B-446

FINAL REPORT
PROJECT NO. B–446

A PROTOTYPE MOBILE SYSTEM FOR PYROLYSIS OF AGRICULTURAL AND/OR SILVICULTURAL WASTES

By

J. W. Tatom, A. R. Colcord, W. M. Williams, and K. R. Purdy
Georgia Institute of Technology
and
J. J. Demeter, C. R. McCann, J. M. Ekmann, and D. Bienstock
Pittsburgh Energy Research Center

Prepared for

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

Grant No. R–803430

June 1978

GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia 30332

1978

A PROTOTYPE MOBILE SYSTEM FOR PYROLYSIS OF AGRICULTURAL AND/OR SILVICULTURAL WASTES

by

J. W. Tatom, A. R. Colcord, W. M. Williams,
and K. R. Purdy
Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

and

J. J. Demeter, C. R. McCann, J. M. Ekmann,
and D. Bienstock
Pittsburgh Energy Research Center
U. S. Energy Research and Development Administration
Pittsburgh, Pennsylvania 15213

Grant No. R 803430

Project Officer

W. W. Liberick, Jr.
Energy Systems Environmental Control Division
Industrial Environmental Research Laboratory
Cincinnati, Ohio 45268

INDUSTRIAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U. S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

ABSTRACT

This research program was initiated to investigate three elements of a prototype mobile system for pyrolysis of agricultural and/or silvicultural wastes into clean, transportable fuels: the pyrolytic converter itself, a pyrolysis-gas-fueled internal combustion engine, and the combustion and emission characteristics of pyrolytic char and oil.

An experimental study of the performance of the Georgia Tech Engineering Experiment Station one-tonne-per-hour pyrolytic converter was conducted. Peanut hulls and pine sawdust were used as representative agricultural and silvicultural waste materials. Effects of converter capacity, feed material, mechanical agitation, bed depth, and air-to-feed ratio on product yields were determined. In addition, the performance of an integrated, mechanical-agitation, process-air-supply system (Airgitator) designed to improve the throughput of the converter was determined.

From these studies and an earlier study performed on a 0.5-tonne-per-hour converter, it appears that feed material, converter capacity, mechanical agitation, and "Airgitation" have little influence on product yields. Bed depth, although not affecting the combined energy yield of the char and oil, substantially influenced the relative amounts of char and oil produced. The air-to-feed ratio was found to be the dominant variable. The combined energy yield of the char and oil was a simple linear function of the air-to-feed ratio.

A spark-ignition internal combustion engine fueled with dry simulated pyrolysis gas was experimentally investigated to determine stable, full-throttle operation of this engine and to compare brake power output with that when the engine was fueled with gasoline. Excellent stability was obtained and the brake power output was found to be 60 to 65 percent of that when the engine was fueled with gasoline.

An experimental study of the combustion and emission characteristics of powdered char was performed by the Pittsburgh Energy Research Center. Stable combustion and satisfactory combustion efficiency were obtained in a 227 kg/hr pulverized-coal-fired, water-wall combustor fueled with powdered high-volatile char alone and with 50-50 blends of high-volatile or low-volatile pulverized char and coal. Excellent flame stability and carbon-combustion efficiency were obtained when powdered char was mixed with pyrolysis oil and No. 6 fuel oil and fired as a slurry in an oil-fired boiler. Studies of the combustor and boiler flue gases showed significant reductions in SO_2 emissions. The low sulfur and nitrogen content of the char makes it an attractive fuel to mix with either high-sulfur coal or oil to meet SO_2 and NO_x emission regulations without emission-control devices other than a baghouse or an electrostatic precipitator for particulate control.

This report was submitted in fulfillment of Grant No. R 803430 by Georgia Institute of Technology under the sponsorship of the U. S. Environment Protection Agency. This report covers a period from May 1, 1975, to July 31, 1977, and the work was completed as of July 31, 1977.

CONTENTS

Appendices

FIGURES

FIGURES (continued)

TABLES

NOMENCLATURE

Symbols	Definition	Units
h	enthalpy	MJ/kg
HV	Heating Value	MJ/kg
L	Losses (see Equation 2)	MJ
M	Mass	kg
w	weight fraction	kg/kg

Subscripts	
a	air
c	carbon
ch	char
f	feed
g	off-gas
h	hydrogen
o	oil and oxygen
n	nitrogen
wi	water in feed
wo	water in off-gas
xch	ash in char
xf	ash in feed

ACKNOWLEDGMENTS

This effort was supported by the Industrial Environmental Research Laboratory (IERL), U.S. Environmental Protection Agency, under Grant No. R 803430. We wish to express our appreciation to Mr. Walter W. Liberick, Jr. of IERL and Mr. Donald A. Oberacker of the Municipal Environmental Research Laboratory for their contributions and suggestions.

The School of Mechanical Engineering, Georgia Institute of Technology, provided the staff and facilities for conducting the internal combustion engine study. We greatly appreciate Dr. Stothe P. Kezios' cooperative efforts in this regard. Special appreciation is expressed to Dr. Wendell M. Williams for directing this study and to Mr. Louis A. Cavalli for his assistance.

The Pittsburgh Energy Research Center, U.S. Energy Research and Development Administration, performed the combustion and emission study. Mr. Daniel Bienstock and Mr. Joseph Demeter directed this excellent investigation.

SECTION 1

PROJECT GOALS

This project was designed to answer specific questions related to the development of a prototype system for pyrolysis of agricultural and silvicultural wastes into clean fuels. These questions were concerned with the operating characteristics of the Georgia Tech Engineering Experiment Station (EES) pyrolytic converter, the utility of pyrolysis gas as a fuel for a spark-ignition internal combustion engine, and the combustion and emission characteristics of pyrolysis char and oil.

The specific project goals were:

1. To determine the influence of system capacity, feed material mechanical agitation, air-to-feed ratio, and bed depth on the product yields of the EES pyrolytic converter.
2. To determine the performance of an integrated mechanical agitation and process-air supply system.
3. To determine the full-throttle performance of a spark-ignition engine fueled with dry simulated pyrolysis gas.
4. To determine the combustion and emission characteristics of powdered char, powdered char and high-sulfur coal, and a slurry of powdered char, pyrolysis oil, and No. 6 fuel oil. (This portion of the project was performed by ERDA's Pittsburgh Energy Research Center through a separate agreement with the US EPA's Industrial Environmental Research Laboratory.)

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

From the results of this project, the following conclusions can be drawn:

1. The effects of converter capacity, feed-material type, mechanical agitation, and "airgitation" are all minor in comparison to that of the air-to-feed ratio.
2. From the results of this project and earlier work, the available energy in the char-oil mixture appears to be solely a function of the air-to-feed ratio; all data are correlated by a single linear relationship between the available energy and the air-to-feed ratio.
3. Although the available energy in the char-oil mixture is only a function of the air-to-feed ratio, the relative amount of char and oil is dependent upon the bed depth.
4. Peanut hulls can be processed easily either with or without mechanical agitation.
5. The char and oil yields are unaffected by the substitution of an integrated mechanical agitator and process-air supply system (Airgitator) for the fixed, water-cooled air tubes of the EES converter. Except for an apparent increase in the off-gas-stream particulate content and temperature, the Airgitator performed well.
6. The conversion of existing intermittent-duty, spark-ignition gasoline engines to continuous-duty, pyrolysis-gas engines appears to require only the development of an automatic fuel-air mixer. The full-throttle brake-power output of a six cylinder engine fueled with dry simulated pyrolysis gas was 60 to 65 percent of that when the engine was run on gasoline.

7. Stable combustion and satisfactory combustion efficiency were maintained in the Pittsburgh Energy Research Center (PERC) 227 kg/hr pulverized-coal-fired, water-wall combustor fueled with high-volatile char alone, and with 50-50 blends of high-volatile or low-volatile char and coal.
8. When pulverized char was mixed with pyrolysis oil and No. 6 fuel oil and fired as a slurry in an oil fired boiler, excellent flame stability was experienced and carbon combustion efficiency was equal to that obtained with No. 6 fuel oil alone.
9. The low sulfur and nitrogen content of the char makes it an attractive fuel additive for either high-sulfur coal or fuel oil. In addition to extending fuel oil supplies, powdered char, added in the proper proportions, will permit compliance with SO_2 and NO_x emission regulations without emission control devices other than a baghouse or an electrostatic precipitator for particulate control.

RECOMMENDATIONS

Although the results of the study strongly support the technical feasibility of the mobile pyrolytic converter concept by providing additional operating data, by demonstrating operation of a spark-ignition engine on simulated pyrolysis gas, and by demonstrating the attractive combustion and emission characteristics of the char and oil, the following tasks are recommended before a complete mobile system demonstration project is initiated:

1. An improved off-gas system should be developed with will permit continuous, round-the-clock operation with at least 90 percent uptime. (The seriousness of the off-gas system servicing problem was not recognized until continuous operation was attempted at the 45 tonne-per-day demonstration plant owned and operated by the Tech-Air Corporation, the exclusive licensee for the process.)
2. An automatic fuel mixer for essentially particulate-free pyrolysis gas should be developed and demonstrated on a spark-ignition engine coupled to an electric generator.

3. The Airgitator should be studied during long-term runs to determine its ability to provide stable operation and its effect on the particulate level of the off-gas stream. Also, a more balanced configuration should be developed to reduce the unsymmetrical forces on the drive system.
4. When tasks one and three have been successfully completed, a full-scale mobile pyrolytic converter should be designed, fabricated, and tested.

SECTION 3

INTRODUCTION

GENERAL

This report describes an experimental program to develop a mobile pyrolysis system for conversion of agricultural and silvicultural wastes at the site of their production into clean and easily transportable fuels. The program included a series of tests using peanut hulls and pine sawdust as feed materials in the one tonne/hr Georgia Tech Engineering Experiment Station (EES) pyrolytic converter pilot plant, and was a follow-on study to earlier work [1,2,3,4] using wood waste as the feed material in a smaller, 227 kg/hr (500 lbm/hr) EES pilot plant.

RATIONALE FOR MOBILE PYROLYSIS CONCEPT

Agricultural wastes represent a huge potential source of energy for the U.S., but certain problems have limited their use as fuels in the past and must be dealt with in any successful energy conversion system. These problems include the following:

- Agricultural and silvicultural wastes (organic matter) typically contain 30 to 70 percent water, and therefore, are relatively low in heating value per kilogram. Since these waste materials would be scattered all over the country-side, transportation costs per megajoule to large thermal conversion plants would be very high.
- Because of the moisture content of these waste materials, the practicability of using existing thermal conversion equipment is doubtful, at least at its rated capacity. Most likely, new or modified facilities will be required. (The overall steam-side efficiency of boilers utilizing wet organic fuels, such as

bagasse and bark, is typically 60 to 65 percent. Thus, a serious conversion penalty results from using these materials as-received.)

- The particulate emissions from boilers operating on raw organic fuels would likely require the installation of expensive flue gas clean-up equipment.
- Agricultural wastes, with a few exceptions, are produced seasonally, rather than continuously. Thus, a steady supply of fuel from these wastes is not available, also it would be impractical to tie up costly equipment that cannot be used year round.
- Associated with the construction of a waste conversion facility dependent upon an adjacent, fixed supply of wastes over a long time period are contractual problems between the producer of the wastes and the waste utilizer. Although the waste producer might initially be spending two to five dollars per tonne for disposal of raw wastes, he might hesitate or refuse in a long-term contract to give away or perhaps pay a charge for disposal of his wastes. And clearly, once a facility for waste utilization has been constructed, the waste producer, upon termination of the original contract, would have the waste utilizer in an uncomfortable economi position.

One solution to these problems is to utilize a mobile pyrolysis system that could be transported to the site of waste production and there convert the wastes into a char, an oil, and a low-quality gas. The gas could be used to dry the wet feed and to operate the associated equipment, and the oil and char could be sold as fuels. The reduced weight and associated transportation costs thereby effected would be very substantial. A further benefit would be the greater leverage provided the waste utilizer in contract negotiations with the waste producer, since the unit could always be moved to a new location. The portability feature would also guarantee greater equipment utilization and, through proper scheduling between seasonal agricultural wastes and continuously available silvicultural wastes, could provide an almost constant supply of fuel. Finally, since the portable system could be assembled in factories using mass production techniques, it would likely be less expensive than a comparable, fixed installation system.

The Engineering Experiment Station (EES) at Georgia Tech over the last eight years has developed a simple, steady-flow, low-temperature, partial-oxidation pyrolysis system which is completely self-sustaining. In the EES design waste material is pyrolyzed in a vertical porous bed. This unit requires no special front-end system, has very few moving parts, and depends upon a relatively small blower to provide the air supply necessary to maintain the partial oxidization of the feed. Typically, a tonne of as-received wastes would be converted, using the EES process, to about 225 kg (495 lbm) of a powdered char-oil fuel, similar to coal, with a heating value of 25.6 to 30.2 MJ/kg (11,000-13,000 Btu/lbm). Thus, depending upon the feed moisture content (50 percent assumed), the energy available for use at the central thermal conversion plant could be 64 to 76 percent of that theoretically available from the original dry waste; and, of a boiler conversion efficiency of 80 to 85 percent, the overall steam-side efficiency of the process could be up to 65 percent. Hence, the percentage of useable energy could be as great as that available with direct burning, but with avoidance or significant reduction of the problems of:

- Transporting the wastes.
- Modification or construction of new facilities compatible with fuels derived from organic wastes.
- Emissions resulting from unburned fuel particles.

The powdered char-oil fuel could be burned in either suspension-fired or in stoker-fired boilers with essentially no modification. Also, it could be blended with cheaper high-sulfur coal to an additional economic advantage.

Two additional elements, which make the concept even more attractive, have recently come to light, i.e.:

- The application of the mobile pyrolysis concept to large barges* moving on the thousands of miles of inland and

---

* The barge concept was developed by Mr. Kevin Everett of the Florida Resource Recovery Council and is described in an unpublished paper [5].

inter-coastal waterways appears to have great promise. This would not only permit an increase in the size of the mobile system, but also would allow its application to the municipal wastes of smaller communities which presently cannot individually justify or afford a large, economical waste conversion system, but with other communities could successfully operate such a system.

