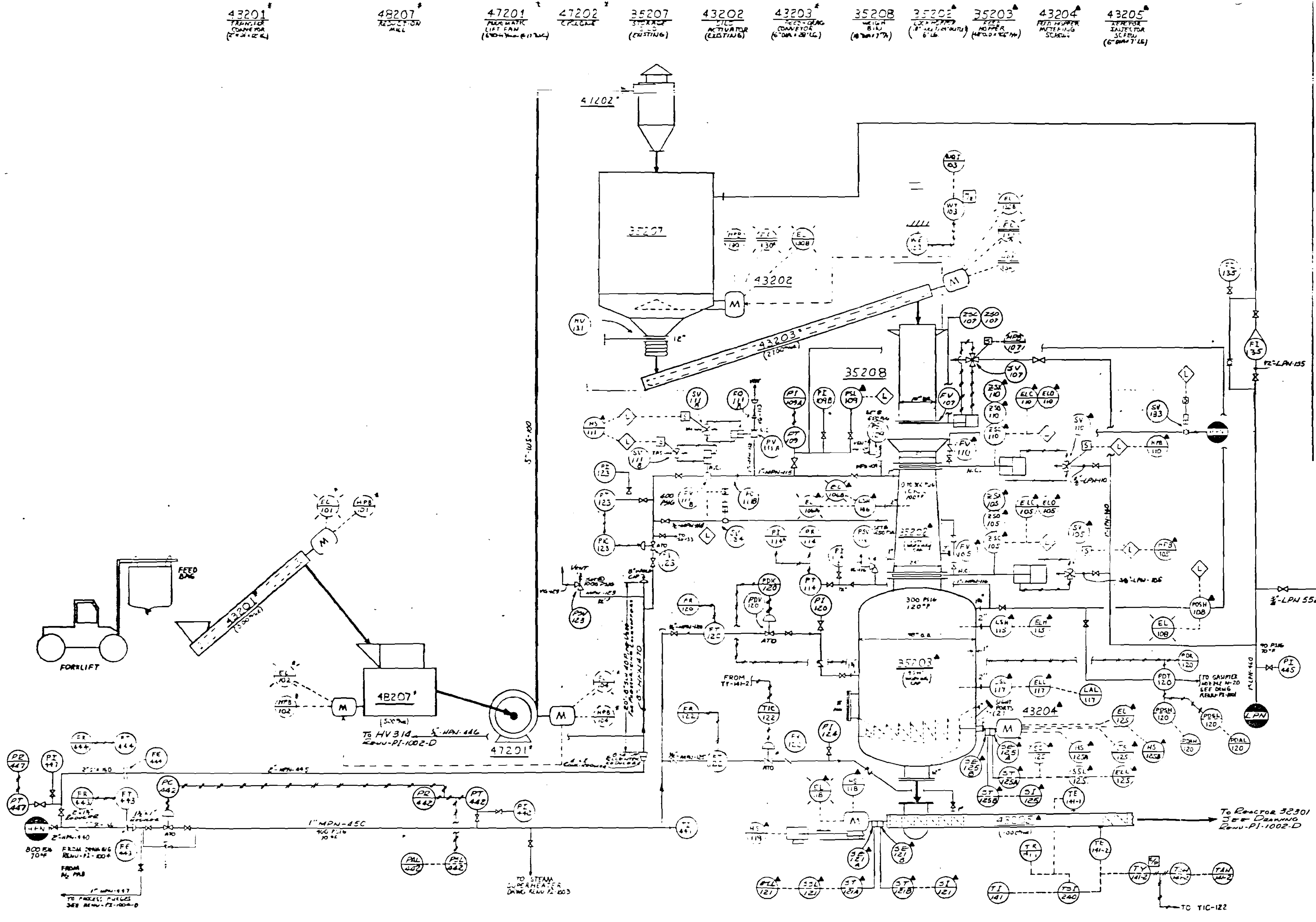
TITLE:
RENUGAS PDU GASIFIER
P.+I.D.

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER
CHICAGO, ILLINOIS

IGT

DRAWING NO.
RENU-PI-1001-D

REV
6



NOTES :

*	INDICATES EQUIPMENT AND INSTRUMENTATION SUPPLIED FROM SPECIALTY ENGR. + EQUIP. CO.
▲	INDICATES EQUIPMENT AND INSTRUMENTATION SUPPLIED FROM T. MILES CONSULTING ENGR.
IAS	INSTRUMENT AIR SUPPLY (60-90 PSIG)
ATO	AIR TO OPEN
N.C.	NORMALLY CLOSED WITHOUT POWER
⊥⊥⊥	HYDRAULIC SIGNAL LINE
◇L	INDICATES INTERLOCK WITH LOCKHOPPER CONTROL LOGIC AND OPERATION
H/E	HYDRAULIC TO VOLTAGE TRANSDUCER
Σ	SUMMING UNIT
⊖	INDICATES LOCAL MOUNTED FEED PREP CONTROL PANEL
⊜	INDICATES LOCAL MOUNTED FEED WEIGHING CONTROL PANEL
┤	INDICATES SCREWED NPT VESSEL CONNECTION
┤	INDICATES A PIPE PLUG
┤	INDICATES FLANGED VESSEL CONNECTION
┤	INDICATES A BLIND FLANGED NOZZLE

NO	REVISION	BY	CK	DATE
5	[illegible] GENERAL REVISION	REL	SJW	11/12/82
4	[illegible]	SJW	SJW	8/25/82
3	REVISED [illegible]	SJW	SJW	7/28/82
2	[illegible]	[illegible]	SJW	6/26/82
1	REDRAWN AND REVISED	SJW	SJW	4-28-82

TOLERANCES EXCEPT AS NOTED: REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

DES	G KOSOWSKI	12-12-81
DR	J.J. AGUIRRE	1-19-82
CK	S J WONADLO	
APP		
MATERIAL		
SCALE		

NOTE: THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY AND SHALL NOT BE TRACED PHOTOGRAPHED, PHOTOSTATED OR REPRODUCED IN ANY MANNER NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

PROJECT NO 65058-40

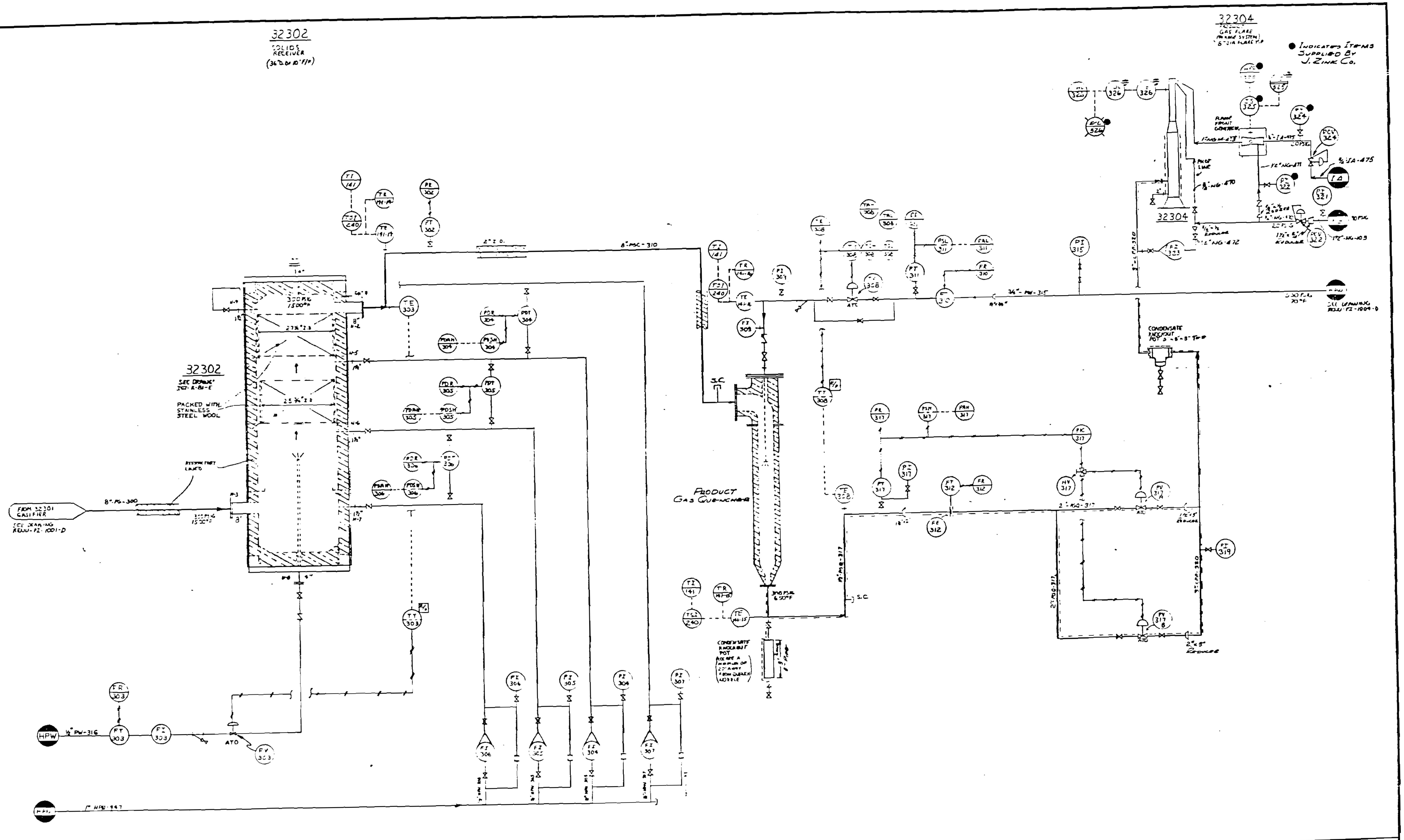
TITLE: RENUGAS FEED PREP, FEED WEIGHING AND FEED LOCKHOPPER P+ID

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER
CHICAGO ILLINOIS

IGT

DRAWING NO RENU-PI-1000-D

REV 6



6	ADDED LOOP 303 + GEN. REV	SK	GY	8-23-84
5	[illegible]	REL	SJW	11/12/83
4	REMOVED HV-33, ADDED FE 327	SJW	SJW	8/27/83
3	RELOCATED PSV 320, ADDED [illegible]	SJW	SJW	7/29/82
2	ADDED LINER AND GENERAL REVISIONS	SJW	SJW	7/29/82
1	REDRAWN + GENERAL REV	SJW	SJW	4-26-83
NO	REVISION	BY	CK	DATE

TOLERANCES (EXCEPT AS NOTED) REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

DES KOSOWSKI 12-12-81
DR J.J. AGUIRRE
CK
APP
MATERIAL
SCALE

NOTE THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY AND SHALL NOT BE TRACED PHOTOGRAPHED PHOTOSTATED OR REPRODUCED IN ANY MANNER NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