- The char-oil fuel produced by the mobile pyrolysis system [1] was considered primarily as a coal substitute which could be used in existing suspension or stoker-fired systems. It appears now, from work with coal-oil slurries at Combustion Engineering [6], General Motors [7], and at ERDA's, Pittsburgh Energy Research Center (PERC) [8], that firing of combinations of petroleum oil and the char-oil mix in energy release ratios of up to 50 percent may be practical in existing oil-fired boilers with minimal or no modification. The low sulfur content and relatively low ash content of the char-oil mixture make it highly desirable as a fuel-oil extender, and presently no technical obstacles preventing its use are anticipated. Because so many existing boilers are oil-fired, this development may represent an important step away from reliance on oil alone as a boiler fuel.

These two considerations should have relatively little influence on the development of a portable system, but strengthen significantly the justification for use of the portable concept for production of the char-oil fuel. (Combustion and emission tests of char/coal and char-oil/fuel-oil mixtures, performed by ERDA/PERC, form a part of this study and are reported in Section 7.)

OBJECTIVES

The investigations, which were primarily experimental, had the following objectives:

- To determine the effects of scale on pyrolytic converter performance.

- To determine the effects of changing feed material on pyrolytic converter performance.
- To determine the effects of mechanical agitation on pyrolytic converter performance.
- To determine the influence of air-to-feed ratio and bed depth on product yields.
- To determine the performance of an integrated mechanical agitation-process air supply system.
- To determine the full-throttle performance of a spark-ignition engine fueled with simulated dry pyrolysis gas.
- To determine the combustion and emission characteristics of powdered char and pyrolysis oil from the thermal conversion of a 50/50-mixture of pine sawdust and bark--char by itself, char blended with powdered coal, and char blended with pyrolysis oil and No. 6 fuel oil.

In the following sections a description of these studies is presented.

SECTION 4

PARAMETRIC STUDY OF EES PYROLYSIS SYSTEM

GENERAL

This experimental program was conducted in the new, one tonne/hr EES pilot plant. Peanut hulls were used as the feed material in a series of nine tests and sawdust was used in two tests, for a total of 11 tests in the complete study. All told, approximately 40 metric tons (44 tons) of feed were used in this program. The tests involved investigation of the influence of scale, feed, air-to-feed ratio, mechanical agitation, and bed depth on product yields. This section presents a description of the test facilities, the calibration and testing procedure, the laboratory procedure, the data reduction methodology, and the results of this test program.

FACILITIES

A process flow diagram of the EES pilot plant is shown in Figure 1. Photographs of this unit showing views of the separate components involved are presented in Figures 2 through 6.

The system operates in the following manner: The peanut hulls (dried at the sheller) are collected, weighed, and stored in drums. During a test, the drums are emptied into a receiving bin which supplies a conveyor to the pyrolysis unit with input feed. The pyrolysis unit is 5.5 meters (18 feet) tall and 1.8 meters (6 feet) on each side. The inside of the unit is cylindrical, with a diameter of 1.2 meters (4 feet) and a depth of 2.4 meters (8 feet). The feed enters the converter through a gate valve at the top and passes down through the vertical bed. Process air tubes are located in the lower portion of the bed. These water-cooled tubes supply enough air to oxidize the feed in their immediate proximity, and thereby produce

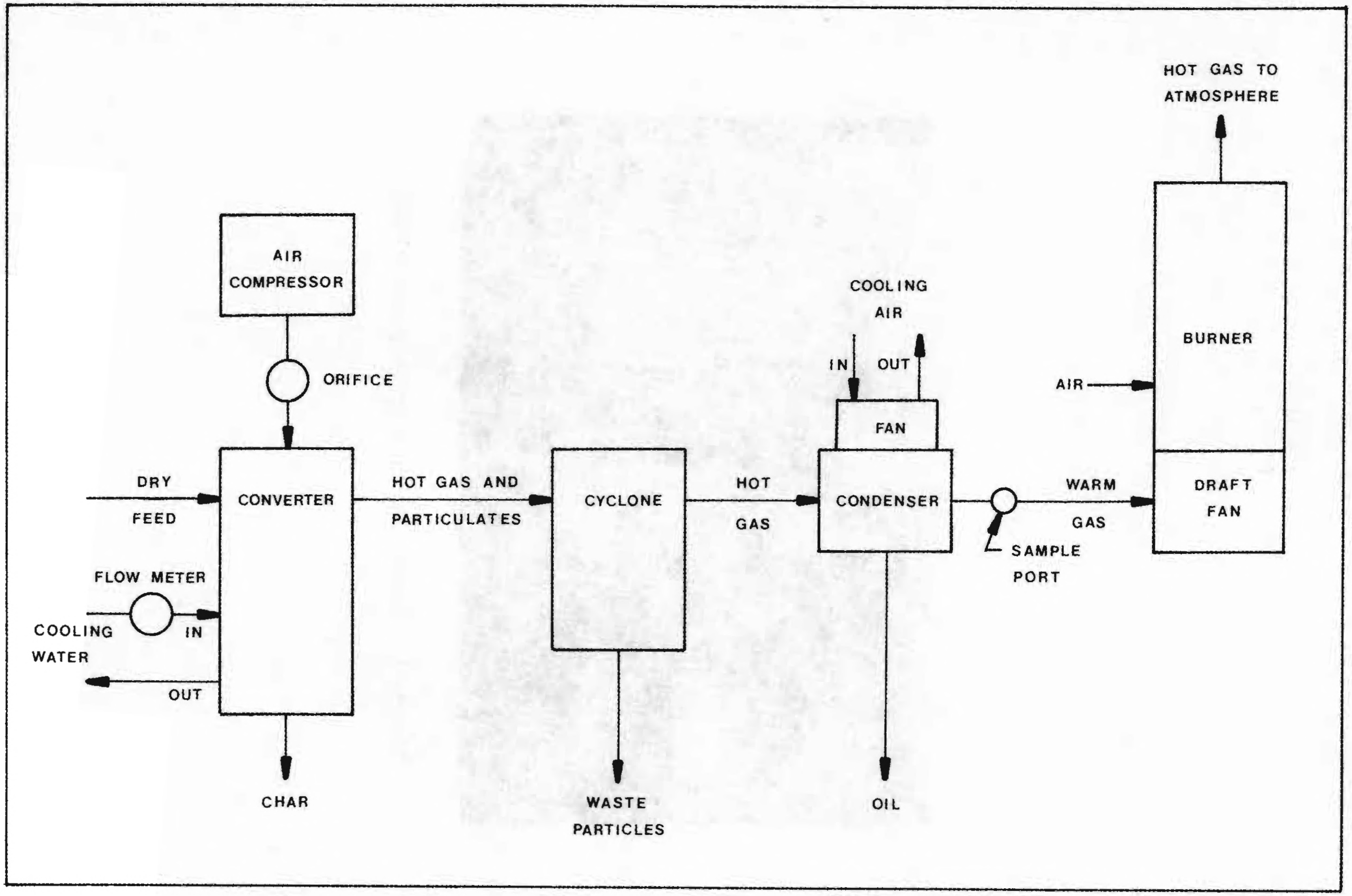


Figure 1. EES pyrolysis system process flow diagram.

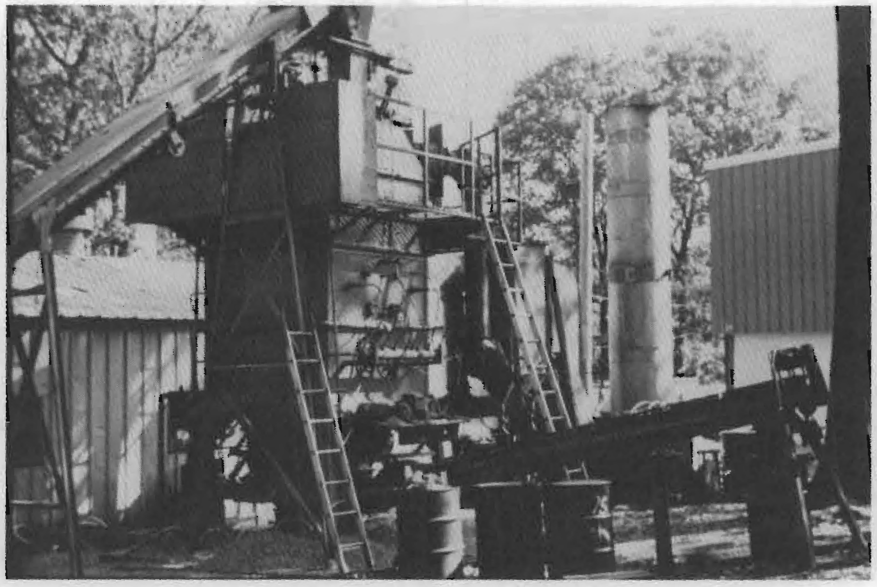


Figure 2. Fourth EES pyrolysis pilot plant.

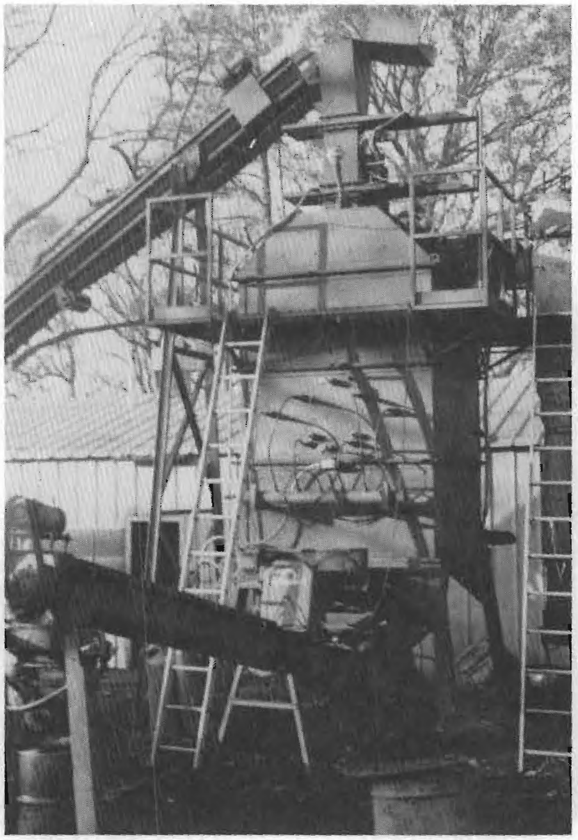


Figure 3. Close-up view of EES pyrolysis pilot plant.

Figure 4. Close-up view of conveyer and input system--EES pyrolysis pilot plant.

Figure 5. Close-up view of cyclone and condenser system--EES pyrolysis pilot plant.

Figure 6. Close-up view of off-gas burner--EES pyrolysis pilot plant.

sufficient heat for pyrolysis of the remaining feed material. The char at the bottom of the bed passes through a mechanical output system and into a screw conveyor that transports it into receiving drums.

The gases produced during decomposition of the feed pass upward through the downward-moving feed and leave the unit near its top. The gases then pass through a cyclone where particulates are removed and then to an air-cooled condenser which operates at a temperature above the dew point of the mixture. The condenser removes the higher boiling point oils, which are collected and weighed. The remainder of the uncondensed oils, the water vapor, some condensed oil droplets, and the noncondensible gases pass through the draft fan and into the burner which incinerates the mixture. The amount of gas production is controlled by the bed temperature, which, in turn, is controlled by the air-to-feed ratio.

The instrumentation used in the study included:

- An in situ calibrated orifice to measure process air flow rate.
- Scales to weigh the dry input feed, the char, and the oil yields.
- A water meter to measure total cooling water flow.
- Dial thermometers to measure inlet and exit cooling water temperatures.
- Various thermocouples to measure the pyrolysis gas temperature at several points in the system, internal bed temperature, external surface temperatures, and the burner temperature.
- A multiple channel recorder to provide continuous read-out of the various thermocouples.
- A gas sampling system for laboratory analysis of off-gas composition.

e system is normally operated at a system pressure of a few centimeters water below ambient; thus, any leaks present generally result in the roduction of air into the system. However, within the cavity between sliding plates of the gate valve, the displacement of the pyrolysis gas e input feed does result in some lost gas when the gate valve operates. e process rate of the unit increases, the gas production increases e system pressure tends to rise. To control the pressure, the draft fan speed can be varied within certain limits. The unit has pressure relief doors which operate at about 25 centimeters (10 inches) of water. These doors provide a safe means of relieving overpressure from any system malfunction.

The process rate of the system is governed by the setting of the output feed mechanism. A level indicator senses the need for additional feed, and activates the gate valve and conveyor system to provide the necessary input. Thus, the feed system is activated only upon demand, not continuously; hence, the gases lost through the gate valve do not represent a significant energy loss or pollution problem.

The condenser is of a relatively simple design having a series of air-cooled vertical tubes through which the hot pyrolysis gases pass. The condenser temperature is governed by a thermostatically operated fan which controls cooling air flow. In all except the last tests, the condenser was operated at about 93°C (200°F). It has been observed that oil droplets are frequentl carried in suspension through the off-gas system, past the draft fan, and into the burner. This results in some loss of oil; however, analytical techniques were used to correct for this loss.

In many of the tests, a simple rotating mechanical agitation system was utilized to enhance the flow of material through the waste converter and to prevent the formation of bridges or arches which can obstruct the downward-moving feed. A schematic view of the agitator used in these tests is shown in Figure 7. The system was operated by a high torque gear drive system. The maximum rotation speed of the agitator was about one revoluti per minute.

It should be noted that the off-gas flow rate was not measured directly during the tests because of the presence of droplets of oil and moisture the stream which make conventional instrumentation techniques impractic Instead, analytical techniques involving nitrogen, carbon, hydrogen, an oxygen balances were used to compute the flows of the various constitu which make up the off-gas stream.