PROJECT NO 65058-40

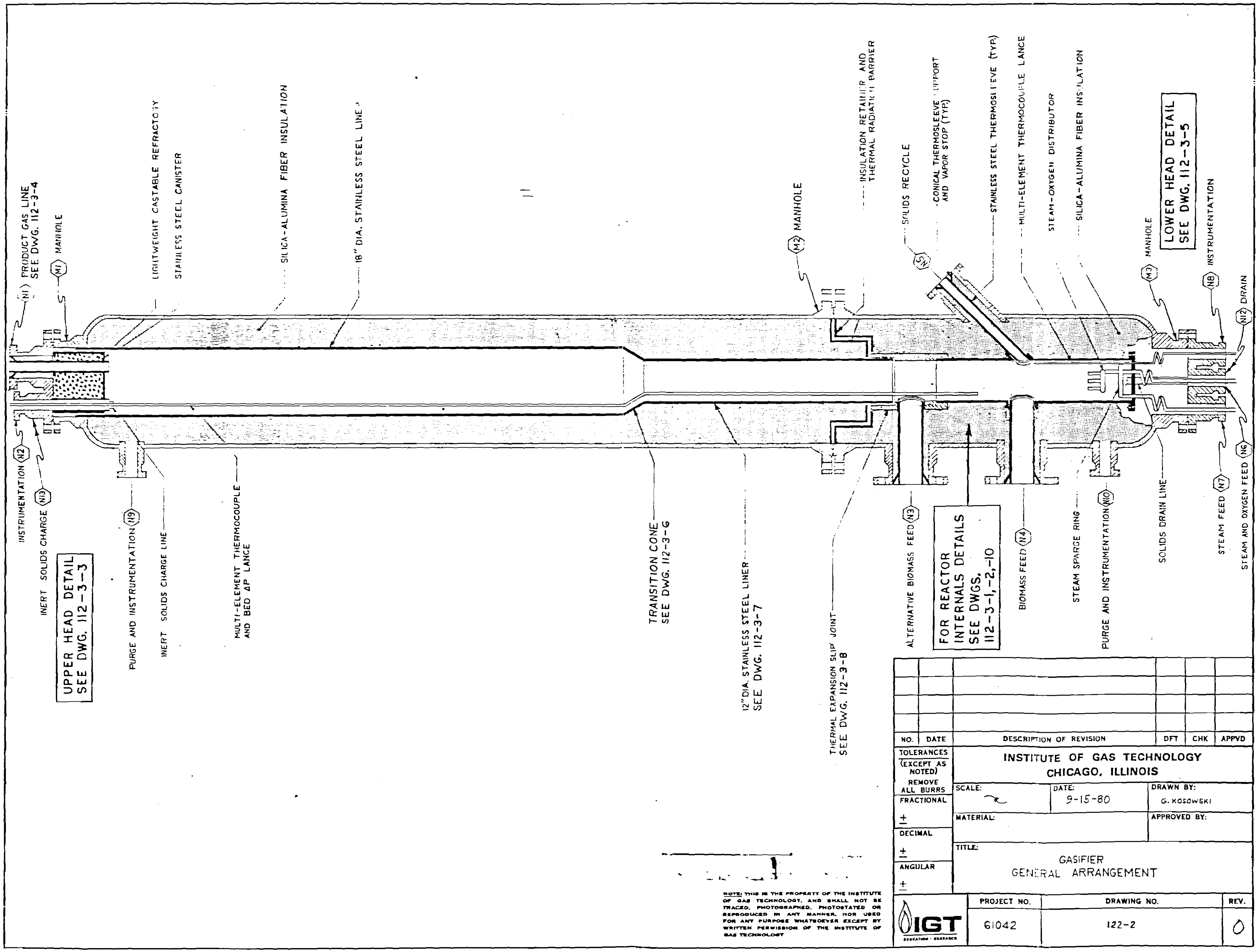
TITLE: RENUGAS QUENCH SYSTEM P+I.D

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER
CHICAGO ILLINOIS

IGT

DRAWING NO RENU-PI-1002-D

REV 6



NOTE: THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY, AND SHALL NOT BE TRACED, PHOTOGRAPHED, PHOTOSTATED OR REPRODUCED IN ANY MANNER, NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

NO.	DATE	DESCRIPTION OF REVISION	DFT	CHK	APPVD

TOLERANCES (EXCEPT AS NOTED)
REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

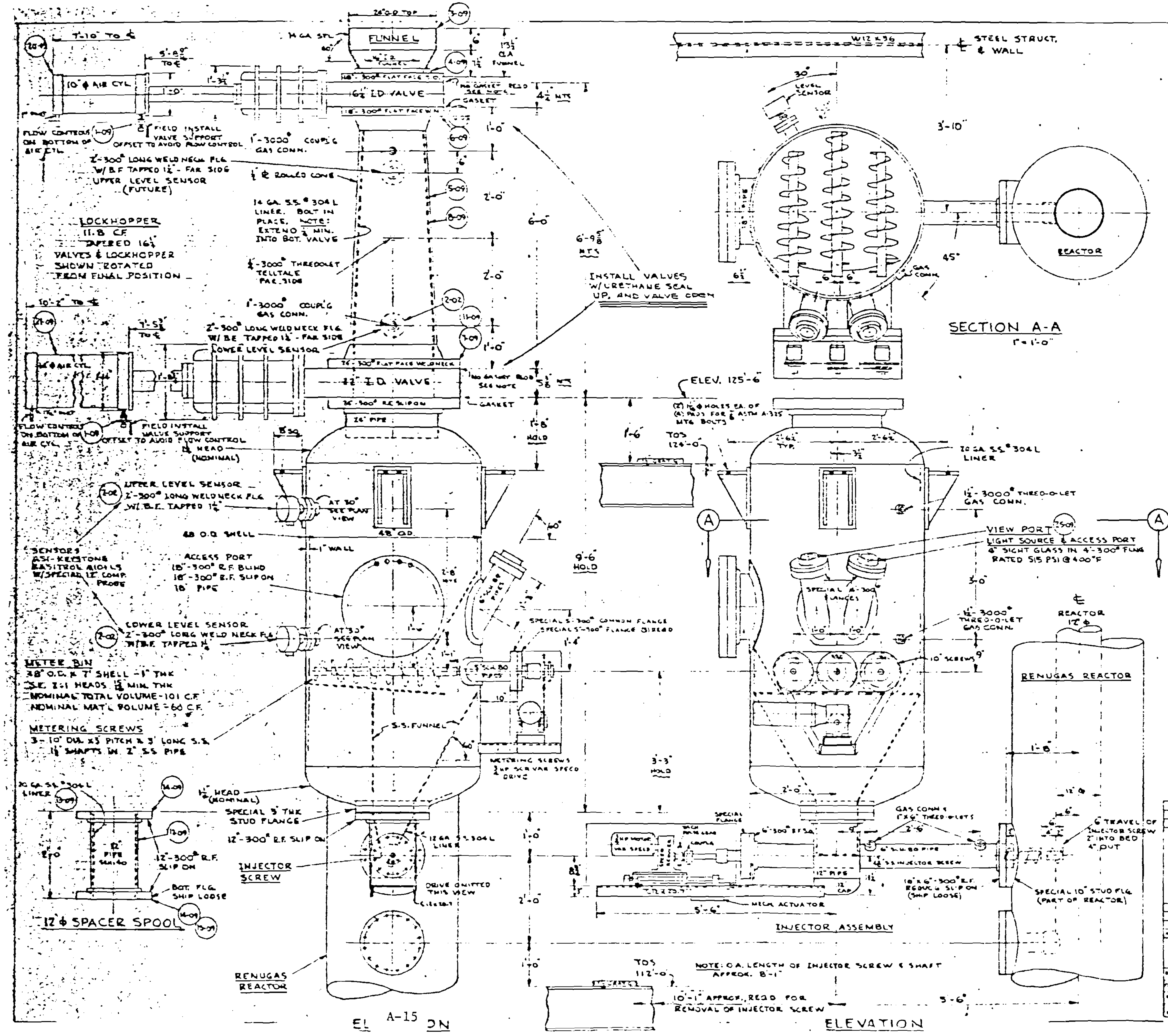
INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

SCALE:
DATE: 9-15-80
DRAWN BY: G. KOSOWSKI
MATERIAL:
APPROVED BY:
TITLE: GASIFIER GENERAL ARRANGEMENT

IGT
EDUCATION · RESEARCH

PROJECT NO.	DRAWING NO.	REV.
61042	122-2	0

ENCLOSURE 6 – GASIFIER INTERNAL DETAILS



REFERENCE DRAWINGS

FOR PRESSURE VESSEL DETAILS SEE PACIFIC TANK & CONSTR. CORP DRWGS No. 1510-01, -02, -03 & MD18-01

485-02 SECTION THRU METER BIN
-03 METER BIN BOTTOM DETAILS
-04 METERING SCREWS DETAILS
-05 METERING SCREWS BEARING ASS'Y
-06 INJECTOR SCREW DETAILS
-07 INJECTOR SCREW INFEED DETAILS
-08 INJECTOR SCREW BEARING ASS'Y
-09 MISC. DETAILS
-10 CONTROL SCHEMATIC
-11 CONTROL PANEL
-12 TEST INSTALLATION

NOTES

18" & 24" FABRI-VALVES FURN. BY I.G.T.

CAUTIONS!

1. NOTE THAT THE BLIND HOLES TAPPED IN THE VALVE FLANGES ARE SHALLOWER IN THE CHEST AREA. USE STUDS OR BOLTS OF CORRECT LENGTH.
2. INSTALLATION W/ VALVE IN PLACE ADJUST VALVE SUPT. SET SCREW TO HOLD VALVE FLANGE FLAT AGAINST MATING SURFACE. STUDS OPPOSITE CHEST SHOULD BE INSERTED & BOLTED UP FIRST. STUDS IN CHEST AREA LAST.
3. REMOVAL W/ VALVE FIRMLY SUPPORTED AT THE AIR CYL. UNBOLT CHEST AREA FIRST. IF ANY STUDS REMAIN IN THE VALVE, LIFT VALVE STRAIGHT UP UNTIL STUDS ARE CLEAR. DO NOT ALLOW VALVE TO TIP AS BREAKAGE OF VALVE BODY CAN RESULT.

METERING SCREWS

SCREW SPEED 0 TO 49 RPM MAX.

CAPACITY 1000#/hr = APPROX. 4 RPM W/ DRY CHIPS @ 12#/C.F.

SEAL OR BRG. MAINT. SEE DRWG -05

SHAFT REMOVAL SEE DRWG -04, -05 REACH INTO METER BIN THRU ACCESS PORT AND REMOVE SINGLE ⅜ BOLT FROM SCREW AT BIN ℄. SHAFT CAN NOW BE WITHDRAWN.

INJECTOR SCREW

SCREW SPEED 0 TO 177.8 RPM MAX. 120 RPM RECOMMENDED OPERATING SPEED.

SEAL OR BRG. MAINT. & SHAFT REMOVAL. SEE DRWG. -06, -08 FIRST REMOVE DRIVE, SLIDE BASE FIXED BASE ETC. AS A UNIT. THIS WILL PERMIT REMOVAL OF THE SPECIAL FLANGE W/ BRG HOUSING AND SHAFT & SCREW IF NECESSARY.

GASKETS REQD ON BOT. ONLY OF FABRI-VALVES. TOP SEAL IS BY 1/32" COMPRESSION OF ELASTOMER VALVE SEAT.

DESIGN TEMPERATURE - 150 F

DESIGN PRESSURE - 500 PSIG

OPERATING PRESSURE - 300 PSIG

CAPACITY - 100# - 1000#/HR DRY WOOD CHIPS (SCREENED THRU 1⅛ ϕ ROUND HOLES)

FOR MORE DETAILS - SEE GENERAL DESIGN SPECS, REFERENCE; IGT No. 61042-83005 QUOTE No. 81-65056-01

G	9-13-82	AS BUILT REVISIONS 02 TO IGT 10-5-82	BOALS
F	4-26-82	REV. INSTALLATION NOTES ADDED VALVE SUPTS. [illegible]	BOALS
E	4-15-82	UPDATED - ADDED NOTES, FUNNEL	BOALS
D	1-6-82	[illegible]	BOALS
C	1-1-81	[illegible] LEVEL SENSORS [illegible]	BOALS
B	11-9-81	REDRAWN ACC'D'G TO IGT COMMENTS & UPDATE DESIGN	BOALS
A	9-28	REVISE ACC'D'G TO IGT COMMENTS & UPDATE DESIGN	TRM

Th. R. Miles

THOMAS R. MILES
CONSULTING ENGINEER
P. O. BOX 216 · BEAVERTON, OREGON 97075

DRAWN BY TRM
CHECKED TRM
DATE JULY 28, 1981
SCALE ¾" = 1'-0"

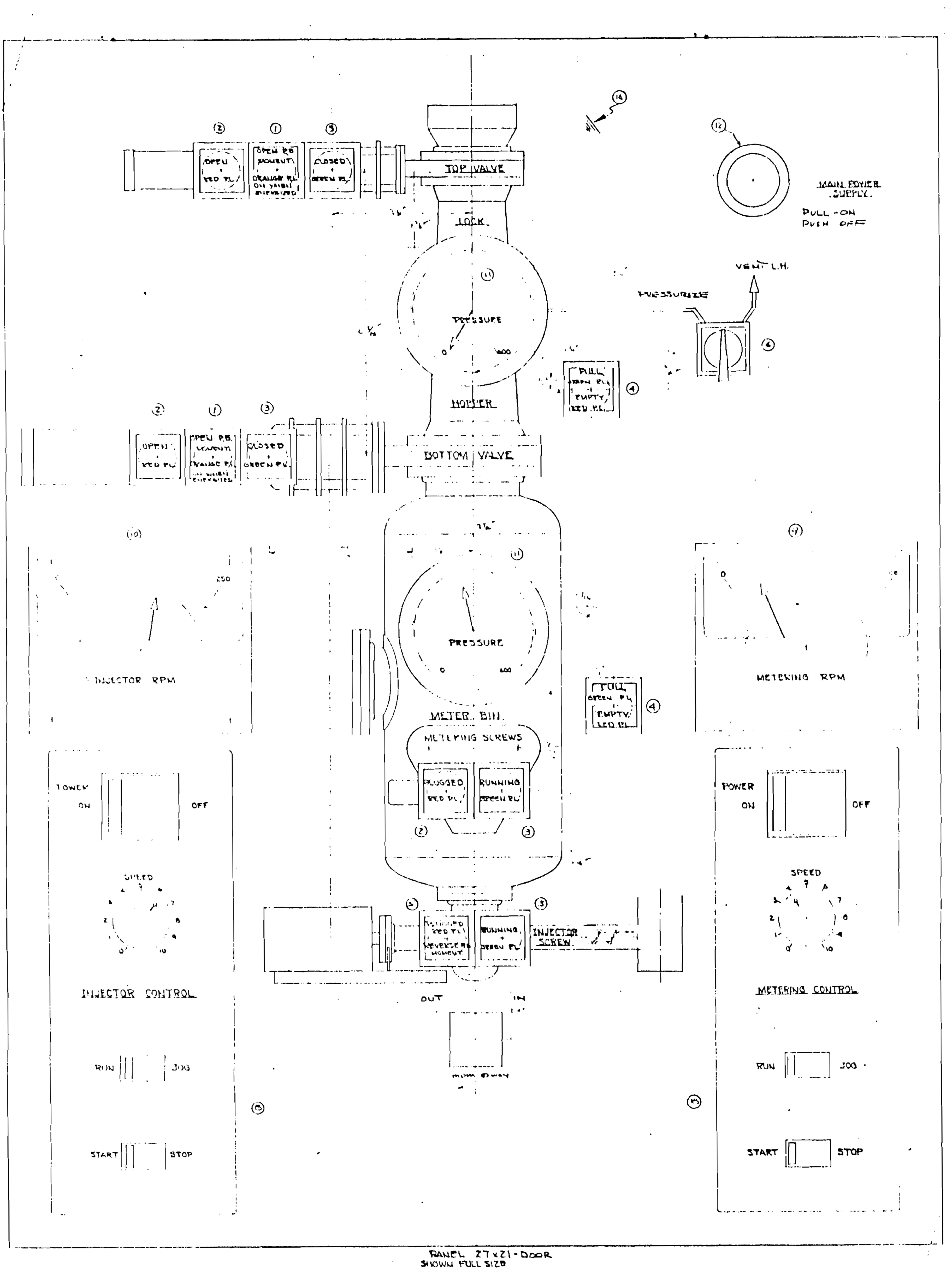
INSTITUTE OF GAS TECHNOLOGY
CHICAGO, ILLINOIS

BIOMASS GASIFIER FEEDER
300 PSI RENUGAS PROJECT

485-01G

1 - MICROSWITCH PW 211C4DF2 DD, OPER. P.B. ILLUM, 2 N.O., BHD, FULL GUARD. 110 V
2 - " PW 2L2C3GF2, INDIC. RED. UNGUARDED "
3 - " PW 2L2C6GF2 INDIC GRN
4 - " PW 20C B3 KF2 DUAL INDIC - TOP WHITE, BOT RED
5 " PW 2H C3DF200 ILL P.B. RED, 2 N.O. FULL GUARD "
6 - " PW 2SHG12DADA WING LEVER OPER. 3 POS SEL SW - MAINT CENTER
7 - " PW 2 BH402DADA KNOB " " " " "
8 - RELIANCE - SCR OPER. PANEL 14C202 (?) - ¼ HP 110V 13 B FLA
9 - ELECTRO 75502 METER (METERING)
10 - " 75501 " (INJECTOR)
11 - PRESS GA - LENZ 2½" 0-600 psi glyc. filled
12 - A-B PUSH-PULL SWITCH

13 - PANEL - HOFFMAN A302408LP - NEMA 12
14 - GRAPHIC - SCOTCHCAL, BY TRM.



PANEL 27×21 - DOOR
SHOWN FULL SIZE

O.D. OF PANEL 30"H × 24" × 8"

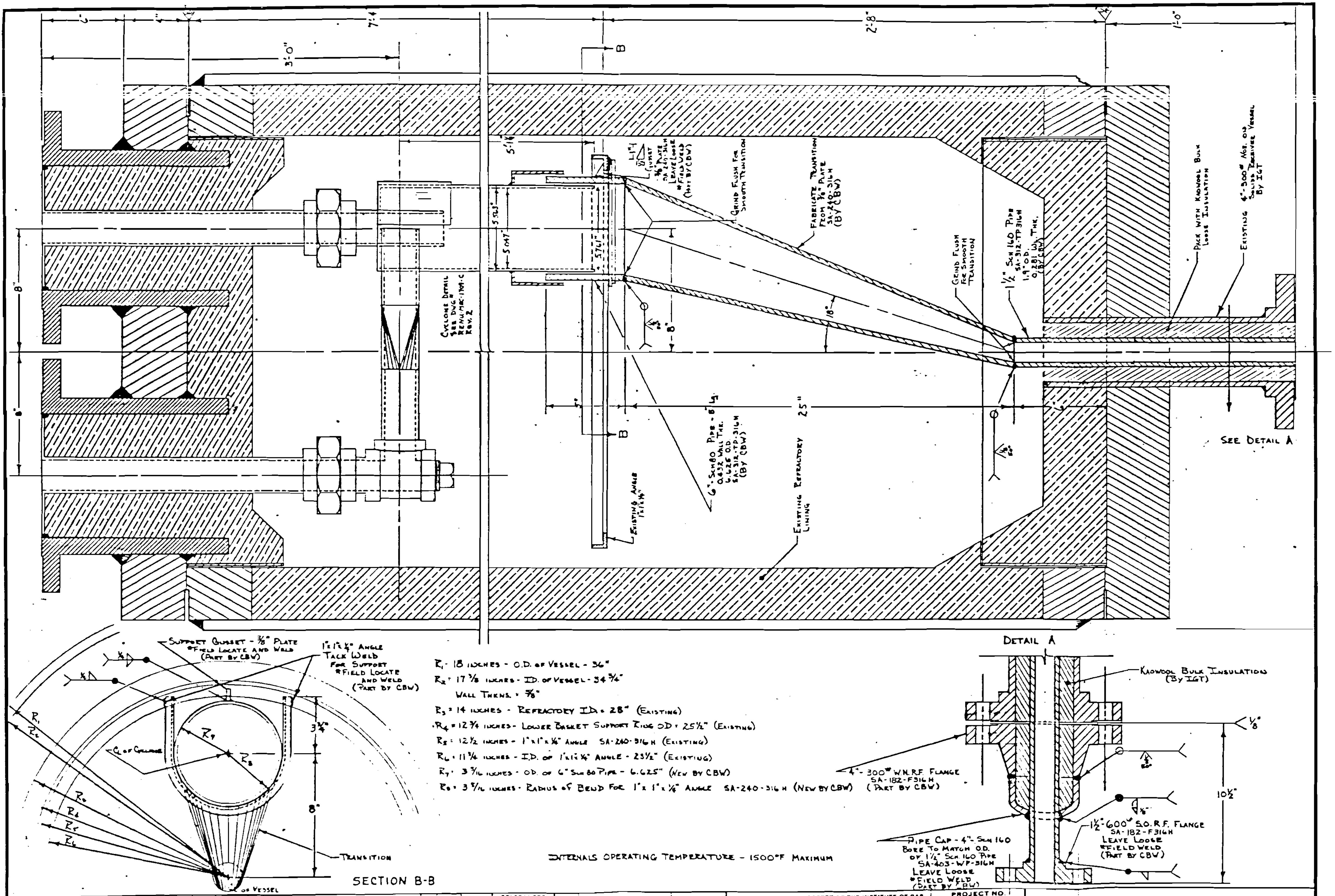
A	9-13-?	AS BUILT REVISIONS	OK TO IGT 10-5-82	TRM

THOMAS R MILES
CONSULTING ENGINEER
216 BEAVERTON OREGON 97225

DRAWN BY F.W.M.
CHECKED TRM
DATE 9/20/82
SCALE FULL

INSTITUTE OF GAS TECHNOLOGY
CHICAGO ILLINOIS
FEEDER CONTROL PANEL
300 MAI RENUGAS PROJECT

DWG No. 485-11A



R1 - 18 inches - O.D. of Vessel - 36"
R2 = 17⅜ inches - I.D. of Vessel - 34¾"
Wall Thkns. = ⅝"
R3 = 14 inches - Refractory I.D. = 28" (Existing)
R4 = 12¾ inches - Lower Basket Support Ring OD = 25½" (Existing)
R5 = 12½ inches - 1"x1"x¼" Angle SA-240-316H (Existing)
R6 = 11¾ inches - I.D. of 1"x1"x¼" Angle - 23½" (Existing)
R7 = 3 5/16 inches - OD. of 6" Sch 80 Pipe - 6.625" (New by CBW)
R8 = 3 5/16 inches - Radius of Bend for 1"x1"x¼" Angle SA-240-316H (New by CBW)

Internals Operating Temperature - 1500°F Maximum

NO	REVISION	BY	CK	DATE

TOLERANCES (EXCEPT AS NOTED)
REMOVE ALL BURRS
FRACTIONAL ±
DECIMAL ±
ANGULAR ±

DES		
DR	J.W. GRIMES	2-18-85
CK		
APP		
MATERIAL:		
SCALE:	3 INCHES = 1 FOOT	

NOTE: THIS IS THE PROPERTY OF THE INSTITUTE OF GAS TECHNOLOGY AND SHALL NOT BE TRACED PHOTOGRAPHED PHOTOSTATED OR REPRODUCED IN ANY MANNER NOR USED FOR ANY PURPOSE WHATSOEVER EXCEPT BY WRITTEN PERMISSION OF THE INSTITUTE OF GAS TECHNOLOGY

PROJECT NO. 65058

TITLE: RENUGAS SOLIDS RECEIVER
INTERNAL CYCLONE LAYOUT
AND INSTALLATION DETAILS

INSTITUTE OF GAS TECHNOLOGY
ENERGY DEVELOPMENT CENTER
CHICAGO, ILLINOIS

IGT

DRAWING NO. RENU-MEC-1711-C
REV. 0

APPENDIX B.
Description of PRU Instrumentation

Description of PRU Instrumentation

Successful PRU operation has been achieved with conventional, off-the-shelf instruments specially adapted to measure and control the special PRU applications. Process variables monitored included: flow, pressure, temperature, and fluidized-bed density and level. These measurements are made at pressures up to 500 psig and temperatures up to 1800°F.

The control system utilizes a pneumatic system with basic feedback type control loops consisting of proportional and integral (PI) and proportional, integral, and derivative (PID) control modes to provide satisfactory control and performance. Pneumatic equipment offers easy maintenance and reliability.

For extended duration tests of several days, a 32 channel multipoint recorder and data logger was used for interfacing with a Compaq Plus portable computer. The multipoint recorder has the feature of both trend recording and data logging. Normal trend recording can be interrupted to allow a digital data logging of all input signals, and then return to trend recording. The computer output built into the recorder/data logger makes possible the sending of process data to the personal computer. The raw data from the tests are permanently stored on floppy disks for easy retrieval. The PRU is also equipped with pneumatic/current (P/I) transducers and computer interface to send RS-232 transmission into the Compaq personal computer for real-time data storage.

An important criteria for proper control of the RENUGAS fluidized-bed system is the accurate knowledge of bed density and total bed height. Conventional differential pressure techniques are used for both measurements. The density of the bed is determined by using the pressure difference between two fixed points of known elevation. Overall bed height is then measured using the total pressure drop over the entire reactor and the bed density measurement.

The differential pressure measurement is done by a sensor utilizing a diaphragm element connected to a force balance transmitter. The transmitter output signal (3 to 15 psig) is sent to a central control panel for recording. Because the reactor system contains suspended solids (fines), inert gas purges keep the pressure impulse lines free from plugging and solids accumulation. Proper purge control is required and regulated through the use of rotameters.

Another use of differential pressure transmitters in the PRU is for gas and liquid flow metering. All liquid, gas, and steam flows are measured by conventional head-type meter installations where differential pressure is measured across a primary element to indicate flow. Industry standardized concentric sharp-edge orifice meter runs are used along with integral-type orifice meters specifically utilized for low flow rates. With head-type meters, pressure and temperature measurements are required for compensation to obtain mass flow for material balance data.

The biomass feed rate to the gasifier is monitored by a hydraulic load cell measuring feed batches dumped into the feed system described earlier. The weight of a single batch is approximately 100 pounds. The solids are dumped out of the lockhopper into the feed hopper, which contains a metering screw regulating the solids flow into the gasifier. Solids level in the metering feed hopper is monitored by a capacitance probe technique that provides a proportional level signal. Solids feed rate can be adjusted through a variable frequency AC motor drive system controlling the metering screw's revolutions per minute. All controls for the lockhopper operation and screw speed control are located at the control panel.

Temperature measurement in the PRU is accomplished by conventional thermometry. Chromel-alumel (Type K) thermocouple junctions are used throughout the unit to monitor temperatures ranging up to 2000°F. The elements are the ceramic-insulated, sheathed type and are 1/8-inch in diameter. Conax sealing glands have successfully been used as a device to route these thermocouples into the PRU pressurized vessels. The thermocouple extension wires used are of the same metallurgy.

Pressure in the PRU is maintained by regulating the flow of reactor off-gas through a pressure letdown valve. The gas flowing through the letdown valve is hot and erosive in nature because of suspended fines. IGT has pioneered work in severe pressure letdown valves in prior coal gasification work (specifically the HYGAS and Steam-Iron Processes) by utilizing a commercially manufactured rotary choke valve constructed with tungsten-carbide discs with diamond lapped mating surfaces. The basic valve was modified by IGT with features that significantly improved service life and control performance. The rotary discs consist of one fixed disc in the valve body while the other is rotated 90° to open or block the flow. Actuation is provided by a spring/diaphragm operator receiving its pneumatic signal from a controller on the control panel.