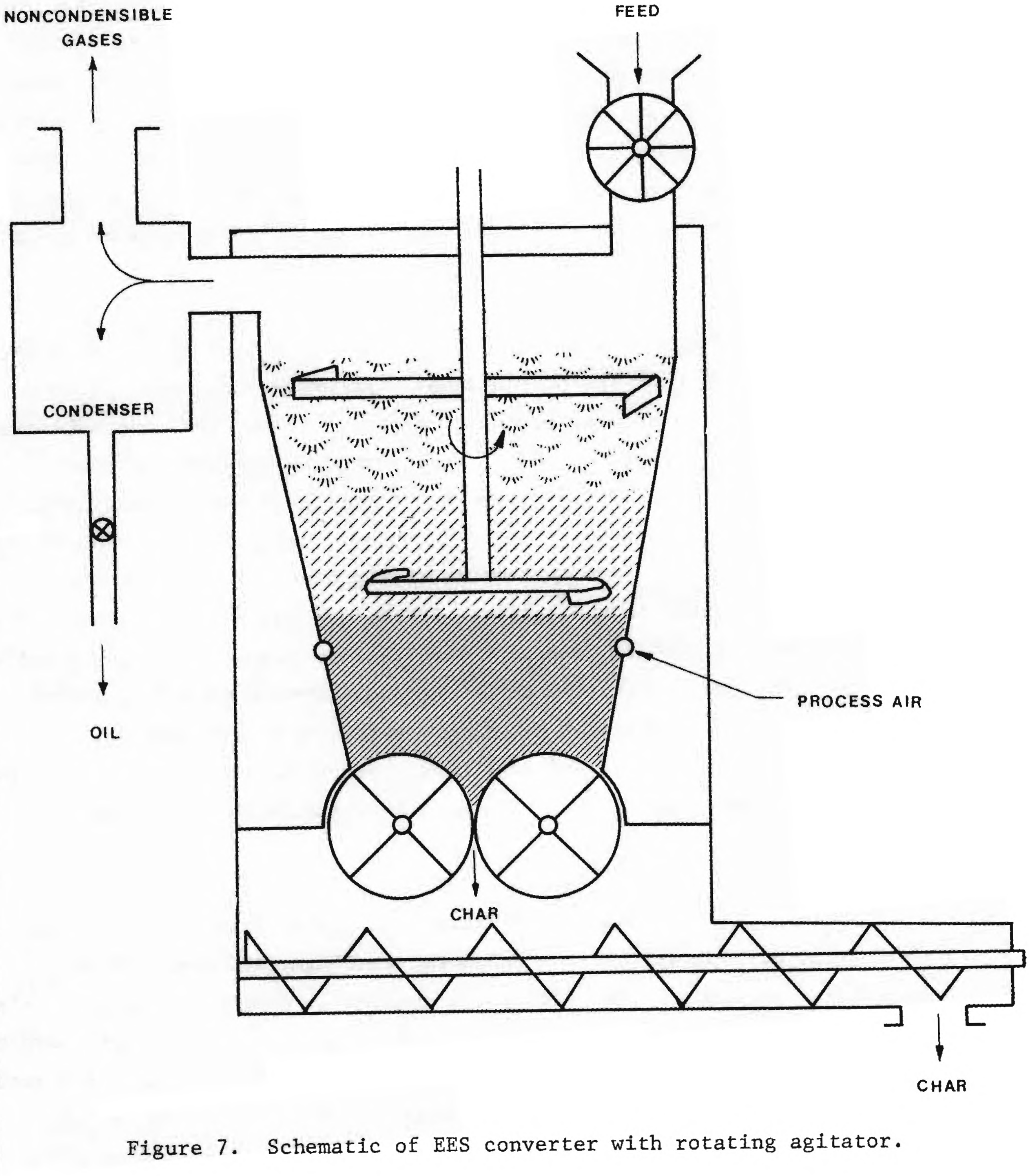


Figure 7. Schematic of EES converter with rotating agitator.

CALIBRATION AND TEST PROCEDURE

Prior to conducting the tests, many elements of the system instrumentation were carefully calibrated. The accuracy of some components, such as the thermocouples, was not checked since the required degree of precision did not demand temperature measurements of greater accuracy than the nominal values of the manufactured wire. Also, the accuracy of the cooling water meter was taken at face value from the name-plate data. Careful attention was given to calibrating the process air orifice against a laminar flow element. This ASME sharp-edged orifice was calibrated in situ to insure accuracy. Tares were individually determined for all the drums in which the dried feed was stored.

The procedure during the tests was relatively straightforward: The unit, loaded with feed or char the previous day, was heated-up by use of an electrical resistance heating element. When the temperature was sufficien elevated, process air was introduced slowly and the element was removed. Once it was apparent that the system was operating in a self-sustaining mode, the output system was activated and slowly brought up to the operati capacity chosen for the test. Likewise, the process air feed rate was adjusted to correspond to the desired air-to-feed ratio for the test. The system was then allowed to come to a steady-state condition, which require a nominal four hours. Constant checks and adjustments were made during this period to insure that the actual operating conditions were those desired. However, it was found that feed process rate and air-to-feed rat could be controlled only within limits of approximately plus or minus 10 percent.

Upon initiation of the test run, continuous records of time, feed input, char output, oil output, orifice manometer readings, and the various temperatures were made. In addition, a continuous sample of the pyrolysis off-gases was taken. Every effort was made to insure that the unit remain in a steady-state operating mode by continuous surveillance and adjustment of the various instruments measuring and controlling the inputs of the system. "Grab samples" of the feed from each drum were taken throughout the run. At the completion of a run, all of the char and oil produced were collected and representative samples of each were obtained. The char sample was obtained by use of a grain sampler. The oil was collected in a large drum, mixed thoroughly, and a sample of about one-half liter (one pint) taken. All of the feed grab samples were mixed and cut using a riffle splitter to obtain a composite sample of about one kilogram.

LABORATORY TESTING

The laboratory determined feed and product characteristics and subsequently analyzed the data. Thus, the work was checked carefully and every precaution was made to insure the accuracy of the results. However, despite these efforts, occasional inconsistencies did arise. Although inherent errors associated with the specific test procedures themselves clearly contributed to the problem, it is believed that the principal explanation for these occasional inconsistencies lies in the difficulty of sampling. Frequently, of necessity, a few grams sampled from a run were taken to represent the entire production of the oil or char in some piece of sensitive, chemical analysis laboratory equipment. Thus, even though several tests were usually made, there were some occasional problems with repeatability of results. Although these variations are predominantly less than one percent, the overwhelming impression is of good repeatability. The presence, especially in the CHNO analysis, of even small inconsistencies was found to have a significant effect on the test results. Thus, while these data stand up well by ordinary standards, the sensitivity of the overall test results to some of these data make close scrutiny necessary. A review of the breadth of the laboratory work done reveals a wide assortment of different analytical procedures. These procedures include analysis of the:

1. Feed for:
    - percent moisture
    - percent ash
    - percent acid-insoluble ash
    - percent carbon
    - percent hydrogen
    - percent nitrogen

- percent oxygen
- heating value

2. Char for:
   - percent moisture
   - percent ash
   - percent acid-insoluble ash
   - percent volatiles
   - percent carbon
   - percent hydrogen
   - percent nitrogen
   - percent oxygen
   - heating value
3. Oils for:
   - percent moisture
   - percent carbon
   - percent hydrogen
   - percent nitrogen
   - percent oxygen

The composition of the off-gas was determined by gas chromatography and reported as:

- percent nitrogen
- percent carbon monoxide
- percent carbon dioxide
- percent hydrogen
- percent methane
- percent C_2 components as C_2H_6 and C_2H_4
- percent C_3 components as C_3H_8 and C_3H_6
- percent C_4 components as C_4H_{10}

Presented in Appendix A are brief descriptions of the laboratory procedures followed to obtain all these data and estimates of the accuracy limits intrinsic to the test themselves. The data are presented in Appendix B.

DATA REDUCTION

General

The primary data obtained from the pilot plant testing, plus the laboratory findings, provided a substantial body of information and a solid basis to conduct complete energy, mass, and elemental balances for each test. In fact, a redundancy in the available information provided the means for an even more complete evaluation of the internal consistency of the data. Presented in this section is a discussion of the rationale by which the data were reduced, and additionally provided is a description of a sensitivity analysis by which the influence on the overall balances of small variations in the measured results is determined. Finally, a method by which the initial data are transformed into a generally consistent set of revised data which simultaneously satisfies the physical conservation principles and the laboratory findings is presented.

Data Reduction Methodology

The data from the pilot plant testing included the mass of feed processed, the corresponding char, recovered oil and aqueous yields, and an integrated off-gas sample. Data regarding pyrolysis bed and off-gas temperatures, cooling water flow and temperatures, and surface temperature completed the information available from the testing. The laboratory findings, as described previously, included percent moisture, ash, carbon, hydrogen, nitrogen, oxygen, and heating values for the feed, char, and oil. In addition, the composition of the noncondensible gas was provided. This then allowed computation of the heating value of the gas.

Using part of these data and the laws of energy, mass, and elemental conservation, a system of algebraic equations were written. These equations have been solved on the computer and the calculated results have been compared with the remaining observed data to obtain a measure of the internal consistency of the entire set of data. The effects on internal consistency of small variations in the values of the original data have also been studied. It has been found that typically variations in specific measured values of no more than a few percent are required to put all the into a generally consistent form. Since it must be recognized that all the data are subject to some uncertainty, it has been assumed that, on the average, the modified values (e.g., the original value plus the computed variation) are likely superior to those actually measured or initially computed and, therefore, these modified values have been used in the data analysis and in the presentation of the results; study of the latter, as presented in the following section, provides further justification for this action since the revised data are generally consistent with earlier results (1) and show an acceptable degree of scatter.

Analysis

The equations used in the data analysis include:

Conservation of Mass:

$$M_g{}^{*} + M_o + M_{ch} + M_{wo} = M_f + M_a + M_{wi} \qquad (1)$$

Conservation of Energy:

$$(HV_g + h_g)\,M_g + (HV_o + h_o)\,M_o + (HV_{ch} + h_{ch})\,M_{ch} + h_{wo}\,M_{wo} =$$

$$(HV_f + h_f)\,M_f + h_a\,M_a + h_{wi}\,M_{wi} - \text{[conduction and cooling-water losses]}$$

By establishing ambient conditions as a reference, h_f and h_a can be set to zero. Since the sensible and latent heat terms involving h_g, h_o, h_{ch}, and h_{wi} and the heat losses are generally small in comparison to the other terms it is convenient to combine these terms into a single expression

$$L = h_g\,M_g + h_o\,M_o + h_{ch}\,M_{ch} - h_{wi}\,M_{wi} + \text{[conduction and cooling-water losses]}$$

and to rewrite the energy equation as:

$$(HV_g)\,M_g + (HV_o)\,M_o + (HV_{ch})\,M_{ch} + h_{wo}\,M_{wo} = (HV_f)\,M_f - L \qquad (2)$$

Since L is small compared with the other terms, approximate values can be taken with little error in the resulting solution.

---

* A table of Nomenclature is presented on page xi.

Conservation of Nitrogen:

$$w_{ng} M_g + w_{no} M_o + w_{nch} M_{ch} = w_{nf} M_f + w_{ha} M_a \tag{3}$$

Conservation of Carbon:

$$w_{cg} M_g + w_{co} M_o + w_{cch} M_{ch} = w_{cf} M_f \tag{4}$$

Conservation of Hydrogen:

$$w_{hg} M_g + w_{ho} M_o + w_{hch} M_{ch} + w_{hwo} M_{wo} = w_{hf} M_f + w_{hwi} M_{wi} \tag{5}$$

Conservation of Oxygen:

$$w_{og} M_g + w_{oo} M_o + w_{och} M_{ch} + w_{owo} M_{wo} = w_{of} M_f + w_{oa} M_a + w_{owi} M_{wi} \tag{6}$$

In addition to these relations, the Dulong-Petit equation was used to calculate the heating value of the oil:

$$HV_o = 14{,}500\ w_{co} + 61{,}000\ w_{ho} \tag{7}$$

The CHNO analysis of the oil requires that:

$$w_{co} + w_{ho} + w_{no} + w_{oo} = 1 \tag{8}$$

Likewise the CHNO analysis of the char and feed requires that:

$$w_{cch} + w_{hch} + w_{nch} + w_{och} = 1 - w_{xch} \tag{9}$$

$$w_{cf} + w_{hf} + w_{nf} + w_{of} = 1 - w_{xf} \tag{10}$$

Correspondingly, a computed CHNO composition of the off-gas from the gas chromatographic results requires that:

$$w_{cg} + w_{hg} + w_{ng} + w_{og} = 1 \tag{11}$$

These 11 equations represent a complete description of the applicable conservation principles for the data, and, upon simultaneous solution and comparison with laboratory data provide a redundant body of information with which to check the internal consistency of the results.

The procedure followed in the data reduction has been to simultaneously solve the first eight equations for the values of:

M_g*, M_o*, M_{wo}*, HV_o+, w_{co}+, w_{ho}+, w_{no}+, and w_{oo}+.

It has been assumed that the 26 terms: M_f, M_{ch}, M_a, M_{wi}, HV_g, HV_o, HV_{ch}, h_{wo}, HV_f, L, w_{ng}, w_{nch}, w_{hf}, w_{na}, w_{cg}, w_{cch}, w_{cf}, w_{hg}, w_{hch}, w_{hw}, w_{hf}, w_{og}, w_{oc} w_{ow}, w_{of}, and w_{oa} are known to within a certain precision--generally less than 10 percent (based on previous pilot plant and laboratory experience).