171/RPP/65058ApB

APPENDIX C.
PRU Experimental Procedures

Startup Procedure

The startup of the PRU is a simple three part procedure. The first part consists of preheating the gasifier, containing about 800 pounds of inert solids, with hot nitrogen. During startup the steam superheater is employed to preheat the nitrogen to about 1100°F. The temperature of the inert fluidized solids reaches about 550°F in about 4 hours. The system is slowly brought to the test pressure in this time. During heatup the nitrogen flow is regulated to maintain minimum fluidization conditions for the inert solids: a superficial gas velocity of at least 0.4 ft/sec at low startup pressure. The differential pressure between the balanced-pressure insulation zone and the liner is maintained at about 15 to 25 psi, which is within the specified mechanical design conditions.

The second part of the startup procedure consists of loading about 120 pounds of coconut shell charcoal (-1/8-inch size) into the live-bottom metering bin. Charcoal feed into the 550°F inert solids fluidized bed is initiated at approximately 60 lb/h. The charcoal is ignited by slowly adding oxygen to the fluidizing nitrogen stream. The fluidized-bed temperature rises uniformly to the gasification test temperature and is maintained there for about 2 hours. Because the charcoal has little or no volatile matter, there is no chance for oil or tar deposition in the cooler downstream section of the PRU system. In these 2 hours of charcoal heatup operation the downstream piping and vessels gradually heat up. The heatup procedure is considered complete and the reactor is ready for gasifying woody biomass when the refractory piping at the downstream water quench reaches 500°F.

The third and final phase of the startup procedure involves initiating wood feed at 300 lb/h and the flow rates of steam and purge nitrogen are established switching from nitrogen to steam flow to the superheater. At this point the oxygen flow is regulated to maintain the predetermined gasification test temperature for about an hour, before increasing the wood feed to the selected test feed rate. The elapsed time from cold start to flow stabilization and beginning of wood gasification steady state is about 10 to 12 hours.

The PRU operating procedures for all the tests were the same. Three tests were conducted with low steam-to-wood ratios (Tests GT-14, GT-15, and GT-17) as a part of the parametric studies with minimal deviations.

Modifications for low flow measurements and consequent instrument range adjustments were made for these tests in order to meet the objectives of the tests.

Shutdown Procedure

Shutdown operations for the PRU system required about 6 hours from the time the wood feed, steam, and oxygen (or air) were stopped. Most of the time was required for depressurization and reduction of the bed temperature to below 500°F. During this time the superheater was slowly cooled with nitrogen, which also flows through the gasifier. This slow cooling procedure assured protection of the PRU equipment. Rapid cool down procedures could be possible if bypass piping and hot service valves were installed at various locations. In either case, the overall shutdown procedure was very simple. When the fluidized-bed temperature was below 500°F, the nitrogen flows were stopped and the inputs to the gasifier were blocked off while the valves at the pressure letdown station were locked open. The entire system then cooled down in this mode.

171/RPP/65058ApC

APPENDIX D.
Description of Gas, Liquids, and Solids Sampling System

Gas Sampling System

The sampling of gases, liquids, and solids from the product gas stream is achieved by the operation of two sampling systems: the gas analyzer system (GAS) and the isokinetic sampling system (ISS). Both streams are withdrawn at a common sampling point close to the gasifier exit. Each sample probe consists of a 1/4-inch 316 SS tube extending into the center of the 2-inch-ID, 8-inch-OD refractory-lined product gas pipe. Both sample tubes are welded to a 1/2-inch NPT pipe cap on the end of a position-adjustable pipe assembly. A cut-away view of the pipe showing the sampling probe arrangement is illustrated in Figure D-1 and the overall sampling system is shown schematically in Figure D-2.

The particulate and condensate ISS probe faces into the center of the flowing gas stream, and withdraws approximately 1% of the total gas flow at isokinetic conditions. The leading edge of the open ended tube is tapered outward to reduce impingement.

The product gas sample is drawn through the ISS probe at a velocity approximately equal to the estimated gas velocity in the product gas line. The product gas velocity is estimated from the gasifier input rates and the feed conversion to gaseous products. Using the steam content measured by the on-line GC, a dry gas flow rate for the sample is calculated and maintained at the dry gas meter. At the proper operating conditions the ISS probe gas sample flow rate is about 1% to 1.5% of the total product gas flow rate. The ISS is operated for 1 hour during the steady operating period. The ISS withdraws a representative sample of product gas, which passes through a preheated (450°F) filter canister housing containing a glass filter element. The entrained particles are trapped here and the clean gas flows through a water-cooled condenser. The condensate is collected in a 1-gallon 316 SS pressure vessel and the cooled stream then passes into a similar pressure vessel submerged in an ice-water bath. The gas stream is then reduced in pressure by a pneumatically operated 1/4-inch regulating valve. A final sintered stainless steel filter removes the remaining entrained particles and the sampled gas flow is measured with a dry test meter. The collected liquid and solid samples are weighed and analyzed, yielding average values for the solids entrainment rate and the condensate water and oil rate during the steady gasification period.

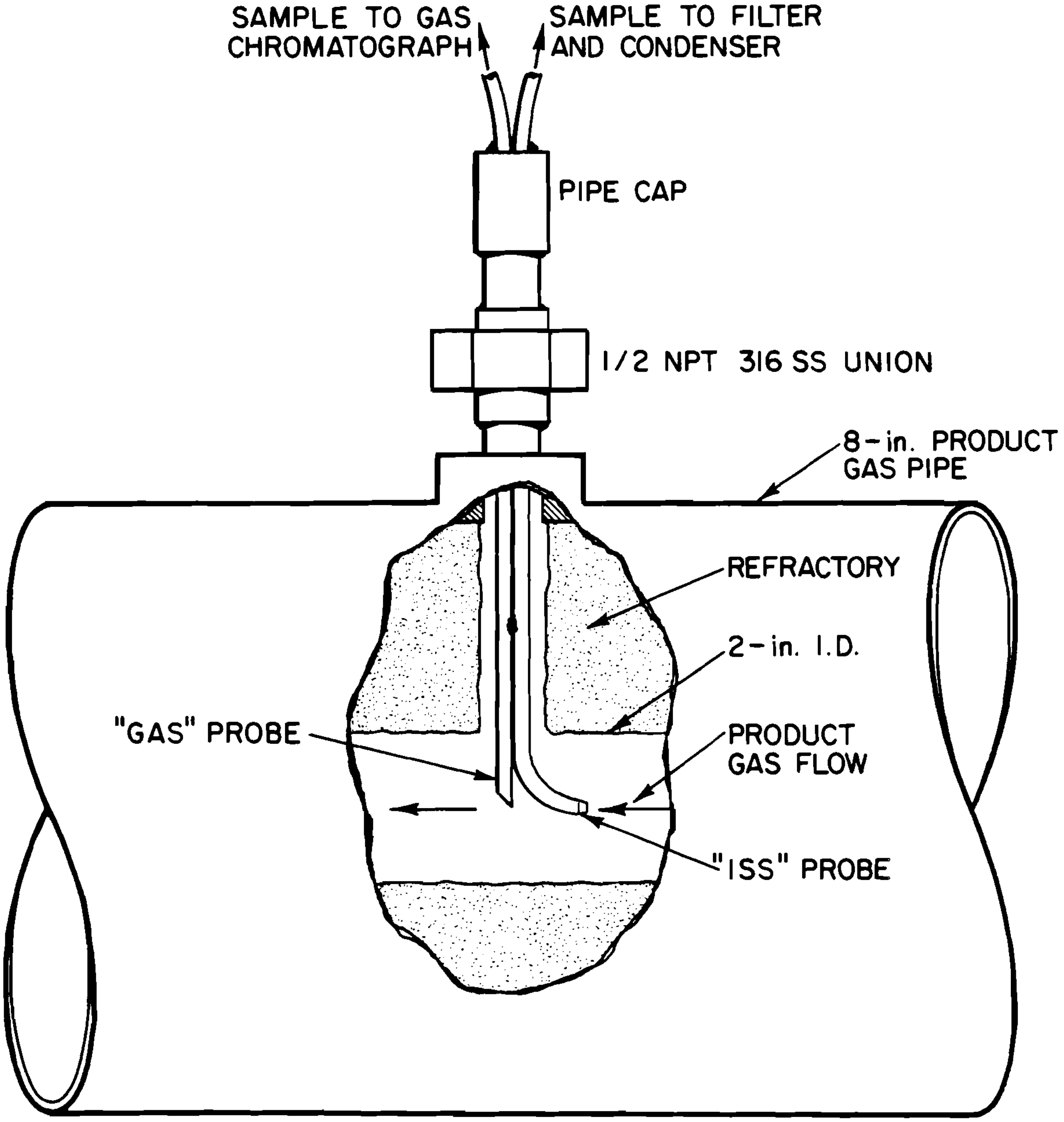


Figure D-1. DUAL SAMPLE PROBE

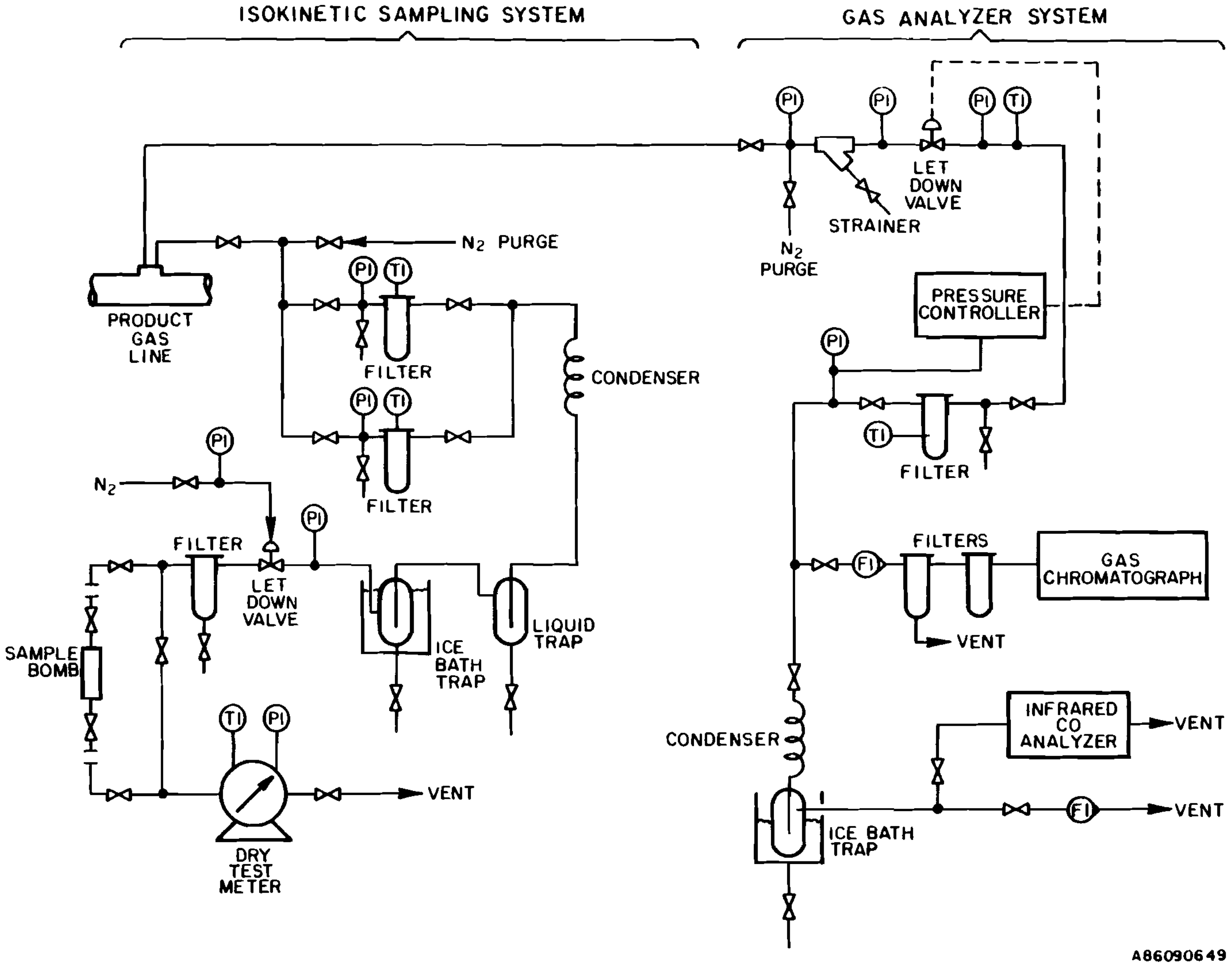


Figure D-2. SAMPLE SYSTEM FOR GASES, LIQUIDS, AND SOLIDS

The ISS and associated instruments are installed close to the sampling point. The entire tubing length from sample inlet to gas flow meter is about 16 feet, which includes a 4-foot coil inside the water condenser. Except for the sample tube inside the product gas line and the line downstream of the ice-water bath, larger 3/8-inch and 1/2-inch 316 stainless steel tubing is used to avoid plugging by tars and particulates.