Once values of the eight unknowns were determined, a sensitivity analysis was made to determine the effect of small changes in the 26 known coefficients on the eight unknowns. This was done with a computer program (SENSAN--presented in Appendix C) which calculated the values of eight unknowns (M_g, M_o, M_{wo}, HV_o, w_{co}, w_{ho}, w_{no}, and w_{oo}) for a plus 10 percent and a minus 10 percent change in each of the 26 known coefficients. The purpose of this analysis was to identify those coefficients which have a major influence on the values of the unknowns, particularly the oil composition. Since the final object was to obtain a set of data as internally consistent as possible, the next step was a least-squares procedure by which variations between the measured and computed values of w_{co}, w_{ho}, w_{no}, and w_{oo} were minimized. This was accomplished by introducing combinations of up to four of the major influencing coefficients previously determined and by allowing the values to vary simultaneously about their "known" value, usually within bounds of ± 10 percent. The calculated oil composition (ITERAT--presented in Appendix C) was compared with the laboratory analysis in an attempt to find a combination of coefficients which gave the best agreement between the calculated and measured oil composition. This generally resu in a complete set of transformed data which is very nearly internally consiste and which represents an exact solution to the first eight equations.

Sample calculations for Test 1, which illustrate the output of the SENSAN anc ITERAT programs, are also presented in Appendix C.

---

* These three values could not be determined simply from the test results, while M_f, M_{ch}, M_a, and M_{wi}, could be measured directly.

\+ The CHNO composition of the oil and its heating value have been chosen as "unknowns" because it is believed there is greater uncertainty in the measure oil composition and heating value than for the feed, char, or gas (which coul have just as easily been used) due to the presence of water.

TEST RESULTS

Overview of Test Conditions

This experimental program involved a series of 11 tests, nine with peanut hulls and two with sawdust. In addition, there were several unreported tests at the beginning of the program to check out the procedures with peanut hulls and the basic agitator used in this study. Two tests were found to have defective off-gas compositions, apparently due to an air leak somewhere in the system. Therefore, the primary basis for the results presented in this section is the nine remaining tests.

Of the nine tests, eight were conducted using peanut hulls and one using sawdust. There was one extended run of 12 hours using peanut hulls (Test 7), but normally the runs lasted two to three hours. In the nine basic tests, the influences of mechanical agitation, changing feed material, changing bed depth, and changing air-to-feed ratio were studied.

Table 1 presents a summary of the test conditions, as well as some of the observed data from the pilot plant tests. Basic agitation was involved in eight of the 11 tests conducted, and three were completed without any form of agitation.

Testing was conducted at two bed depths, 127-132 cm (50-52 inches) and 89 cm (35 inches). The air-to-feed ratio was varied from 0.172 to 0.613, the normal range of operation. Off-gas temperatures were generally in the range of 77 to 88°C, except in the two tests with sawdust, which ran somewhat hotter. Although not reported, the condenser thermostat temperature was usually set in the range of 93 to 99°C.

The dry feed rates varied from slightly under 400 kg/hr (882 lbm/hr) to nearly 700 kg/hr (1,543 lbm/hr). One puzzling result was the wide variation in the recovered oil and aqueous phases from the condenser. Reference to Appendix B reveals that sometimes the water content was quite significant, and other times it was small. Apparently, minor variations in the off-gas and condenser temperatures can produce significant changes in oil yields.

TABLE 1. TEST SUMMARY-PARAMETRIC STUDY

Test Number *	Feed Material	Feed Rate kg/hr	Yields + Char (kg/kg)	Oil & Aqueous (kg/kg)	Off-Gas ǂ (kg/kg)	Air-to-Feed Ratio (kg/kg)	Off-Gas Temperature § (°C)	Bed Temperature # (°C)	Bed Depth (cm)	Agitation
1	Peanut Hulls	572	0.217	0.039	1.100	0.364	111	649	132	No
2	Peanut Hulls	390	0.239	0.085	0.941	0.265	93	732	132	No
3	Pine Sawdust	676	0.266	0.057	0.849	0.172	113	760	132	No
4	Pine Sawdust	464	0.249	0.070	0.932	0.251	140	732	132	Yes
5	Peanut Hulls	494	0.288	0.079	0.860	0.227	86	649	132	Yes
6	Peanut Hulls	481	0.321	0.072	0.884	0.277	85	716	132	Yes
7	Peanut Hulls	476	0.229	0.047	0.994	0.270	88	704	132	Yes
9	Peanut Hulls	408	0.400	0.161	0.897	0.458	78	960	89	Yes
10	Peanut Hulls	501	0.249	0.0453	1.170	0.464	88	560	89	Yes
11	Peanut Hulls	570	0.270	0.234	1.040	0.539	87	682	89	Yes
12	Peanut Hulls	471	0.284	0.178	1.510	0.613	83	787	89	Yes

TOTAL FEED PROCESSED = 40 Mg

TOTAL OPERATING TIME = 107.5 hr

---

* Test runs were of two to three hours duration, except number 7, which was a 12-hour run.

\+ Yields in mass of product per mass of dry feed.

ǂ The "off-gas yield" (including moisture of combustion, uncondensed oil, oil in suspension and noncondensible gas) is determined by difference.

§ The "off-gas" temperature is that measured as the gas exits from the pyrolytic converter.

The indicated temperatures correspond to the average maximum measured by the thermocouples in the lower bed of the converter. Since the temperature of the bed varies three-dimensionally in space and also varies in time (due to variations in the environment near the sensing element), the quantitative significance of the specific indicated temperatures is doubtful. However, they are presented for completeness and to indicate the range of temperatures encountered.

Recovered yields (on a dry basis) are generally much smaller than computed yields, as discussed in the following section.

In the course of the testing almost 40,000 kg (88,000 lbm) of feed were consumed, and the unit was operated a total of 107.5 hours.

Analysis of the Data

In addition to the data shown in Table 1, the laboratory analysis of the feed, char, oil, and noncondensible off-gas are presented in Appendix B. The data from these tables were transformed in the manner described in the previous section to produce a generally consistent set of results, which is believed to be, on the average, more accurate than the original raw data. These transformed data are presented in Table 2 and constitute the basis for all further discussion of the testing. Shown also in the table, in parentheses, are the amounts the values were altered from the original. Inspection reveals that only a few of the data were modified and the changes were generally small.

Although many of the modifications appear to have been made randomly, there is a rough pattern to some of the changes. For example, there appear to be relatively frequent reductions in the order of eight percent of the off-gas nitrogen composition and in the char carbon content required to make the data more consistent. Likewise, there appear to be several cases in which the carbon content of the feed and the heating value of the feed must be increased about six percent to make the results internally consistent. An explanation for the need for nitrogen reduction is the possibility that some air may have leaked into the system. At present, no plausible explanations can be offered regarding the three remaining changes.

An area of concern, at first glance, is the considerable variations present in the computed oil heating values and also in the measured values tabulated in Appendix B. Comparison shows frequent, substantial variations between individual values of these two sets of numbers. These differences require some explanation. Concerning the calculated values, since the computed oil CHNO analysis is often somewhat different than the measured analysis, which

TABLE 2. SUMMARY OF TRANSFORMED DATA-PARAMETRIC STUDY

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12
GAS										
N_2	kg/kg	0.485	0.530 (-8%)	0.382 (-8%)	0.442	0.434	0.517 (-8%)	0.574	0.478	0.510 (-8%)
C	kg/kg	0.191	0.199	0.258 (-2%)	0.194	0.201	0.199	0.163	0.189	0.199
H_2	kg/kg	0.021	0.021	0.027	0.028	0.028	0.017	0.019	0.017	0.016
O_2[a]	kg/kg	0.303	0.289	0.364	0.336	0.338	0.306	0.244	0.314	0.314
HV	MJ/kg	4.184	6.226	8.226	6.393	6.393	5.577	5.510	5.368	5.883 (-8%)
CHAR										
N_2	kg/kg	0.025	0.021	0.011	0.029	0.027	0.027	0.008	0.008	0.011
C	kg/kg	0.721 (4%)	0.829	0.844	0.724	0.795 (-8%)	0.677 (8%)	0.808 (-8%)	0.809 (-4%)	0.773
H_2	kg/kg	0.026	0.018	0.017	0.017	0.016 (5%)	0.018	0.015	0.013	0.009
O_2[*]	kg/kg	0.089	0.032	0.064	0.165	0.121	0.121	0.103	0.031	0.089
HV[‡]	MJ/kg	25.57	29.75	30.68	28.36 (10%)	29.29 (2%)	28.13	27.66	28.59	26.73
FEED										
N_2	kg/kg	0.017	0.021	0.001	0.012	0.012	0.012	0.012	0.012	0.012
C	kg/kg	0.457 (6%)	0.462 (2%)	0.450 (2%)	0.445 (6%)	0.473	0.444 (8%)	0.464 (4%)	0.444 (8%)	0.483
H_2	kg/kg	0.061	0.058	0.054	0.057	0.057	0.059	0.059	0.059	0.059
O_2[a]	kg/kg	0.437	0.452	0.488	0.457	0.458	0.446	0.446	0.446	0.446
HV	MJ/kg	19.46	18.41	17.97 (6%)	18.99	19.36 (-2%)	19.99 (2%)	19.18 (6%)	18.36 (10%)	19.99 (-2%)

(continued)

[*] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

[‡] Not ash free; on dry basis.

TABLE 2 (continued). SUMMARY OF TRANSFORMED DATA-PARAMETRIC STUDY

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12
OIL (Measured)										
N_2	kg/kg	0.040	0.047	0.016	0.029	0.078	0.014	0.015	0.015	0.017
C	kg/kg	0.657	0.831	0.758	0.732	0.687	0.737	0.725	0.722	0.712
H_2	kg/kg	0.071	0.059	0.067	0.080	0.081	0.080	0.084	0.080	0.075
O_2*	kg/kg	0.242	0.064	0.145	0.158	0.155	0.168	0.176	0.182	0.197
OIL (Computed)										
N_2	kg/kg	0.034	0.039	0.024	0.046	0.078	0.056	0.028	0.008	0.043
C	kg/kg	0.650	0.813	0.670	0.723	0.723	0.582	0.743	0.691	0.679
H_2	kg/kg	0.043	0.004	0.001	0.021	0.024	0.093	0.013	0.090	0.097
O_2	kg/kg	0.269	0.144	0.306	0.210	0.175	0.270	0.215	0.212	0.181
HV	MJ/kg	28.13	28.13	22.69	27.90	27.20	32.77	26.96	36.03	36.73
AIR	kg/kg‡	0.364	0.265	0.172	0.277	0.270	0.458	0.464	0.539	0.613
MOISTURE (in)	kg/kg‡	0.046	0.045	0.053	0.048	0.048	0.287	0.287	0.287	0.287
CHAR	kg/kg‡	0.217	0.239	0.266	0.321	0.229	0.400	0.249	0.270	0.284
OIL	kg/kg‡	0.291	0.228	0.207	0.140	0.279	0.065	0.214	0.085	0.113
OFF-GAS	kg/kg‡	0.577	0.395	0.333	0.478	0.442	0.682	0.634	0.886	0.940
MOISTURE (out)	kg/kg‡	0.325	0.449	0.420	0.361	0.367	0.598	0.654	0.585	0.564
ENERGY LOSSES	MJ/kg‡	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26

* Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

‡ Mass of material per mass of dry feed.

in turn varies considerably, it is not surprising that the calculated heating value, via the Dulong-Petit equation, varies also. Perhaps, therefore, a more meaningful value would be an average, which is 31.01 MJ/kg (13,335 Btu/lbm). Regarding the laboratory-reported heating values for the indicated moisture contents, an average of the dry heating values is again probably a more accurate value. It should be noted that the uncertainty in the moisture percentage can be significant; thus, the corrected heating value is also uncertain. However, upon adjusting the indicated values to a dry basis and after computing an average value, the result obtained is 33.08 MJ/kg, which is 6.7 percent greater than the average of the computed results. It is believed that the justification for working with this average value is adequate, and that these two values are in sufficient agreement to satisfy the accuracy requirements of the study. Several informative graphs can be derived from the results presented in Table 2. These are presented in the next six figures, which correlate closely with corresponding figures in Reference 1.

Graphical Data Presentations

Perhaps the most important results of the entire program are those given in Figure 8, which presents the percent available energy of the char and oil (relative to that of the feed) as a function of the air-to-feed ratio. The figure shows that for all the tests at various bed depths, with and without agitation and with both sawdust and peanut hulls, the data correlate to a single line. This line is identical to that reported in Reference 1 for sawdust converted in a unit with half the capacity of the present unit. In fact, when the data from the present program and that from the earlier study are combined, the agreement is striking. This is illustrated in Figure 9 for which the best-fit straight line is again identical to both that in Figure 8 and that from Reference 1.