The GAS probe faces away from the direction of gas flow to minimize solids withdrawal. The tube size increases to 1/2-inch as it leaves the probe and the pressure is reduced to 15 psig by use of a pneumatically-controlled 1/4-inch regulating valve. From this point, the sample lines are electrically heated to prevent condensation. The sample enters a canister type filter housing containing a 1-micron fibrous glass filter element to trap almost all of the particulates. The canister is also electrically heated to 300°F to ensure that no water condenses. The stream goes directly to a bypass filter inside a heated cabinet and then passes through a final sintered metal filter before entering the on-line gas chromatograph (GC). The GC automatically analyzes H_2, CO_2, Ar/O_2, CH_4, CO, and H_2O once every 12 minutes.

The gas chromatograph and instruments were installed as close as possible to the sampling point to minimize the lag time and the potential for cold spots and tar build-up.

The gas analysis instruments are calibrated with a standard gas mixture before and after each test. In addition, the GC is calibrated on a dry basis every 90 minutes during a test. A wet-gas calibration of the GC is done before each test by bubbling dry calibration gas through an electrically heated bubbler filled with distilled water.

During the steady-state operation, samples of cool, dry, clean gas are also taken in stainless steel sample bombs for a confirmatory analysis by a laboratory gas chromatograph that analyzes for additional hydrocarbon species.

An "Annubar" pressure differential flow meter installed in the gasifier exit line, and a standard orifice meter in the product gas line measure the product gases before and after quenching. A purge-nitrogen balance is routinely made to verify the product gas flow rate. In addition, the PRU operating procedure can also use a metered injected argon tracer gas to serve as a double check on the raw gas production rate.

Over 19 adiabatic biomass gasification tests have been conducted in the PRU at feed rates of up to 1430 lb/ft^2-h of biomass at 300 psig and 1500°F. The large-scale operation, combined with the use of the on-line isokinetic sampling system, the on-line wet-GC, and off-line gas and liquid sample analyses ensures the collection of the field of data necessary to prepare accurate material and energy balances for process evaluation and scale-up.

171/RPP/65058ApA

APPENDIX E.
Summary of Material and Energy Balances for Individual Gasification Tests

Summary of Material and Energy Balances for Individual Gasification Tests

Each test was conducted at predetermined gasification conditions to develop process scale-up information. Tests were conducted for steady-state periods of approximately 4 hours except for the long duration tests which were conducted for steady-state periods of up to 3 days.

Determination of steady-state operation is defined by the following:

1. Changes or deviations in the wood feed rate are about: ±5%-10%
2. Adjustments or deviations to the steam and oxygen input rates are about: ±2%
3. Deviations or differences in the product gas composition as observed by the on-line gas chromatograph are about: ±2%
4. The variations in reactor bed temperature profiles is on the order of: ±75°F

Once these criteria are met, the PRU is operated for a predetermined duration. Data are collected during this time period that enable the establishment of material and energy balances. Corrections are made to the raw data to establish 100% elemental and material balances before any correlation of the data to predict gasifier performance is made.

The following procedure was adopted to adjust the raw data to a 100% elemental and material balance and used for all of the gasification tests:

1. The product gas flow rate based on the orifice meter measurement has inherent inaccuracies due to the buildup of carryover solids across the orifice plate. Thus, the product gas flow rate was obtained by using the product gas composition from the off-line GC and calculating a 100% carbon balance. Four equations with four unknowns were solved simultaneously to obtain the product gas flow rate and the quantities of carbon in the entrained solids, in the tars and oils, and in the dry product gas.
2. Next, the hydrogen balance was obtained by adjusting the liquid condensate rate to match the total hydrogen in the input streams.
3. After the product gas flow rate and the condensate collection rate were corrected, the input oxygen rate was adjusted to balance with the total oxygen in the output streams.
4. The input nitrogen flow rate was adjusted to match the nitrogen in the product gases.
5. Because the fluidized-bed gasifier contains very little of the feed material in a residual form, it is assumed that the entire ash in the

feed material is carried overhead by the product gases. The input feed ash is assigned to the ash in the entrained solids to obtain a 100% ash balance.

Using this procedure, the measured results from all the tests were adjusted to close the elemental and mass balances, which are summarized in the following tables. The overall energy balances calculated from the adjusted material balances are also presented.

171/RPP/65058ApD

Table E-1. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-1

Test Date: 3-21-84
Study Period: From 1645 Hour to 2045 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	364.1	45.5	325.4	0.0	10.4	745.5	6.1
Moisture		7.5	60.4			67.9	
Steam to Ring		42.7	341.3			384.0	0.5
Steam to Nozzle		29.1	232.7			261.8	0.3
Oxygen to Nozzle			171.8			171.8	
Nitrogen Purge				421.9		421.9	
Total Input	364.1	124.9	1131.9	421.9	10.4	2052.9	6.9

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	29.1	0.0			10.4	39.5	0.5
Oil/Tars	13.8	2.4				16.2	0.3
Product Gas Components							
H_2		18.7				18.7	
CO	64.5		86.0			150.5	
CO_2	165.5		441.4			606.9	
CH_4	78.3	26.1				104.3	
C_2H_4	2.1	0.4				2.5	
C_2H_6	5.7	1.4				7.1	
C_3H_8	0.0	0.0				0.0	
C_6H_6	5.1	0.4				5.5	
N_2				422.0		422.0	
H_2O		75.5	604.1			679.6	
Total Gas	321.2	122.5	1131.4	422.0		1997.1	6.1
Total Output	364.1	124.9	1131.4	422.0	10.4	2052.9	6.9
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	100.0

171/RPP/65058ApE

Table E-2. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-2

Test Date: 4-11-84
Study Period: From 1325 Hour to 1725 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	305.2	38.2	276.7	0.0	4.8	625.0	5.2
Moisture		7.3	58.3			65.6	
Steam to Ring		35.6	284.5			320.1	0.4
Steam to Nozzle		19.1	152.5			171.6	0.2
Oxygen to Nozzle			170.0			170.0	
Nitrogen Purge				309.3		309.3	
Total Input	305.2	100.2	942.1	309.3	4.8	1661.6	5.8

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	17.1	0.0			4.8	21.9	0.3
Oil/Tars	6.7	1.2				7.9	0.2
Product Gas Components							
H_2		16.9				16.9	
CO	54.9		73.1			128.0	
CO_2	147.5		393.2			540.7	
CH_4	63.5	21.2				84.7	
C_2H_4	0.0	0.0				0.0	
C_2H_6	0.5	0.1				0.6	
C_3H_8	0.0	0.0				0.0	
C_6H_6	15.0	1.2				16.2	
N_2				309.3		309.3	
H_2O		59.5	476.0			535.5	
Total Gas	281.3	99.0	942.3	309.3		1632.0	5.2
Total Output	305.1	100.2	942.3	309.3	4.8	1661.8	5.7
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	98.3

171/RPP/65058ApE

Table E-3. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-4

Test Date: 5-24-84
Study Period: From 1230 Hour to 1630 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	322.1	40.7	294.3	0.7	3.1	660.9	5.5
Moisture		7.9	63.1			71.0	
Steam to Ring		29.5	235.6			265.1	0.4
Steam to Nozzle		19.6	157.2			176.8	0.2
Oxygen to Nozzle			249.4			249.4	
Nitrogen Purge				373.5		373.5	
Total Input	322.1	97.7	999.6	374.2	3.1	1796.7	6.1

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	16.7	0.0			3.1	19.7	0.2
Oil/Tars	1.9	0.3				2.2	
Product Gas Components							
H_2		22.4				22.4	
CO	98.1		130.7			228.8	
CO_2	153.1		408.3			561.4	
CH_4	52.3	17.4				69.7	
C_2H_4	0.0	0.0				0.0	
C_2H_6	0.0	0.0				0.0	
C_3H_8	0.0	0.0				0.0	
C_6H_6	0.0	0.0				0.0	
N_2				374.3		374.3	
H_2O		57.6	460.7			518.3	
Total Gas	303.5	97.4	999.8	374.3		1775.0	5.4
Total Output	322.1	97.7	999.8	374.3	3.1	1797.0	5.6
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	91.8

171/RPP/65058ApE

Table E-4. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-5

Test Date: 6-13-84
Study Period: From 1250 Hour to 1650 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	312.9	40.2	292.5	0.3	2.6	648.5	5.3
Moisture		8.4	67.4			75.8	
Steam to Ring		38.0	304.4			342.4	0.5
Steam to Nozzle		24.1	193.1			217.2	0.3
Oxygen to Nozzle			123.4			123.4	
Nitrogen Purge				304.9		304.9	
Total Input	312.9	110.8	980.8	305.2	2.6	1712.2	6.1
Output							
Entrained Solids	39.9	0.7			2.6	43.4	0.6
Oil/Tars	15.6	2.8				18.4	0.4
Product Gas Components							
H_2		14.0				14.0	
CO	35.6		47.5			83.2	
CO_2	139.4		371.8			511.3	
CH_4	54.3	18.1				72.4	
C_2H_4	1.8	0.3				2.0	
C_2H_6	14.7	3.7				18.4	
C_3H_8	0.5	0.1				0.6	
C_6H_6	11.0	0.9				12.0	
N_2				305.1		305.1	
H_2O		70.2	561.6			631.8	
Total Gas	257.4	107.4	981.0	305.1		1650.8	4.8
Total Output	312.9	110.8	981.0	305.1	2.6	1712.4	5.8
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	95.1

171/RPP/65058ApE

Table E-5. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-6

Test Date: 6-28-84
Study Period: From 1130 Hour to 1530 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	302.6	38.3	273.9	0.2	4.1	619.2	5.1
Moisture		8.3	66.1			74.3	
Steam to Ring		40.8	326.5			367.3	0.5
Steam to Nozzle		25.3	202.2			227.5	0.3
Oxygen to Nozzle			167.3			167.3	
Nitrogen Purge				349.1		349.1	
Total Input	302.6	112.7	1036.0	349.3	4.1	1804.7	5.9
Output							
Entrained Solids	24.2	0.0			4.1	28.3	0.4
Oil/Tars	11.5	2.0				13.5	0.3
Product Gas Components							
H_2		13.3				13.3	
CO	52.9		70.5			123.4	
CO_2	137.9		367.7			505.7	
CH_4	58.7	19.6				78.3	
C_2H_4	1.6	0.3				1.8	
C_2H_6	8.9	2.2				11.1	
C_3H_8	0.0	0.0				0.0	
C_6H_6	7.1	0.6				7.7	
N_2				349.2		349.2	
H_2O		74.7	597.7			672.4	
Total Gas	267.0	110.6	1035.9	349.2		1762.7	5.0
Total Output	302.8	112.6	1035.9	349.2	4.1	1804.6	5.7
Balance (Output/Input), %	100.1	100.0	100.0	99.9	100.0	100.0	96.6

171/RPP/65058ApE

Table E-6. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-8

Test Date: 8-2-84
Study Period: From 1130 Hour to 1400 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	326.1	41.9	295.6	0.7	2.5	666.7	5.5
Moisture		9.3	74.4			83.7	
Steam to Ring		33.1	264.4			297.5	0.4
Steam to Nozzle		21.2	169.9			191.1	0.2
Oxygen to Nozzle			166.3			166.3	
Nitrogen Purge				390.8		390.8	
Total Input	326.1	105.5	970.6	391.5	2.5	1796.1	6.1
Output							
Entrained Solids	23.8	0.4			2.5	26.3	0.4
Oil/Tars	7.1	1.8				8.9	0.2
Product Gas Components							
H_2		16.0				16.0	
CO	63.8		85.0			148.8	
CO_2	144.6		385.7			530.3	
CH_4	65.2	21.7				86.9	
C_2H_4	3.7	0.6				4.3	
C_2H_6	6.0	1.5				7.5	
C_3H_8	0.0	0.0				0.0	
C_6H_6	12.1	1.0				13.1	
N_2				391.5		391.5	
H_2O		62.5	500.0			562.5	
Total Gas	295.3	103.3	970.7	391.5		1760.9	5.5
Total Output	326.2	105.5	970.7	391.5	2.5	1796.5	6.1
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table E-7. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-9

Test Date: 10-11-84
Study Period: From 1300 Hour to 1600 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	331.8	41.0	294.7	0.6	2.5	670.6	5.6
Moisture		10.6	84.7			95.3	
Steam to Ring		25.7	205.6			231.3	0.3
Steam to Nozzle		16.9	135.0			151.9	0.2
Oxygen to Nozzle			161.4			161.4	
Nitrogen Purge				159.5		159.5	
Total Input	331.8	94.1	881.4	160.1	2.5	1470.0	6.1

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	26.7	0.4			2.5	29.7	0.4
Oil/Tars	11.5	0.8				12.3	0.3
Product Gas Components							
H_2		13.0				13.0	
CO	56.0		74.7			130.7	
CO_2	140.2		373.9			514.1	
CH_4	63.3	21.1				84.4	
C_2H_4	4.3	0.7				5.0	
C_2H_6	8.9	2.2				11.1	
C_3H_8	0.0	0.0				0.0	
C_6H_6	21.0	1.7				22.7	
N_2				160.2		160.2	
H_2O		54.1	432.8			486.9	
Total Gas	293.7	92.9	881.4	160.2		1428.2	5.2
Total Output	331.9	94.1	881.4	160.2	2.5	1470.2	5.9
Balance (Output/Input), %	100.0	99.9	100.0	100.1	100.0	100.0	96.7

171/RPP/65058ApE

Table E-8. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-10

Test Date: 10-25-84
Study Period: From 1415 Hour to 1800 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	174.2	21.4	153.1	0.4	2.1	351.2	2.9
Moisture		5.4	42.9			48.3	0.2
Steam to Ring		16.7	133.4			150.1	0.1
Steam to Nozzle		10.8	86.5			97.3	
Oxygen to Nozzle			91.5			91.5	
Nitrogen Purge				302.0		302.0	
Total Input	174.2	54.3	507.4	302.4	2.1	1040.4	3.2
Output							
Entrained Solids	7.0	0.1			2.1	8.4	0.1
Oil/Tars	1.1	0.1				1.2	--
Product Gas Components							
H_2		7.1				7.1	
CO	41.1		54.8			95.8	
CO_2	67.5		179.9			247.3	
CH_4	27.6	9.2				36.8	
C_2H_4	5.1	0.9				6.0	
C_2H_6	4.2	1.0				5.2	
C_3H_8	0.2	0.0				0.2	
C_6H_6	20.4	1.7				22.1	
N_2				302.5		302.5	
H_2O		34.1	272.8			306.9	
Total Gas	166.1	54.1	507.4	302.5		1030.0	3.0
Total Output	174.2	54.3	507.4	302.5	2.1	1040.5	3.1
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	96.9

171/RPP/65058ApE

Table E-9. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-11

Test Date: 11-8-84
Study Period: From 1130 Hour to 1600 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	455.0	56.7	410.6	0.0	4.2	926.5	7.7
Moisture		11.5	91.7			103.2	
Steam to Ring		33.3	266.3			299.6	0.4
Steam to Nozzle		21.4	171.6			193.0	0.2
Oxygen to Nozzle			203.3			203.3	
Nitrogen Purge				297.7		297.7	
Total Input	455.0	122.9	1143.5	297.7	4.2	2023.3	8.3

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	37.3	0.6			4.2	41.7	0.6
Oil/Tars	20.1	1.5				21.6	0.4
Product Gas Components							
H_2		18.8				18.8	
CO	102.3		136.4			238.7	
CO_2	170.1		453.5			623.5	
CH_4	79.5	26.5				106.0	
C_2H_4	5.9	1.0				6.9	
C_2H_6	11.8	2.9				14.7	
C_3H_8	0.0	0.0				0.0	
C_6H_6	28.1	2.3				30.4	
N_2				297.7		297.7	
H_2O		69.2	553.6			622.8	
Total Gas	397.6	120.8	1143.4	297.7		1959.5	7.2
Total Output	455.1	122.8	1143.4	297.7	4.2	2023.2	8.2
Balance (Output/Input), %	100.0	99.9	100.0	100.0	100.0	100.0	98.8

171/RPP/65058ApE

Table E-10. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-13

Test Date: 12-13-84
Study Period: From 1300 Hour to 1645 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	322.8	41.7	298.7	0.8	7.0	671.0	5.5
Moisture		7.9	63.2			71.1	
Steam to Ring		25.9	207.0			232.9	0.3
Steam to Nozzle		18.0	143.9			161.9	0.2
Oxygen to Nozzle			168.1			168.1	
Nitrogen Purge				263.7		263.7	
Total Input	322.8	93.4	880.9	264.5	7.0	1568.7	6.0
Output							
Entrained Solids	32.5	0.4			7.0	38.2	0.5
Oil/Tars	5.4	0.4				5.8	0.1
Product Gas Components							
H_2		19.9				19.9	
CO	61.0		81.4			142.4	
CO_2	148.9		397.1			546.1	
CH_4	58.8	19.6				78.4	
C_2H_4	0.2	0.0				0.2	
C_2H_6	8.8	2.2				11.0	
C_3H_8	0.0	0.0				0.0	
C_6H_6	7.2	0.6				7.8	
N_2				264.6		264.6	
H_2O		50.3	402.4			452.7	
Total Gas	284.9	92.6	880.9	264.6		1523.1	5.2
Total Output	322.8	93.4	880.9	264.6	7.0	1568.8	5.8
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	96.7

Table E-11. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-14

Test Date: 2-14-85
Study Period: From 1200 Hour to 1630 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	339.8	42.0	307.4	1.3	12.2	702.7	5.8
Moisture		13.8	110.4			124.2	
Nitrogen to Ring				365.9		365.9	0.1
Nitrogen to Nozzle				416.6		416.6	0.1
Oxygen to Nozzle			147.9			147.9	
Nitrogen Purge				167.8		167.8	
Total Input	339.8	55.8	565.7	951.9	12.2	1925.1	6.0

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	26.9	0.4			12.2	33.0	0.4
Oil/Tars	20.7	1.4				22.1	0.4
Product Gas Components							
H_2		8.2				8.2	
CO	63.3		84.4			147.7	
CO_2	116.6		310.9			427.5	
CH_4	51.3	17.1				68.4	
C_2H_4	6.3	1.1				7.4	
C_2H_6	10.6	2.6				13.2	
C_3H_8	0.0	0.0				0.0	
C_6H_6	44.3	3.7				48.0	
N_2				951.4		951.4	
H_2O		21.3	169.6			191.7	
Total Gas	292.4	54.0	571.7	951.4		1863.5	5.2
Total Output	339.9	55.7	571.7	951.4	12.2	1925.0	6.0
Balance (Output/Input), %	100.0	99.8	100.0	100.0	100.0	100.0	100.0

171/RPP/65058ApE

Table E-12. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-15

Test Date: 3-1-85
Study Period: From 1130 Hour to 1500 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	282.8	34.7	251.6	0.9	5.9	576.0	4.8
Moisture		10.8	86.6			97.4	
Steam to Ring		18.0	144.4			162.4	0.2
Steam to Nozzle		12.7	101.5			114.2	0.1
Oxygen to Nozzle			165.2			165.2	
Nitrogen Purge				588.9		588.9	0.1
Total Input	282.8	76.3	749.3	589.8	5.9	1704.1	5.2
Output							
Entrained Solids	15.5	0.2			5.9	19.5	0.2
Oil/Tars	12.1	0.8				12.9	0.3
Product Gas Components							
H_2		12.1				12.1	
CO	61.7		82.2			143.9	
CO_2	115.7		308.6			424.4	
CH_4	42.9	14.3				57.2	
C_2H_4	3.6	0.6				4.2	
C_2H_6	4.8	1.2				6.0	
C_3H_8	0.0	0.0				0.0	
C_6H_6	26.3	2.2				28.5	
N_2				589.8		589.8	
H_2O		44.8	358.4			403.2	
Total Gas	255.0	75.2	749.3	589.8		1669.3	4.5
Total Output	282.6	76.3	749.3	589.8	5.9	1703.9	5.0
Balance (Output/Input), %	99.9	100.0	100.0	100.0	100.0	100.0	96.2

Table E-13. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-16

Test Date: 3-15-85
Study Period: From 1130 Hour to 1500 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	335.0	44.4	324.3	0.5	5.1	709.3	5.6
Moisture		6.6	52.7			59.3	
Steam to Ring		45.4	363.3			408.7	0.6
Steam to Nozzle		17.8	142.3			160.1	0.2
Oxygen to Nozzle			172.4			172.4	
Nitrogen Purge				340.1		340.1	
Total Input	335.0	114.2	1055.0	340.6	5.1	1849.9	6.4
Output							
Entrained Solids	19.1	0.3			5.1	22.0	0.3
Oil/Tars	13.8	1.0				14.8	0.3
Product Gas Components							
H_2		16.7				16.7	
CO	58.2		77.6			135.7	
CO_2	151.8		404.7			556.5	
CH_4	58.9	19.6				78.6	
C_2H_4	2.3	0.4				2.7	
C_2H_6	11.7	2.9				14.6	
C_3H_8	0.0	0.0				0.0	
C_6H_6	19.5	1.6				21.1	
N_2				340.5		340.5	
H_2O		71.6	572.8			644.4	
Total Gas	302.3	112.9	1055.0	340.5		1810.7	5.6
Total Output	335.2	114.2	1055.0	340.5	5.1	1850.1	6.2
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	96.9

Table E-14. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST GT-17

Test Date: 3-29-85
Study Period: From 1615 Hour to 1800 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	244.1	30.9	220.6	0.6	5.5	501.7	4.1
Moisture		20.3	162.8			183.1	
Steam to Ring		20.7	165.9			186.6	0.2
Steam to Nozzle		14.4	115.5			129.9	0.2
Oxygen to Nozzle			223.3			223.3	
Nitrogen Purge				914.9		914.9	0.1
Total Input	244.1	86.4	888.0	915.5	5.5	2139.5	4.6

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	8.1	0.1			5.5	10.1	0.1
Oil/Tars	0.0	0.0				0.0	
Product Gas Components							
H_2		13.9				13.9	
CO	41.7		55.6			97.3	
CO_2	140.3		374.1			514.4	
CH_4	41.3	13.8				55.1	
C_2H_4	0.0	0.0				0.0	
C_2H_6	1.9	0.5				2.4	
C_3H_8	0.0	0.0				0.0	
C_6H_6	10.7	0.9				11.6	
N_2				915.4		915.4	
H_2O		57.3	458.4			515.7	
Total Gas	235.8	86.3	888.1	915.4		2125.7	4.2
Total Output	243.9	86.4	881.1	915.4	5.5	2139.4	4.3
Balance (Output/Input), %	99.9	100.0	100.0	100.0	100.0	100.0	93.5

Table E-15. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-1

Test Date: 6-20-85
Study Period: From 1030 Hour to 2100 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	298.4	38.3	270.7	1.2	3.5	612.1	5.1
Moisture		3.5	28.3			31.8	
Steam to Ring		26.0	207.8			233.8	0.3
Steam to Nozzle		17.4	139.4			156.8	0.2
Oxygen to Nozzle			163.3			163.3	
Nitrogen Purge				347.6		347.6	
Total Input	298.4	85.3	809.4	348.8	3.5	1545.4	5.6

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	13.0	0.2			3.5	15.4	0.2
Oil/Tars	16.3	1.8				18.1	0.4
Product Gas Components							
H_2		15.6				15.6	
CO	62.3		83.1			145.4	
CO_2	132.9		354.4			487.3	
CH_4	57.4	19.1				76.5	
C_2H_4	0.5	0.1				0.5	
C_2H_6	3.4	0.9				4.3	
C_3H_8	0.0	0.0				0.0	
C_6H_6	12.6	1.1				13.7	
N_2				348.6		348.6	
H_2O		46.5	372.0			418.6	
Total Gas	269.1	83.3	809.5	348.6		1510.6	4.8
Total Output	298.4	85.3	809.5	348.6	3.5	1545.3	5.4
Balance (Output/Input), %	100.0	100.1	100.0	99.9	100.0	100.0	96.4

171/RPP/65058ApE

Table E-16. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-2

Test Date: 7-18, 7-19-85
Study Period: From 1030 Hour to 0700 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	157.6	20.5	144.1	0.7	2.7	325.7	2.7
Moisture		3.0	24.2			27.2	
Steam to Ring		16.9	135.3			152.2	0.2
Steam to Nozzle		10.3	82.7			93.0	0.1
Oxygen to Nozzle			90.3			90.3	
Nitrogen Purge				319.8		319.8	
Total Input	157.6	50.8	476.6	320.5	2.7	1008.2	3.0
Output							
Entrained Solids	11.5	0.2			2.7	14.2	0.2
Oil/Tars	8.4	0.9				9.3	0.2
Product Gas Components							
H_2		4.9				4.9	
CO	38.4		51.1			89.5	
CO_2	57.2		152.6			209.9	
CH_4	22.8	7.6				30.3	
C_2H_4	6.5	1.1				7.5	
C_2H_6	5.6	1.4				7.0	
C_3H_8	0.1	0.0				0.2	
C_6H_6	7.2	0.6				7.8	
N_2				320.5		320.5	
H_2O		34.1	272.8			306.9	
Total Gas	137.7	49.7	476.6	320.5		984.4	2.5
Total Output	157.6	50.8	476.6	320.5	2.7	1008.2	2.9
Balance (Output/Input), %	100.0	99.9	100.0	100.0	100.0	100.0	96.7