This suggests, therefore, that to an acceptable degree of engineering precision, the available energy fraction of the feed in the char-oil mixture is independent of unit size, feed material, bed depth, and the presence of mechanical agitation, and is a linear function of only the air-to-feed ratio Figure 10 presents an energy breakdown of the pyrolysis products as a

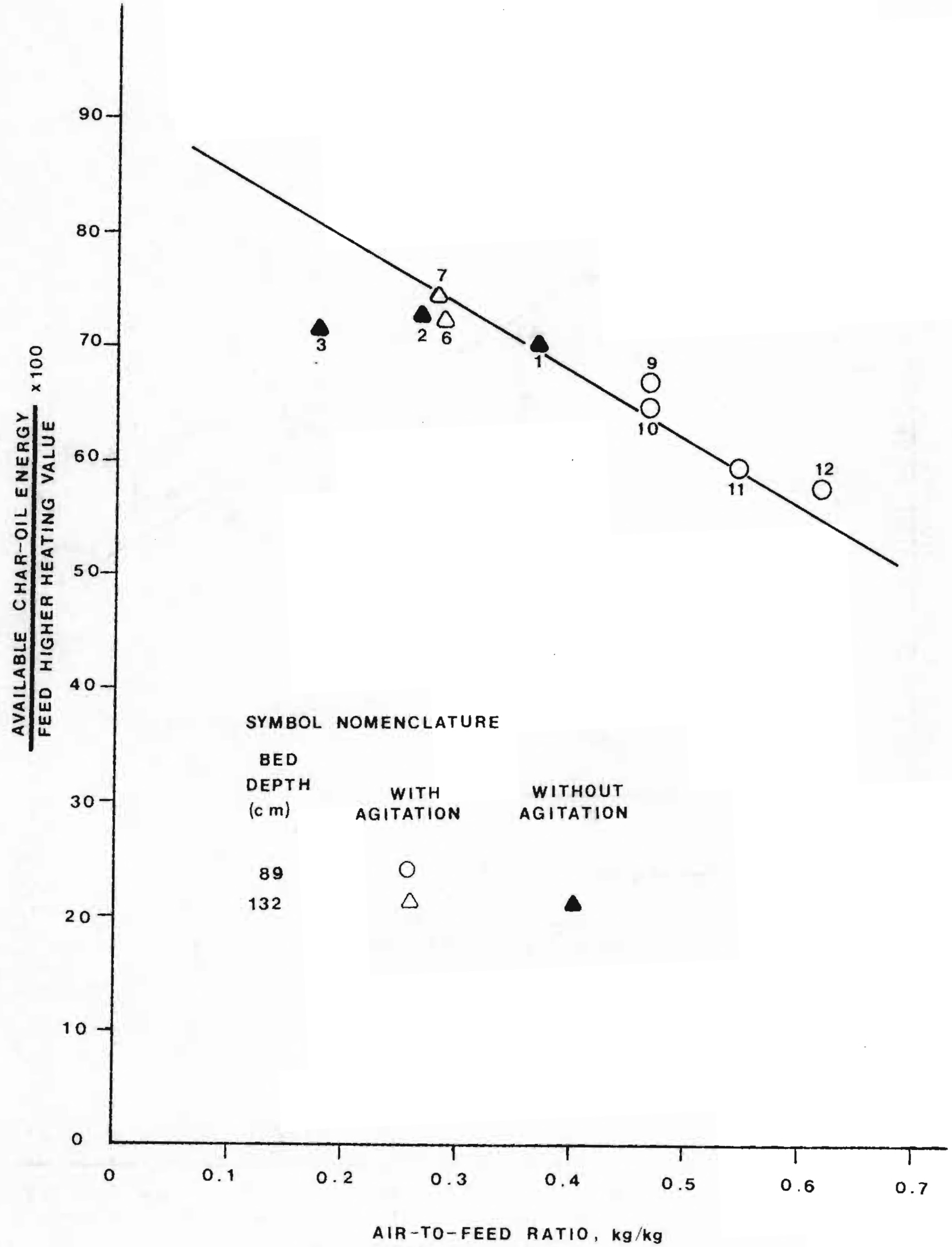


Figure 8. Percent available energy in char-oil mixture--parametric study.

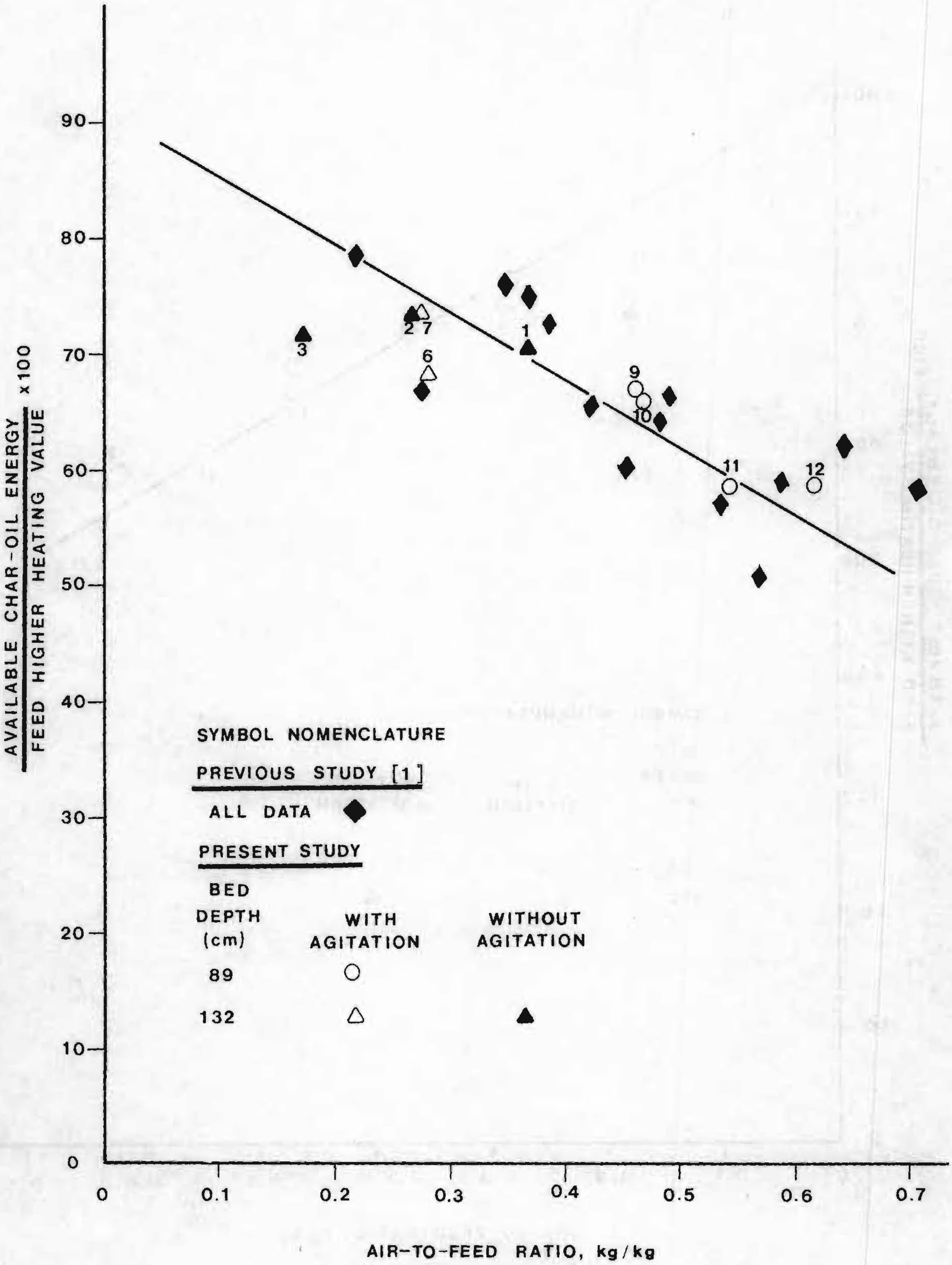


Figure 9. Percent available energy in char-oil mixture--parametric study/Reference 1 composite.

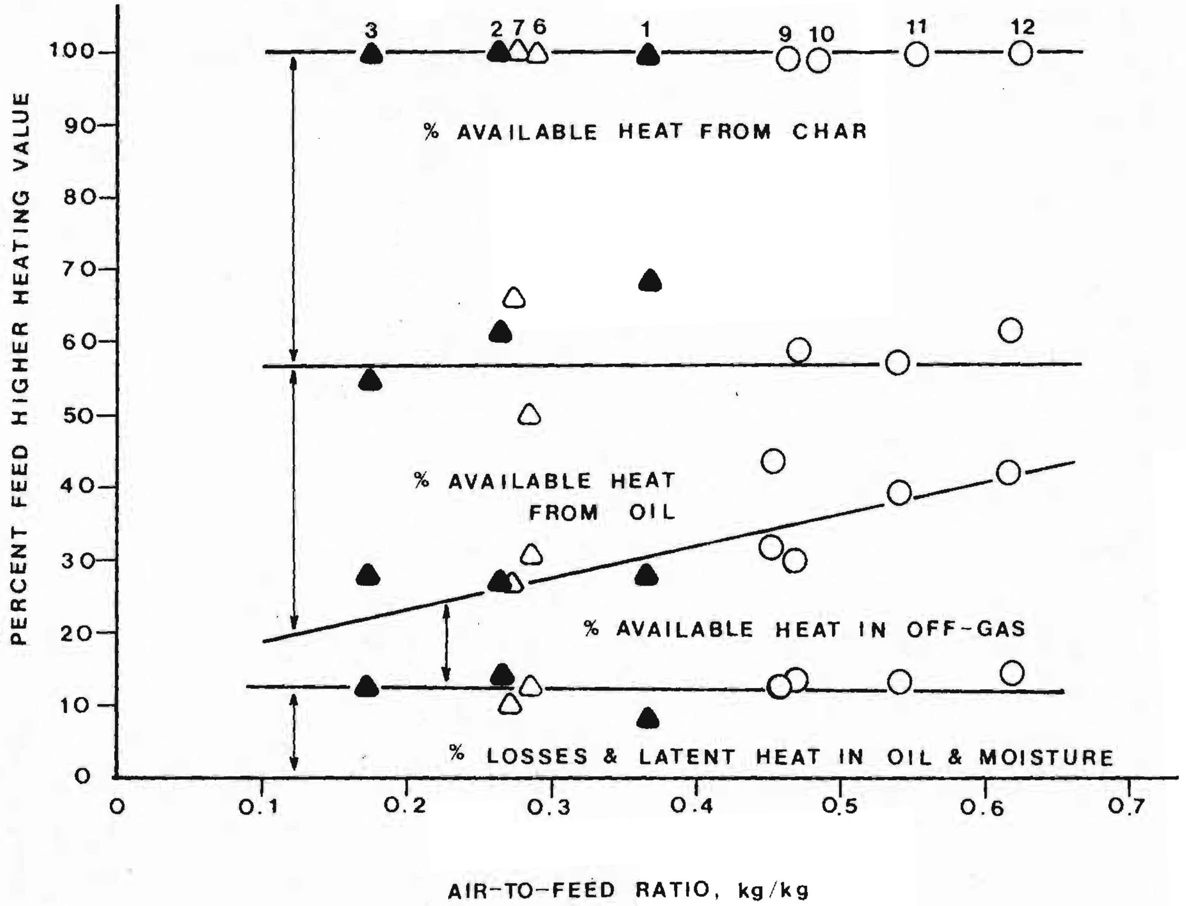


Figure 10. Energy breakdown of pyrolysis products--parametric study.

function of the air-to-feed ratio. Examination of the figure reveals the relative consistency of the data and, as in Figure 8, suggests that the dominant influencing variable is the air-to-feed ratio. Comparison of similar results from Reference 1 shows generally good agreement with the total of the sensible energy in the oil and water in the off-gas, and heat lost by conduction and to the cooling water. Likewise, the energy in the off-gas is almost identical to that reported in Reference 1. Finally, the combined energy in the char-oil blend agrees very well with that reported in Reference 1.

However, there is a significant difference in the way in which the separate energies in the oil and char vary from those presented in Reference 1. An explanation for this difference may shed considerable light on the physical processes at work, and provide a means of varying the relative amounts of oil and char produced at a given, fixed air-to-feed ratio.

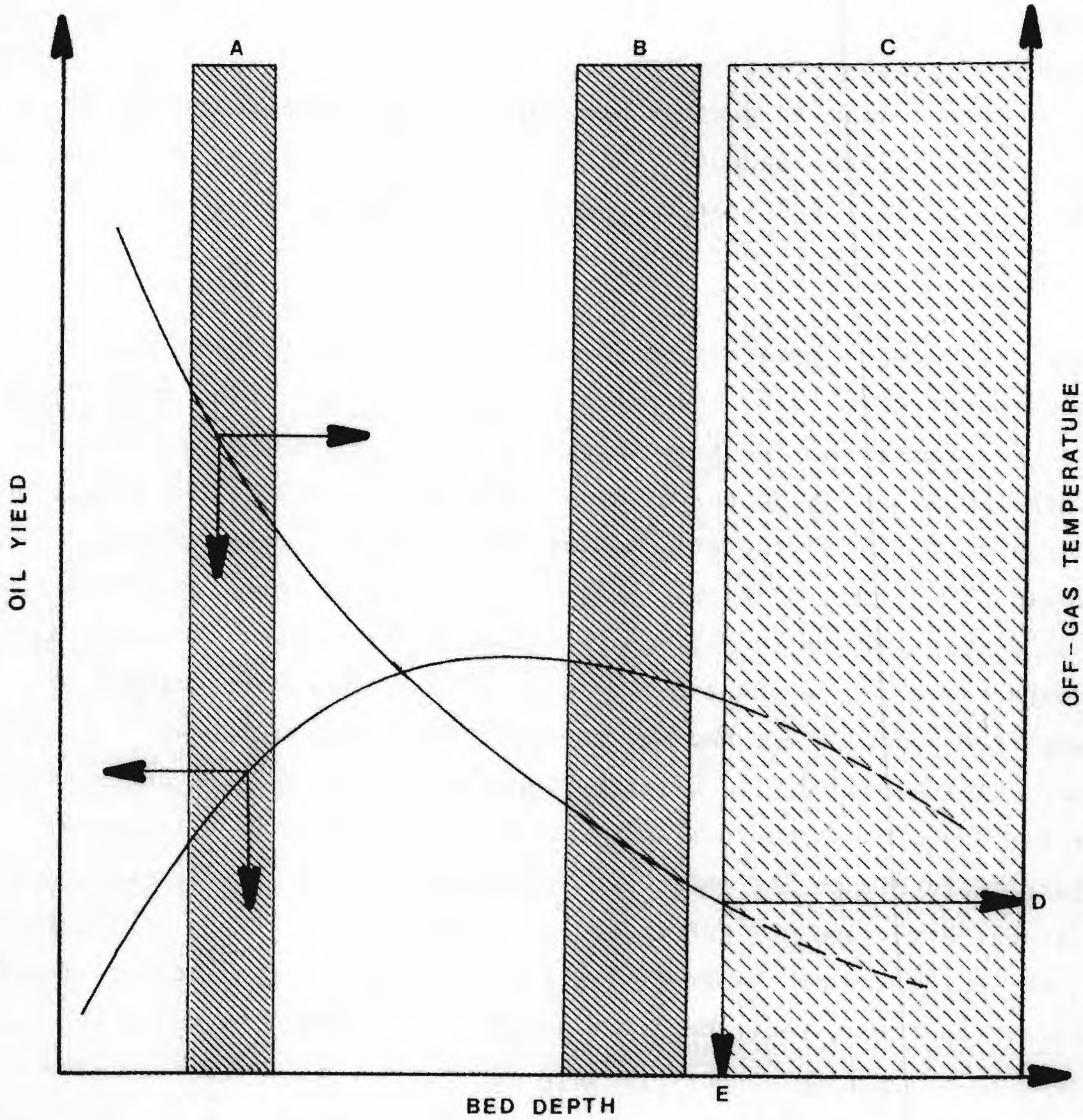
In Reference 1, the char yields decreased linearly and the oil yields increased linearly with increasing air-to-feed ratio, whereas in the present study the char yields remain practically constant and independent of air-to-feed ratio, and the oil yields decrease with increasing air-to-feed ratio. However, in Reference 1 the pyrolysis off-gas temperatures were always in the range of 150-175°C, whereas in the present study the off-gas temperatures using peanut hulls were in the range of 75-95°C. This difference in the off-gas temperature is very significant because, in the latter case, the higher boiling point oils are condensing in the bed. Laboratory experience has shown that when pyrolytic oils are heated, a significant amount of carbonization occurs along with evaporation. Hence, in the current study, once the oils condensed and were reheated in the downward-moving feed, only a portion of the original oil evaporated and the remainder was converted into solid carbon. The result was an almost constant char yield and a diminishing oil yield with increasing air-to-feed ratio.