171/RPP/65058ApE

Table E-17. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T3D-1a

Test Date: 8-13, 8-15-85
Study Period: From 1109 Hour to 2348 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	185.9	23.9	168.2	0.6	2.7	381.3	3.2
Moisture		5.1	41.0			46.2	
Steam to Ring		34.9	279.3			314.2	0.4
Steam to Nozzle		21.0	167.8			188.8	0.2
Oxygen to Nozzle			112.5			112.5	
Nitrogen Purge				316.0		316.0	
Total Input	185.9	84.9	768.9	316.6	2.7	1359.0	3.8
Output							
Entrained Solids	7.4	0.1			2.7	9.3	0.1
Oil/Tars	5.7	0.4				6.1	0.1
Product Gas Components							
H_2		13.2				13.2	
CO	26.1		34.9			61.0	
CO_2	100.9		269.2			370.1	
CH_4	34.9	11.6				46.5	
C_2H_4	0.6	0.1				0.7	
C_2H_6	2.5	0.6				3.1	
C_3H_8	0.0	0.0				0.0	
C_6H_6	7.9	0.7				8.5	
N_2				316.6		316.6	
H_2O		58.1	464.8			522.9	
Total Gas	172.9	84.3	768.8	316.6		1342.6	3.5
Total Output	185.9	84.8	768.8	316.6	2.7	1358.9	3.7
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	97.4

171/RPP/65058ApE

Table E-18· MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T3D-1b

Test Date: 8-16-85
Study Period: From 0228 Hour to 0528 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	325.3	41.8	294.3	1.1	4.8	667.2	5.5
Moisture		9.0	71.8			80.8	
Steam to Ring		31.6	252.5			284.1	0.4
Steam to Nozzle		21.1	169.0			190.1	0.2
Oxygen to Nozzle			168.9			168.9	
Nitrogen Purge				317.9		317.9	
Total Input	325.3	103.4	956.5	319.0	4.8	1709.0	6.1
Output							
Entrained Solids	10.5	0.2			4.8	13.1	0.2
Oil/Tars	9.7	0.7				10.4	0.2
Product Gas Components							
H_2		18.0				18.0	
CO	48.9		65.2			114.2	
CO_2	151.9		405.0			556.9	
CH_4	57.5	19.2				76.7	
C_2H_4	0.7	0.1				0.8	
C_2H_6	3.5	0.9				4.4	
C_3H_8	0.0	0.0				0.0	
C_6H_6	42.6	3.6				46.2	
N_2				319.0		319.0	
H_2O		60.8	486.4			547.2	
Total Gas	305.2	102.5	956.6	319.0		1683.3	5.6
Total Output	325.4	103.4	956.6	319.0	4.8	1709.2	6.0
Balance (Output/Input), %	100.0	100.0	100.0	100.0	100.0	100.0	98.4

171/RPP/65058ApD

Table E-19. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-3a

Test Date: 9-19-85
Study Period: From 1100 Hour to 1430 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	314.1	40.0	282.6	1.2	5.5	643.4	5.3
Moisture		7.2	57.5			64.7	
Steam to Ring		32.7	261.2			293.9	0.4
Steam to Nozzle		21.4	170.9			192.3	0.3
Oxygen to Nozzle			182.9			182.9	
Nitrogen Purge				289.8		289.8	
Total Input	314.1	101.2	955.2	291.0	5.5	1667.0	6.0
Output							
Entrained Solids	5.4	0.1			5.5	6.6	0.1
Oil/Tars	6.8	0.5				7.2	0.1
Product Gas Components							
H_2		18.4				18.4	
CO	62.8		83.7			146.5	
CO_2	151.5		404.1			555.6	
CH_4	66.1	22.0				88.1	
C_2H_4	0.0	0.0				0.0	
C_2H_6	0.3	0.1				0.4	
C_3H_8	0.0	0.0				0.0	
C_6H_6	21.4	1.8				23.2	
N_2				291.0		291.0	
H_2O		58.4	467.4			525.8	
Total Gas	302.2	100.7	955.2	291.0		1649.1	5.6
Total Output	314.3	101.3	955.2	291.0	5.5	1667.3	5.8
Balance (Output/Input), %	100.1	100.0	100.0	100.0	100.0	100.0	96.7

171/RPP/65058ApD

Table E-20. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-3b

Test Date: 9-19-85
Study Period: From 1600 Hour to 2000 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	314.1	40.0	282.6	1.2	5.5	643.4	5.3
Moisture		7.2	57.5			64.7	
Steam to Ring		32.0	256.4			288.4	0.4
Steam to Nozzle		21.2	169.8			191.0	0.3
Oxygen to Nozzle			126.4			126.4	
Nitrogen Purge				282.5		282.5	
Total Input	314.1	100.5	892.6	283.7	5.5	1596.4	6.0

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	19.4	0.3			5.5	23.0	0.3
Oil/Tars	21.1	1.5				22.6	0.5
Product Gas Components							
H_2		11.4				11.4	
CO	44.9		59.9			104.8	
CO_2	126.3		336.8			463.1	
CH_4	55.8	18.6				74.4	
C_2H_4	4.5	0.7				5.2	
C_2H_6	14.5	3.6				18.1	
C_3H_8	0.0	0.0				0.0	
C_6H_6	27.5	2.3				29.8	
N_2				283.6		283.6	
H_2O		62.0	496.0			558.0	
Total Gas	273.5	98.7	892.7	283.6		1548.5	5.1
Total Output	313.9	100.6	892.7	283.6	5.5	1596.3	5.9
Balance (Output/Input), %	99.9	100.1	100.0	100.0	100.0	100.0	98.3

171/RPP/65058ApD

Table E-21. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-4a

Test Date: 10-10-85
Study Period: From 1230 Hour to 1600 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	167.9	21.1	147.3	0.9	4.4	341.7	2.8
Moisture		3.7	30.0			33.7	
Steam to Ring		18.1	144.7			162.8	0.2
Steam to Nozzle		12.0	95.6			107.6	0.2
Oxygen to Nozzle			99.6			99.6	
Nitrogen Purge				319.7		319.7	
Total Input	167.9	54.9	517.3	320.6	4.4	1065.1	3.2

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	5.2	0.1			4.4	6.6	0.1
Oil/Tars	8.6	0.6				9.2	0.2
Product Gas Components							
H_2		6.6				6.6	
CO	41.5		55.3			96.8	
CO_2	63.8		170.1			233.8	
CH_4	23.0	7.7				30.7	
C_2H_4	6.9	1.2				8.1	
C_2H_6	3.7	0.9				4.7	
C_3H_8	0.2	0.0				0.2	
C_6H_6	15.0	1.3				16.3	
N_2				320.5		320.5	
H_2O		36.5	292.0			328.5	
Total Gas	154.1	54.2	517.4	320.5		1046.1	2.9
Total Output	167.9	54.8	517.4	320.5	4.4	1065.1	3.2
Balance (Output/Input), %	100.0	99.9	100.0	100.0	100.0	100.0	100.0

171/RPP/65058ApD

Table E-22. MATERIAL AND ENERGY BALANCE SUMMARY FOR RENUGAS PRU TEST T12-4b

Test Date: 10-10-85
Study Period: From 1700 Hour to 1830 Hour

Basis: 1 Hour; All Units in Pounds Unless Otherwise Noted.

Input	C	H	O	N	Ash	Total	10^6 Btu
Biomass (Dry)	166.7	21.1	146.7	0.7	4.2	339.4	2.8
Moisture		4.0	32.0			36.0	
Steam to Ring		18.3	146.1			164.4	0.2
Steam to Nozzle		12.1	96.5			108.6	0.1
Oxygen to Nozzle			104.6			104.6	
Nitrogen Purge				350.9		350.9	
Total Input	166.7	55.5	525.9	351.6	4.2	1103.9	3.1

Output	C	H	O	N	Ash	Total	10^6 Btu
Entrained Solids	3.4	0.1			4.2	4.5	
Oil/Tars	7.9	0.5				8.4	0.2
Product Gas Components							
H_2		6.8				6.8	
CO	41.9		55.9			97.8	
CO_2	65.9		175.7			241.5	
CH_4	25.5	8.5				33.9	
C_2H_4	5.5	0.9				6.4	
C_2H_6	3.3	0.8				4.1	
C_3H_8	0.2	0.0				0.2	
C_6H_6	13.3	1.1				14.4	
N_2				351.6		351.6	
H_2O		36.8	294.4			331.2	
Total Gas	155.5	55.0	526.0	351.6		1088.0	2.9
Total Output	166.7	55.6	526.0	351.6	4.2	1104.0	3.1
Balance (Output/Input), %	100.0	100.2	100.0	100.0	100.0	100.0	100.0

171/RPP/65058ApD

APPENDIX F.
Properties of Entrained Solids

Properties of Entrained Solids

For tests GT-1, GT-2, and GT-4, the entrained solids were collected from the solids reciever vessel at the end of each test. Starting with test GT-5 and onward, all entrained solids have been collected during the tests by the isokinetic sampling system that has been described in Appendix D.

The complete analyses (including size distribution, proximate and ultimate analyses, heating value, and bulk density) of these solids are presented in this Appendix. The anaylses show that no inert bed material was carried overhead along with the entrained solids and that approximately 80% by weight of the material is sized 200 mesh or smaller. The high heating value of ~12,000 Btu/dry lb makes this material attractive as boiler feed or can be reinjected into the gasifier bed to achieve greater carbon conversion. The subsieve particle analysis of the material collected in the pan was conducted using a coulter-counter.

Table F-1, Part 1. PROPERTIES OF ENTRAINED SOLIDS

Test No.	GT-1	GT-2	GT-4	GT-5	GT-6
IGT Sample No.	49281 49282	49405 49406	49729 49730	49835 49836	49871
Screen Analysis					
20 (wt % Retained)	0.3	N/A	0	0.7	0.3
30	0		0	0	0
40	0.1		0	0	0.3
60	0.5		1.5	0.7	0.9
80	2.5		2.9	3.3	2.4
100	3.0		2.9	4.6	3.3
120	4.0		4.4	3.9	3.3
140	5.0		10.1	6.5	5.1
200	16.0		19.6	17.6	14.4
270	21.0		13.5	22.9	19.5
325	9.6		4.4	12.4	9.6
PAN	38.0		40.7	27.4	40.9
Proximate Analysis, wt %					
Moisture	5.24	3.21	4.13	5.11	2.04
Volatile Matter	5.19	N/A	7.47	N/A	N/A
Ash	9.68	13.45	14.02	4.89	8.33
Fixed Carbon	79.89	N/A	74.38	N/A	N/A
Total	100.00	--	100.00	--	--
Ultimate Analysis, dry wt %					
Ash	10.21	13.91	14.63	5.14	8.50
Carbon	85.40	81.86	80.41	89.51	85.65
Hydrogen	1.23	1.22	1.05	1.62	1.47
Sulfur	N/A	N/A	N/A	N/A	N/A
Nitrogen	N/A	N/A	N/A	N/A	N/A
Oxygen (by difference)	N/A	N/A	N/A	N/A	N/A
Total	--	--	--	--	--
Gross Heating Value, Btu/dry lb	12,832	11,394	11,788	13,550	13,008
Bulk Density, lb/ft^3	25.1	18.2	13.4	21.4	19.2

N/A = Not Analyzed.

Table F-1, Part 2. PROPERTIES OF ENTRAINED SOLIDS

Test No.	GT-8	GT-9	GT-10	GT-11	GT-13
IGT Sample No.	50053	50544	50590	50656	50929
Screen Analysis					
20 (wt % Retained)	0	0	0	0	0
30	0	0	0.4	0	0
40	0	0.5	0.4	0.2	0
60	0.6	0.5	2.3	0.5	0.6
80	2.6	2.2	3.0	2.2	3.8
100	3.5	2.7	2.7	2.5	4.4
120	2.9	3.8	N/A	N/A	4.7
140	5.5	N/A	5.7	7.5	5.3
200	13.2	15.8	10.2	13.7	11.7
270	21.0	17.5	17.0	20.6	15.5
325	18.4	9.3	10.6	10.0	6.7
PAN	32.3	47.5	47.7	43.0	47.3
Proximate Analysis, wt %					
Moisture	3.08	7.87	4.10	18.47	4.12
Volatile Matter	6.97	6.08	N/A	4.16	8.84
Ash	7.59	5.82	11.15	3.55	12.15
Fixed Carbon	82.36	80.23	N/A	73.82	74.89
Total	100.00	100.00	--	100.00	100.00
Ultimate Analysis, dry wt %					
Ash	7.83	6.32	11.62	4.36	12.67
Carbon	86.90	89.80	83.40	89.54	82.18
Hydrogen	1.44	1.34	1.42	1.32	1.03
Sulfur	0.04	0.03	N/A	0.03	0.03
Nitrogen	0.16	0.13	N/A	0.15	0.07
Oxygen (by difference)	3.63	2.38	N/A	4.60	4.02
Total	100.00	100.00	--	100.00	100.00
Gross Heating Value, Btu/dry lb	13,204	13,505	12,617	13,692	12,196
Bulk Density, lb/ft^3	19.2	18.6	20.9	18.2	20.5

N/A = Not Analyzed.

Table F-1, Part 3. PROPERTIES OF ENTRAINED SOLIDS

Test No.	GT-14	GT-15	GT-16	GT-17	T12-1
IGT Sample No.	51127	51255	51373	51548	850604101
Screen Analysis					
20 (wt % Retained)	N/A	N/A	N/A	N/A	N/A
30	N/A	N/A	N/A	N/A	N/A
40	0.5	0	0.5	0	0
60	N/A	N/A	N/A	N/A	N/A
80	N/A	N/A	N/A	N/A	N/A
100	N/A	N/A	N/A	N/A	N/A
120	N/A	N/A	N/A	N/A	N/A
140	16.4	18.2	17.4	11.9	9.9
200	16.9	13.1	11.4	11.0	16.9
270	N/A	N/A	N/A	N/A	N/A
325	N/A	N/A	N/A	N/A	N/A
PAN	45.0	57.0	61.1	67.9	55.0
Proximate Analysis, wt %					
Moisture	0.70	1.68	1.50	2.06	1.74
Volatile Matter	8.73	10.04	6.61	11.97	7.90
Ash	12.39	14.03	7.78	24.45	8.47
Fixed Carbon	78.18	74.25	84.11	61.52	81.89
Total	100.00	100.00	100.00	100.00	100.00
Ultimate Analysis, dry wt %					
Ash	12.48	14.27	7.90	24.96	8.62
Carbon	81.47	79.72	87.02	68.33	84.17
Hydrogen	1.08	1.04	1.49	1.21	1.41
Sulfur	0.04	0.06	0.41	0.07	0.05
Nitrogen	0.17	0.10	0.06	0.04	0.19
Oxygen (by difference)	4.76	4.81	3.12	5.39	5.56
Total	100.00	100.00	100.00	100.00	100.00
Gross Heating Value, Btu/dry lb	12,168	11,724	13,237	10,064	12,732
Bulk Density, lb/ft^3	17.4	17.3	18.6	20.1	13.7

N/A = Not Analyzed.

Table F-1, Part 4. PROPERTIES OF ENTRAINED SOLIDS

Test No.	T12-2	T3D-1a	T3D-1b	T12-3a
IGT Sample No.	850702703 850702704	850802205 850802206 850802207	850802208	850902901
Screen Analysis				
20 (wt % Retained)	N/A	0	0	0
30	N/A	0	0	0
40	4.8	0	0	0
60	N/A	0	0.3	0
80	N/A	1.1	1.2	2.3
100	N/A	2.9	2.7	3.5
120	N/A	2.9	2.7	2.3
140	26.2	4.9	5.4	5.2
200	21.1	11.1	10.5	16.2
270	N/A	20.9	18.7	33.5
325	N/A	17.3	29.9	21.4
PAN	32.3	38.9	28.6	15.6
Proximate Analysis, wt %				
Moisture	4.80	5.24	1.22	3.45
Volatile Matter	10.99	9.37	8.41	9.13
Ash	11.18	13.52	13.08	11.99
Fixed Carbon	73.03	71.87	77.29	75.43
Total	100.00	100.00	100.00	100.00
Ultimate Analysis, dry wt %				
Ash	11.76	14.20	13.24	12.42
Carbon	81.31	79.07	80.45	81.25
Hydrogen	1.53	1.38	1.37	1.47
Sulfur	0.05	0.03	0.07	0.04
Nitrogen	0.29	0.14	0.15	0.09
Oxygen (by difference)	5.06	5.18	4.72	4.73
Total	100.00	100.00	100.00	100.00
Gross Heating Value, Btu/dry lb	12,364	11,934	12,140	12,244
Bulk Density, lb/ft^3	17.2	15.4	14.7	14.8

N/A = Not Analyzed.

Table F-1, Part 5. PROPERTIES OF ENTRAINED SOLIDS

Test No.	T12-3b	T12-4a	T12-4b
IGT Sample No.	850902902	851001803	851001804
Screen Analysis			
20 (wt % Retained)	0	0	0
30	0	0	0
40	0	0.3	0
60	0.3	1.1	0.7
80	3.4	2.2	0.7
100	3.1	1.3	0.7
120	2.8	1.6	0.7
140	7.9	3.2	2.0
200	19.7	8.9	6.1
270	29.4	11.3	14.9
325	19.3	33.4	28.4
PAN	14.1	36.7	45.8
Proximate Analysis, wt %			
Moisture	1.37	2.04	1.33
Volatile Matter	8.55	9.11	10.54
Ash	9.55	13.37	15.90
Fixed Carbon	80.53	75.48	72.23
Total	100.00	100.00	100.00
Ultimate Analysis, dry wt %			
Ash	9.68	13.64	16.12
Carbon	84.16	79.49	75.52
Hydrogen	1.49	1.27	1.31
Sulfur	0.04	0.06	0.06
Nitrogen	0.20	0.21	0.25
Oxygen (by difference)	4.43	5.33	6.74
Total	100.00	100.00	100.00
Gross Heating Value, Btu/dry lb	12,825	11,946	11,412
Bulk Density, lb/ft^3	15.0	23.2	20.1

N/A = Not Analyzed.

Table F-2. SUBSIEVE PARTICLE ANALYSES OF ENTRAINED SOLIDS

Test No.	GT-1	GT-2	GT-4	GT-5	GT-6	GT-8	GT-9	GT-10	GT-11	GT-13	GT-14
	cum %										
Subsieve Particle Analysis μ											
50.8	N/A	N/A	0.0	N/A	N/A	0.3	0.0	0.0	0.0	0.0	0.0
40.3			0.3			0.3	0.2	0.5	0.5	0.4	2.6
32.0			3.2			1.7	6.8	4.7	4.4	4.9	9.4
25.4			8.8			6.2	15.8	12.0	11.8	12.8	16.9
20.2			17.2			12.3	25.4	20.1	20.9	21.2	25.4
16.0			24.4			18.2	33.2	27.7	28.0	28.4	31.7
12.7			29.6			23.0	38.9	34.1	33.1	33.7	36.2
10.1			33.6			26.6	42.7	39.5	37.0	38.4	39.5
8.0			36.9			29.4	45.3	43.4	39.8	42.2	41.9
6.4			39.5			31.2	46.9	46.2	41.8	45.2	43.8
5.0			40.6			31.9	47.4	47.3	42.6	46.5	44.5
4.0			40.7			32.3	47.5	47.7	43.0	47.3	45.0

	GT-15	GT-16	GT-17	T12-1	T12-2	T3D-1a	T3D-1b	T12-3a	T12-3b	T12-4a	T12-4b
	cum %										
μ											
50.8	2.3	0.4	2.8	0.0	0.4	0.0	0.0	N/A	N/A	N/A	N/A
40.3	7.2	5.3	10.9	2.4	3.6	0.0	0.1				
32.0	16.3	15.3	23.0	9.3	10.3	1.6	1.1				
25.4	25.8	25.8	34.0	19.2	17.5	6.9	4.5				
20.2	34.3	35.1	43.2	29.1	23.6	15.0	9.8				
16.0	41.3	42.9	50.5	37.3	27.3	22.4	15.1				
12.7	46.1	48.2	55.5	42.9	29.6	28.2	19.5				
10.1	50.0	52.5	59.7	47.2	31.0	32.4	23.0				
8.0	53.2	56.0	63.2	50.6	31.8	35.4	25.6				
6.4	55.7	59.1	66.1	53.3	32.3	37.5	27.4				
5.0	56.6	60.3	67.1	54.4	32.3	38.3	28.2				
4.0	57.0	61.1	67.9	55.0	32.3	38.9	28.6				

DISTRIBUTION

No. of
Copies

OFFSITE

10 DOE/Office of Scientific
and Technical Information

William Ayres
Pyrotech, Inc.
8016 Stateline
Suite 101
Leawood, KS 66208

6 Suresh Babu
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

Phillip Badger
Biomass Fuels Program
Tennessee Valley Authority
Muscle Shoals, AL 35660

William Bair
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

David Bancroft
Council of Great Lakes
Governors
122 West Washington Ave.,
#801A
Madison, WI 53703

David S. Backner
Office of Solid Waste and
Renewable Resources
Illinois Department of Energy
and Natural Resources
325 W. Adams St., Room 300
Springfield, IL 62704-1892

K. Durai-Swamy
Management and Technical
Consultants, Inc.
13080 Park Street
Santa Fe Springs, CA 90670

Robert Evans
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

Herman F. Feldmann
Battelle-Columbus
Laboratories
505 King Avenue
Columbus, OH 43201

No. of
Copies

Virgil J. Flanigan
Univ. of Missouri-Rolla
223 Engineering Research Lab.
Rolla, MO 65401

Patrick Fox
Pacific Northwest and Alaska
Bioenergy Program
Bonneville Power
Administration
Routing, EPG
U.S. Department of Energy
P.O. Box 3261
Portland, OR 97208

4 Simon Friedrich
Biofuels and Municipal Waste
Technology Division
U.S. Department of Energy
Forrestal Building (CE-341)
1000 Independence Avenue
Washington, D.C. 20585

Robert Gyllenborg
Southwest Regional Biomass
Energy Program
Western Area Power Authority
P.O. Box 3402
Golden, CO 80401

Barbara Goodman
Solar Energy Research
Institute
1617 Cole Blvd.
Golden, CO 80401

John Goss
Department of Agricultural
Engineering
2030 Baines Hall
University of California,
Davis
Davis, CA 95616

Michael S. Graboski
Syngas Systems Inc.
P.O. Box 757
Golden, CO 80402-0757

No. of
Copies

James E. Helt
Chemical Engineer
Argonne National Laboratory
Building 205
9700 S. Cass Avenue
Argonne, IL 60439

W. Densmore Hunter, Manager
Energy Technology Department
Weyerhaeuser Company
WTC-1B-30
Tacoma, WA 98477

James D. Kerstetter
Washington State Energy
Office
State of Washington
809 Legion Way S.E.
ER-11
Olympia, WA 98504-1211

Donald L. Klass
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

Richard Knight
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

James Kuester
Dept. of Chem. Engineering
Arizona State University
Tempe, AZ 85281

Ronald Loose, Director
Office of Renewable
Technology
U.S. Department of Energy
Forrestal Building
1000 Independence Avenue
Washington, D.C. 20585

Parker D. Mathusa
Program Director
New York State Energy Research
and Development Authority
2 Rockefeller Plaza
Albany, NY 12223

No. of
Copies

Thomas R. Miles, Sr.
Consulting Design Engineers
5475 S.W. Arrowwood Lane
Portland, OR 97225

Terrance R. Miller, Manager
Office of Solid Waste and
Renewable Resources
Illinois Dept. of Energy &
Natural Resources
325 W. Adams, Room 300
Springfield, IL 62704-1892

Thomas A. Milne
Solar Energy Research Inst.
1617 Cole Blvd.
Golden, CO 80401

Russell O'Connell
Northwest Regional Biomass
Energy Program
Coalition of Northeastern
Governors
400 N. Capital St., NW,
Suite 38
Washington, D.C. 20001

Michael Onischak
Institute of Gas Technology
IIT Center
3424 South State Street
Chicago, IL 60616

Mark Paisley
Battelle-Columbus
Laboratories
505 King Avenue
Columbus, OH 43201

Thomas Reed
Department of Engineering
Colorado School of Mines
Golden, CO 80401

George Simons
California Energy Commission
1516 - 9th Street, MS-43
Sacramento, CA 9581

Stanley Sobczynski
Division of Improved Energy
Productivity
U.S. Department of Energy
Forrestal Building CE-142
1000 Independence Avenue
Washington, DC 20585

C. Edward Taylor
Corporate Energy & Env. Mgr.
Louisiana-Pacific Corporation
P.O. Box 158
Samoa, CA 95564

No. of
Copies

Carl J. Wallace
Solar Energy Research
Institute
5109 Leesburg Pike,
Suite 414
Falls Church, VA 22041

Donald K. Walter, Director
Biofuels and Municipal Waste
Technology Division
U.S. Department of Energy
Forrestal Building (CE-341)
1000 Independence Avenue
Washington, D.C. 20585

Edward I. Wan
Science Applications
International Corporation
1710 Goodridge Drive
McLean, VA 22102

Ed Wood
Energetics, Inc.
9210 Route 108
Columbia, MD 21045

Richard C. Wright
Energy Research Associates
2115 W. Norfolk
Mequon, WI 53092

FOREIGN

Tony Bridgwater
The University of Aston in
Birmingham
Dept. of Chemical Engineering
Gosta Green
Birmingham
ENGLAND B4 7ET

ONSITE

DOE Richland
Operations Office

D. R. Segna

19 Pacific Northwest
Laboratory

E. G. Baker
M. A. Gerber
R. J. Hall
L. K. Mudge
G. F. Schiefelbein (5)
L. J. Sealock
D. J. Stevens
P. C. Walkup
Publishing
Coordination (2)
Technical Report Files (5)