The reason the off-gas temperatures in the present study were so low compare with those of Reference 1 is that the bed depth was generally near the maximum. The results from Reference 1, at a smaller scale, had suggested that for maximum oil yields a greater bed depth was desirable; therefore, in the present study the greater bed depths had been deliberately chosen to obtain the greatest amounts of oil. It appears, however, that the bed depths selected were considerably greater than the optimum for oil production.

Physical reasoning suggests that for a given feed, for fixed values of process air and feed rate, and for a very shallow bed depth, the off-gas temperature approaches the temperature in the combustion zone and there is little or no pyrolytic conversion of the feed. Under these conditions breakdown of the oily products produces more gaseous constituents. For increasing bed depth, pyrolytic conversion of the feed begins to occur and the oil yields grow as the off-gas temperature decreases. However, as the bed depth increases beyond some optimum point, significant amounts of condensation occur in the bed and the oil yields are diminished. Clearly, at some critical bed depth, moisture condensation occurs and above this point the process becomes unstable. All this behavior is illustrated graphically in Figure 11, which also shows the surmised operating zones for the present study and for Reference 1. Taken together, this all suggests that, while the sum of the energy in the char and oil is basically dependent on the air-to-feed ratio, the distribution of the energy between the oil and the char is a function of both the bed depth and the air-to-feed ratio. Thus, a means to independently vary the relative amounts of oil and char in the pyrolysis products for a fixed air-to-feed ratio exists. Conveniently, over a range of bed depths the off-gas yields appear to be relatively independent of the bed depth and only a function of air-to-feed ratio.* In more specific terms, to maximize char yields the pyrolysis unit should be operated at the greatest allowable bed depth. Conversely, to optimize oil yields, the corresponding optimum bed depth should be determined and the unit operated near this point. It should be recognized that when the

---

* This indicates that in this image the carbonization of the oil results in a minor amount of oil gasification and, therefore, that the oils are broken down into the more volatile fractions. Since the condenser temperature in the testing was limited by moisture condensation considerations, this would explain why the recovered oil yields were generally so small.



A OPERATING ZONE IN REFERENCE 1

B OPERATING ZONE IN PRESENT STUDY

C FORBIDDEN OPERATING ZONE DUE TO MOISTURE CONDENSATION

D OFF-GAS DEWPOINT

E MAXIMUM PRACTICAL BED DEPTH

Figure 11. Oil yield variation with increasing bed depth.

char yields are maximized, a very large portion of the oil produced is likely to be unrecoverable because its boiling point lies below the dew point of the off-gas mixture. Thus, while the available energy in the char-oil mixture is approximately constant (at a given air-to-feed ratio), it may be more desirable in many situations to avoid a deep bed in order to actually recover a maximum percentage of the oil in a useable form. Therefore, it appears that for maximum recovery of both the char and the oil, operation near the point of maximum oil production is indicated.

It should be noted that the presence of water in the feed acts effectively to increase the bed depth, since greater amounts of energy are required to pyrolyze the feed and, thus, the off-gas temperature tends to be reduced. Therefore, if a maximum of both char and recoverable oil is desired, it would be best to operate with as dry a feed as possible.

Figure 12 is a crossplot of computed data from Reference 1 and experimental data from the present study. The figure provides a convenient means for determining the required air-to-feed ratio for a given feed moisture percentage; further, it allows computation of the available energy in the char-oil mixture. The computation assumptions regarding the energy requirements to operate the portable unit are taken from Reference 1. To illustrate the use of the figure, at a feed moisture percentage of 20 percent, the required energy for drying and processing is 1.71 MJ/kg (735 Btu/lbm) dry feed. At an air-to-feed ratio of 0.19, the available energy in the gas is 1.71 MJ/kg (735 Btu/lbm) dry feed, and that available in the char-oil is 15.3 MJ/kg (6,600 Btu/lbm). This establishes the relation between the moisture content and the air-to-feed ratio.

Figure 13 presents a plot of the heating value of the noncondensible component of the off-gas in MJ/m^3 as a function of the air-to-feed ratio. As before and as in Reference 1, there is a correlation with this parameter, although the data scatter is greater than desired. The curve drawn through the data lies within 5 to 10 percent of the corresponding curve from Reference 1 and, thus, again establishes the close correlation of the data from the two studies.

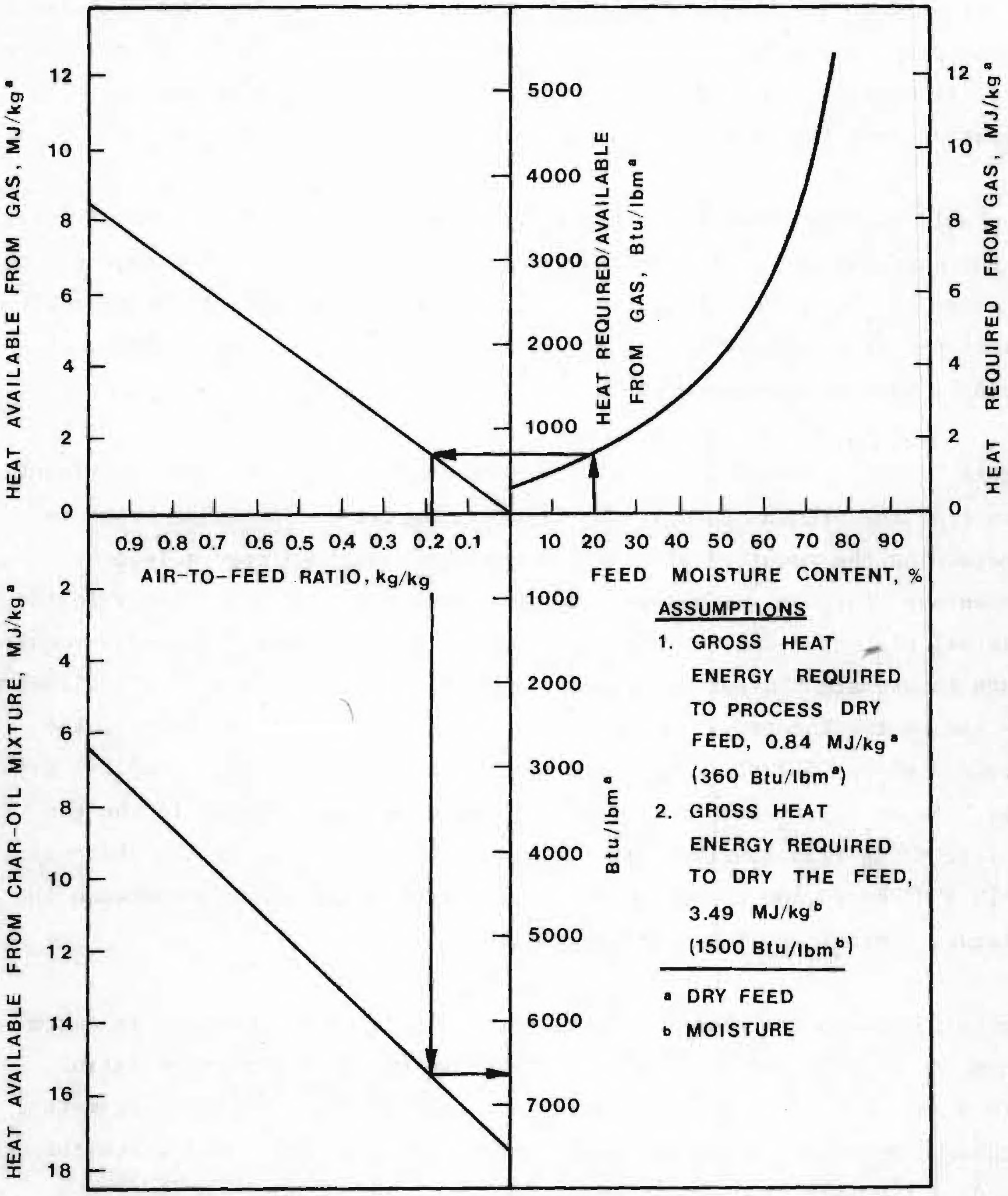


Figure 12. Effects of feed moisture on available energy from char-oil mixture (ref. 1)

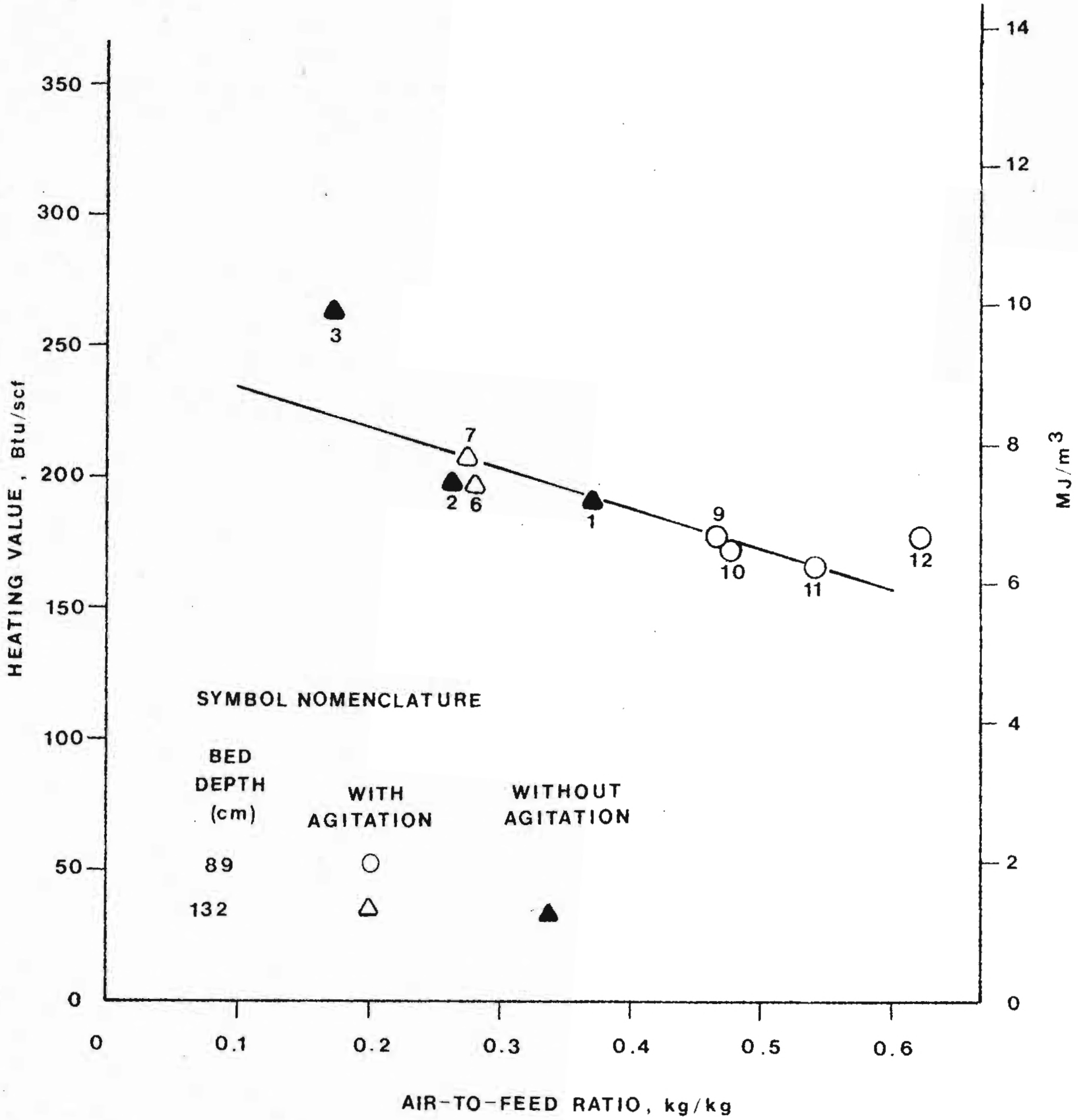


Figure 13. Heating value of noncondensible gas--parametric study.

SECTION 5

PERFORMANCE STUDY OF INTEGRATED MECHANICAL AGITATION--AIR SUPPLY SYSTEM

GENERAL

The present concept of the EES waste converter system operation involves the addition of process air near the bottom of the vertical, gravity-fed porous bed. This air allows combustion of a small fraction of the feed material and, thus, provides the heat required for pyrolysis. The air is added by means of several fixed, water-cooled air tubes. The presence of these air tubes represents a hindrance to the flow of the feed material and is, thus, partially responsible for the need for a mechanical agitation system to enhance feed throughput. There is also the fact that, since the system throughput is limited to a large extent by gravity, residence times are far greater than required to pyrolyze the feed.

Thus, there appears to be considerable advantage in the use of an integrated mechanical agitation-process air system, especially if the mechanical agitation system is a requirement in any case to process bulky wastes. By adding such a system, the principal hindrance to flow through the converter is changed into a means for facilitating the flow. Such a system may also allow the processing of somewhat wetter feed than the present EES waste converter permits.

This section presents a description of a "first-generation" integrated mechanical agitation-process air supply system, or "AIRGITATOR," and a discussion of the tests conducted with it.

SYSTEM DESIGN

There are conceptually a large number of possible configurations that the system might have taken. However, it was decided at the outset that the simplest configuration possible was to be selected. This was done in order to minimize fabrication problems and to avoid, as much as practical, the possibility of failure and the opportunity for leaks by minimizing the number of welds. Thus an "L" shaped system was chosen.

The AIRGITATOR is presented schematically in Figure 14, and the final design is shown in Figure 15. Its outer tube is made of 4130 high-strength alloy steel 5.08 cm (2 inches) in outside diameter with 0.635-cm (0.25-inch) walls. Designed to withstand the high-torsional loads and hostile environment inside the reactor, the outer tube provides a passage for cooling water.

To introduce process air and circulate cooling water while the device is being rotated, a three-passage union was required. A Deublin three-passage union was used during the initial tests. However, because of the high pressure drop across this union, sufficient process air could not be introduced through the AIRGITATOR. To eliminate this problem: (1) a three-passage union was designed, fabricated, and installed; and (2) the diameter of the air discharge holes was increased.

In the initial design the horizontal portion of the unit extended to within 2.5 cm of the inside wall of the converter and the end was cut off squarely. A later modification involved the removal of 2.5 cm from this horizontal portion and the beveling of the end so that the end surface formed a sharp edge which cut through the char. These modifications were made to avoid the binding of feed between the walls and the end of the unit in situations where, due to irregularities in the inner surface, the end approached the wall too closely.

The final design of the AIRGITATOR, including the three-passage union, is shown in Figure 15. A photograph of the unit, fabricated in the EES shop, is presented in Figure 16. Figure 17 is a close-up view of the AIRGITATOR

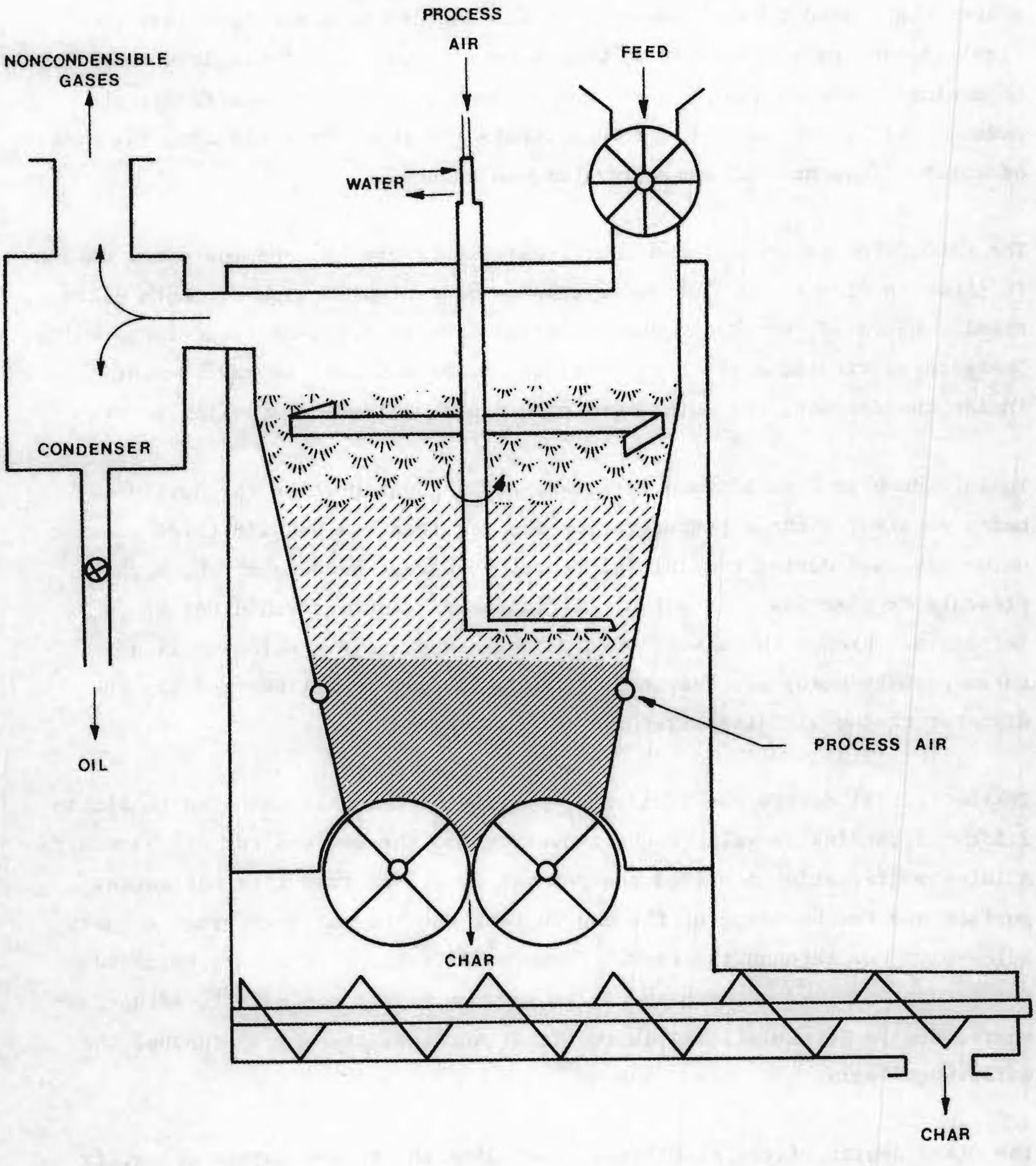
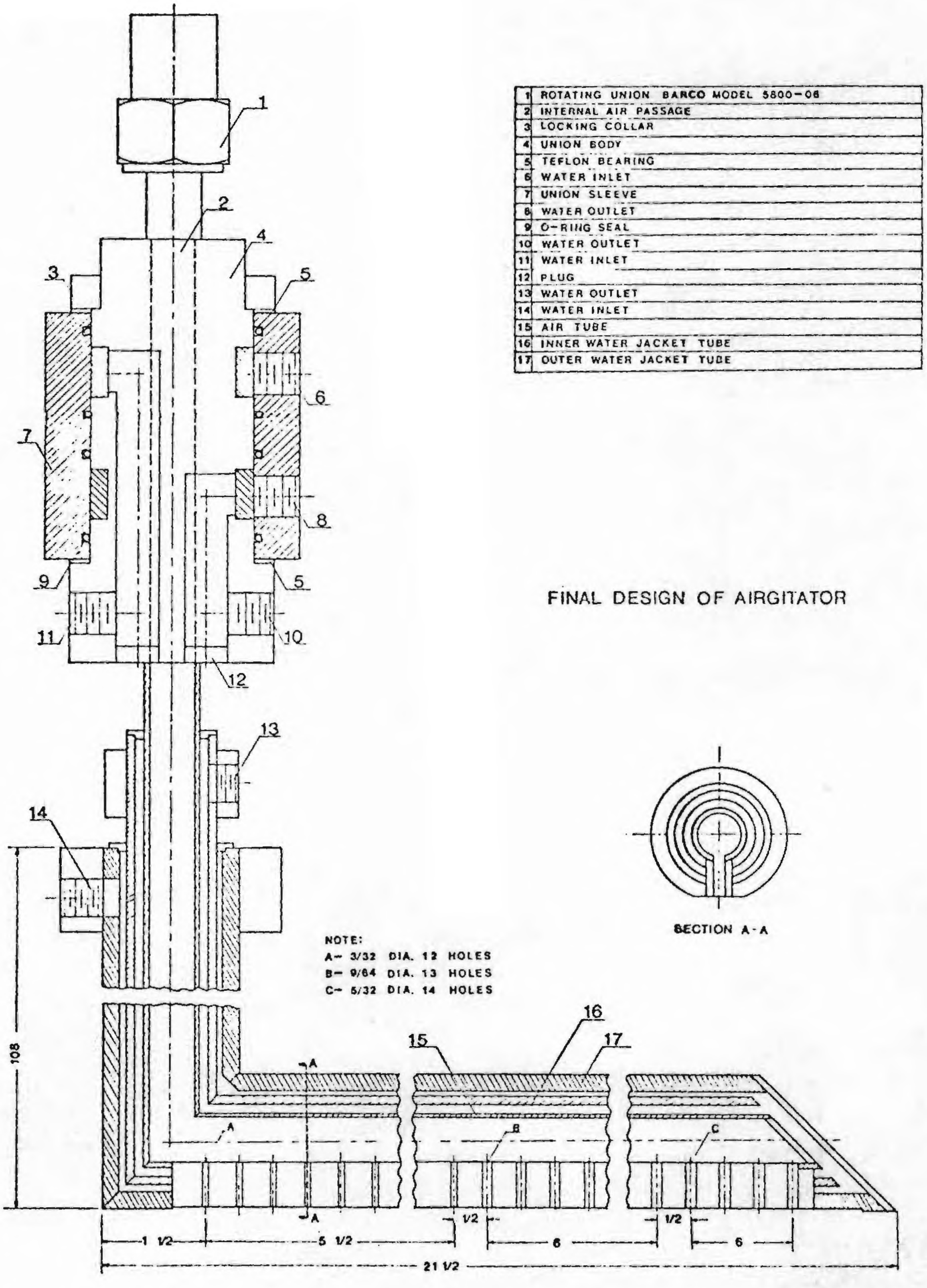


Figure 14. Schematic of EES converter with integrated mechanical agitation--air supply system.



1	ROTATING UNION BARCO MODEL 5800-06
2	INTERNAL AIR PASSAGE
3	LOCKING COLLAR
4	UNION BODY
5	TEFLON BEARING
6	WATER INLET
7	UNION SLEEVE
8	WATER OUTLET
9	O-RING SEAL
10	WATER OUTLET
11	WATER INLET
12	PLUG
13	WATER OUTLET
14	WATER INLET
15	AIR TUBE
16	INNER WATER JACKET TUBE
17	OUTER WATER JACKET TUBE

NOTE:
A- 3/32 DIA. 12 HOLES
B- 9/64 DIA. 13 HOLES
C- 5/32 DIA. 14 HOLES

Figure 15. Final design of Airgitator.

Figure 16. Overview of Airgitator.

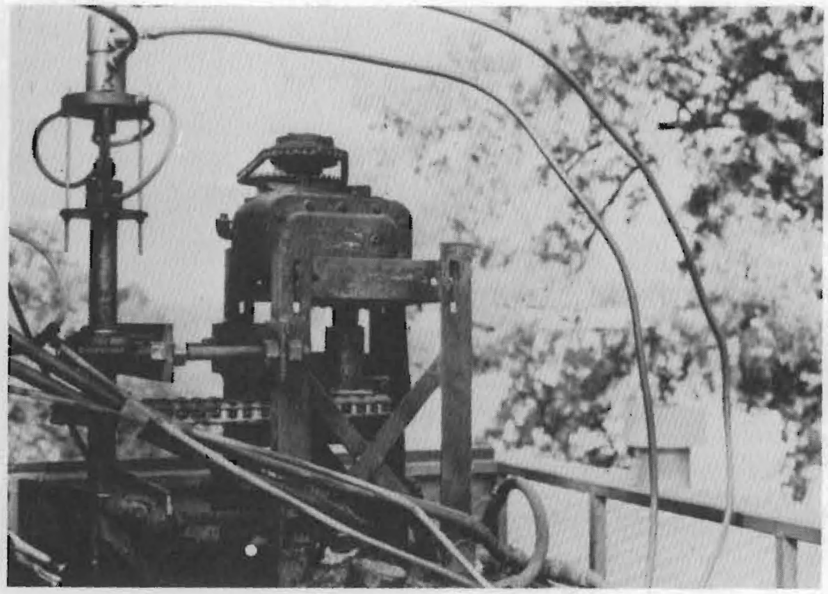


Figure 17. Airgitator as installed.

as installed. As can be seen, the installed system is not complex--it involves only a drive system, the three-passage union, and the "L" shaped AIRGITATOR.

FACILITIES

The facilities for this study were the same as those used in the parametric study. Their description begins on page 10.

CALIBRATION AND TEST PROCEDURE

The calibration and test procedure was the same as that used in the parametric study. Its description begins on page 18.

LABORATORY TESTING

The laboratory testing was also the same as that used in the parametric study. The description begins on page 19.

DATA REDUCTION

The data reduction procedure was the same as that used in the parametric study. Its description begins on page 21.

TEST RESULTS

Overview of Test Conditions

This experimental program, with a total of 10 tests, involved two phases. A series of four tests was conducted first to determine the feasibility of combining agitation with process air injection. A series of six tests was then designed to study the performance of a particular form of integrated mechanical agitator--process air supply system (AIRGITATOR).

In the first phase peanut hulls were used as the feed material. Two of the four tests in this phase were considered to be checkouts and no data were taken. As proposed, peanut hulls were also to be used as the feed material; however, peanut hulls were no longer available when the project go-ahead was received. Since earlier work [1] using sawdust as the feed material could be used as a basis for comparison, pine sawdust was substituted for the proposed peanut hulls.

The main objective of the phase-two tests was to operate the AIRGITATOR over a range of air-to-feed ratios and determine the maximum processing rate. Air-to-feed ratios of 0.14 to 0.34 were used and the maximum process rate was over 800 kg/hr (1,760 lbm/hr).

Table 3 presents a summary of the test conditions and selected observed data from these tests. Data are given for two checkouts and two peanut-hull runs (phase one) and the six sawdust runs. Two bed depths were used--127 cm with the peanut hulls and 89 cm with the sawdust. The off-gas temperatures ranged from 121 to 260°C and the processing rate varied from 324 kg/hr (714 lbm/hr) for peanut hulls to a maximum of 833 kg/hr (1,836 lbm/hr) for the pine sawdust.

System Testing

The checkout tests of the AIRGITATOR resulted in almost disastrous results. The main bearings supporting the unit failed after several hours of testing, apparently as a result of very large torques that were occasionally required to rotate the system. It was concluded that the tip binding, described earlier, was the cause. The tip was modified and the complete drive system was strengthened substantially. This modified unit was then tested and no problems were encountered. Apparently these improvements were sufficient to overcome the difficulty.

One important feature in latter tests was the use of two wall-mounted air tubes in the start-up of the unit and also occasionally to stabilize the hot char bed during normal operation. The extra depth to the hot char bed provided by these two tubes not only made it possible to establish a stable hot char zone initially, but also provided a cushion against "losing the char bed" in anomalous circumstances in which the instantaneous feed rate exceeded the charring rate and threatened the loss of the hot char which sustains the bed operation.

TABLE 3. TEST SUMMARY-AIRGITATOR STUDY

Test Number	Feed Material	Feed Rate (kg/hr)	Yields[*] Char (kg/kg)	Yields[*] Oil & Aqueous (kg/kg)	Yields[*] Off-Gas[+] (kg/kg)	Air-to-Feed Ratio (kg/kg)	Off-Gas Temperature[‡] (°C)	Bed Temperature[§] (°C)	Bed Depth (cm)
8	Peanut Hulls	CHECK OUT "AIRGITATOR"							
13	Peanut Hulls	CHECK OUT MODIFIED "AIRGITATOR"							
14	Peanut Hulls	490	0.414	0.035	0.691	0.140	174	471	127
15	Peanut Hulls	324	0.283	0.262	0.645	0.190	226	471	127
16	Sawdust	416	0.460	0.164	0.624	0.245	121	538	89
17	Sawdust	569	0.389	0.111	0.699	0.199	149	371	89
18	Sawdust	570	0.420	0.096	0.752	0.268	177	510	89
19	Sawdust	833	0.247	0.114	0.818	0.179	160	482	89
20	Sawdust	597	0.405	0.178	0.714	0.297	149	510	89
21	Sawdust	463	0.240	0.087	1.100	0.337	260	482	89

[*] Yields in mass of product per mass of dry feed.

[+] The "off-gas yield" (including moisture of combustion, uncondensed oil, oil in suspension and noncondensible gas) is determined by difference.

[‡] The "off-gas" temperature is that measured as the gas exits from the pyrolytic converter.

[§] The indicated temperatures correspond to the average maximum measured by the thermocouples in the lower bed of the converter. Since the temperature of the bed varies three-dimensionally in space and also varies in time (due to variations in the environment near the sensing element), the quantitative significance of the specific indicated temperatures is doubtful. However, they are presented for completeness and to indicate the range of temperatures encountered.

An additional problem apparently occurred at shallow bed depths. The rotating vertical shaft of the AIRGITATOR appears to have provided a lower resistance path to a portion of the off-gases than the porous bed of pyrolyzing feed material, especially to those combustion products generated by introduction of the process air near the axis of rotation. Such a short circuit of the off-gas flow field in the bed could cause abnormally high off-gas temperatures and particulate levels. If this in fact occurred, then two possible solutions are (1) to construct baffles on the rotating shaft to increase the gas flow resistance or (2) to redesign the AIRGITATOR to permit its introduction through the bottom of the converter.

Analysis of Data

In addition to the data presented in Table 3, the laboratory analysis of the feed, char, oil, and noncondensible off-gas is presented in Appendix B, Tables B-12 through B-17. These data were transformed in the manner previously described (pages 21-23) to produce a generally consistent set of results. The transformed data are presented in Table 4 and they form the basis for all further discussion of the data.

The numbers shown in parentheses in Table 4 are the percentage changes which were made in the original data. As in the parametric study, these changes were generally less than 10 percent. In general, the corrections have been to the analysis of the feed material. Since a very small sample is used in the CHNO analysis to represent as much as several thousand kilograms of feed material, these corrections appear to be within the degree of precision with which the feed material can be representatively sampled.

Graphs similar to those for the parametric study were derived from the data of Table 4.

Graphical Data Presentations

Figure 18 shows the energy content of the char-oil mixture, in terms of the energy content of the input feed, as a function of the air-to-feed ratio. Data are presented for both the AIRGITATOR study and the parametric study. These data are well correlated by a single straight line, even though three

TABLE 4. SUMMARY OF TRANSFORMED DATA-AIRGITATOR STUDY

Data	Units	Test 14	Test 15	Test 16	Test 17	Test 18	Test 19	Test 20*	Test 21
GAS									
N_2	kg/kg	0.396	0.351	0.432	0.421	0.454	0.331		0.386
C	kg/kg	0.216	0.218	0.206	0.205	0.197	0.234		0.221
H_2	kg/kg	0.018	0.011	0.014	0.012	0.012	0.013		0.012
O_2^+	kg/kg	0.369	0.422	0.349	0.363	0.336	0.420		0.381
HV	MJ/kg	5.531	3.582	4.795	4.247	4.544	4.736		4.736
CHAR									
N_2	kg/kg	0.011	0.007	0.000	0.000	0.001	0.005		0.003
C	kg/kg	0.393 (-50%)	0.818 (-4%)	0.750	0.727	0.739	0.812		0.827
H_2	kg/kg	0.018	0.014	0.036	0.037	0.036	0.029		0.028
O_2	kg/kg	0.115	0.091	0.180	0.209	0.180	0.126		0.115
HV‡	MJ/kg	29.05	28.82	27.95	27.43	27.84	31.30		31.68
FEED									
N_2	kg/kg	0.007	0.007	0.001	0.004	0.004	0.000		0.001
C	kg/kg	0.304 (40%)	0.466 (8%)	0.482 (1.9%)	0.483	0.468 (2%)	0.442 (-8%)		0.477
H_2	kg/kg	0.061	0.061	0.060	0.054 (-10%)	0.058	0.061 (3%)		0.054 (8%)
O_2	kg/kg	0.427	0.427	0.438 (-6%)	0.444 (2%)	0.450 (-6%)	0.489 (6%)		0.463
HV	MJ/kg	19.78	19.78	19.92	19.47	19.15	19.13		19.64

* Error in collected data prevented a meaningful analysis.

(continued)

\+ Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

‡ Not ash free; on dry basis.

TABLE 4 (continued). SUMMARY OF TRANSFORMED DATA-AIRGITATOR STUDY

Data	Units	Test 14	Test 15	Test 16	Test 17	Test 18	Test 19	Test 20	Test 21
OIL									
(Measured)									
N_2	kg/kg	0.012	0.012	0.009	0.011	0.007	0.009	0.010	0.011
C	kg/kg	0.703	0.694	0.608	0.719	0.614	0.612	0.611	0.595
H_2	kg/kg	0.077	0.077	0.073	0.029	0.058	0.062	0.061	0.060
O_2*	kg/kg	0.208	0.217	0.322	0.241	0.321	0.317	0.318	0.334
(Computed)									
N_2	kg/kg	0.087	0.111	0.045	0.038	0.013	0.012		0.003
C	kg/kg	0.660	0.676	0.564	0.684	0.609	0.635		0.588
H_2	kg/kg	0.102	0.106	0.100	0.037	0.066	0.071		0.075
O_2	kg/kg	0.152	0.107	0.291	0.242	0.316	0.282		0.334
HV	MJ/kg	36.73	37.89	33.13	28.24	29.37	31.59		30.47
AIR	kg/kg+	0.140	0.190	0.245	0.199	0.268	0.179		0.337
MOISTURE (in)	kg/kg+	0.065	0.065	0.078	0.049	0.050	0.036		0.082
CHAR	kg/kg+	0.414	0.283	0.460	0.389	0.420	0.247		0.240
OIL	kg/kg+	0.124	0.209	0.115	0.182	0.110	0.230		0.223
OFF-GAS	kg/kg+	0.275	0.424	0.437	0.369	0.461	0.406		0.667
MOISTURE (out)	kg/kg+	0.392	0.339	0.311	0.308	0.327	0.332		0.289
ENERGY LOSSES	MJ/kg+	1.26	1.26	1.26	1.26	1.26	1.26		1.26

* Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

\+ Mass of material per mass of dry feed.

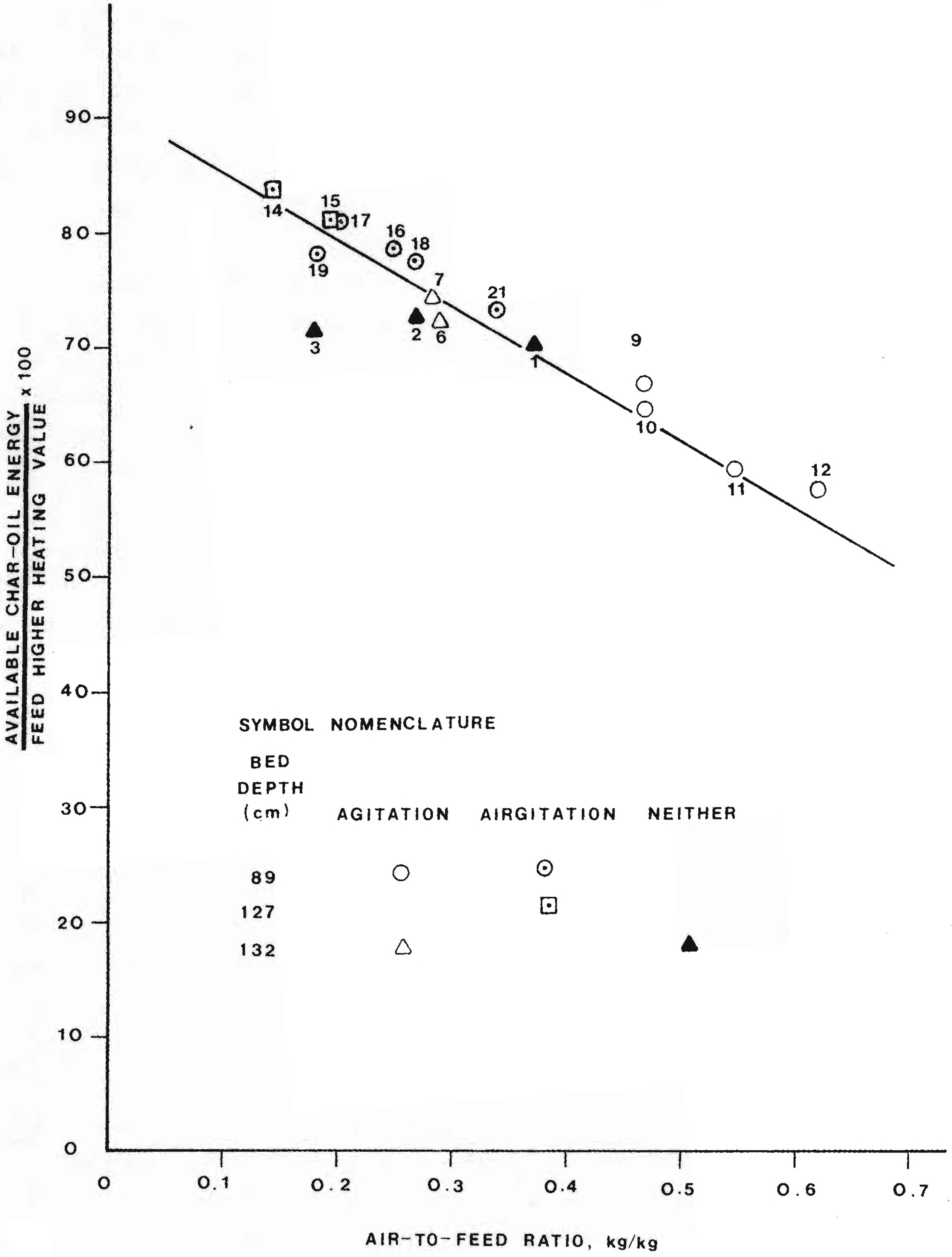


Figure 18. Percent available energy in char-oil mixture--Airgitator/parametric study composite.

bed depths and two feed materials were used. The apparent generality of this correlation is even more convincing when the data in Figure 18 are combined with those in Reference 1, as shown in Figure 19. Thus the available char-oil mixture energy seems to be practically independent of the unit site (cross-sectional area), feed material, bed depth, mechanical agitation, and "airgitation;" it seemingly depends only on the air-to-feed ratio.

Figure 20 displays the data in the manner of Figure 10 of the parametric study. The open-dotted symbols for tests 14 through 21 use the nomenclature of Figures 18 and 19. The filled symbols represent data of Reference 1, which were also obtained for pyrolysis of pine sawdust, but in a smaller converter which had only fixed air tubes. Comparing Figures 10 and 20, it appears that the losses (e.g., sensible heat of the off-gas steam and cooling-water stream, latent heat of the water in the off-gas stream and the condensed oil, heat losses to the atmosphere) and the available heat (of combustion) from the off-gas stream are practically the same. However, even though the total available heat (of combustion) of the char-oil mixture is the same (see Figure 18), the manner in which the separate energies in the oil and char vary with air-to-feed ratio is considerably different. The AIRGITATOR test data apparently agree with those from Reference 1, but the peanut hull data (Figure 10) have quite a different nature--the available heat from the char is practically independent of the air-to-feed ratio. This feature, as discussed in Section 4 is apparently due to condensation of the higher temperature oils in the bed since the off-gas temperatures were quite low (78 to 96°C). In the AIRGITATOR tests the off-gas temperatures ranged from 121 to 260°C, even though peanut hulls were used as the feed material in two of the runs.

Figure 21 presents the heating value of the noncondensible gas as a function of the air-to-feed ratio. For comparison, the AIRGITATOR data are shown together with the data from the parametric study. There are apparently two separate correlations--one for the parametric study data and one for the AIRGITATOR data. In spite of this difference, when the product of the heating value and the mass of gas per kilogram of dry feed is formed, a singl correlation results, as shown in Figure 20.

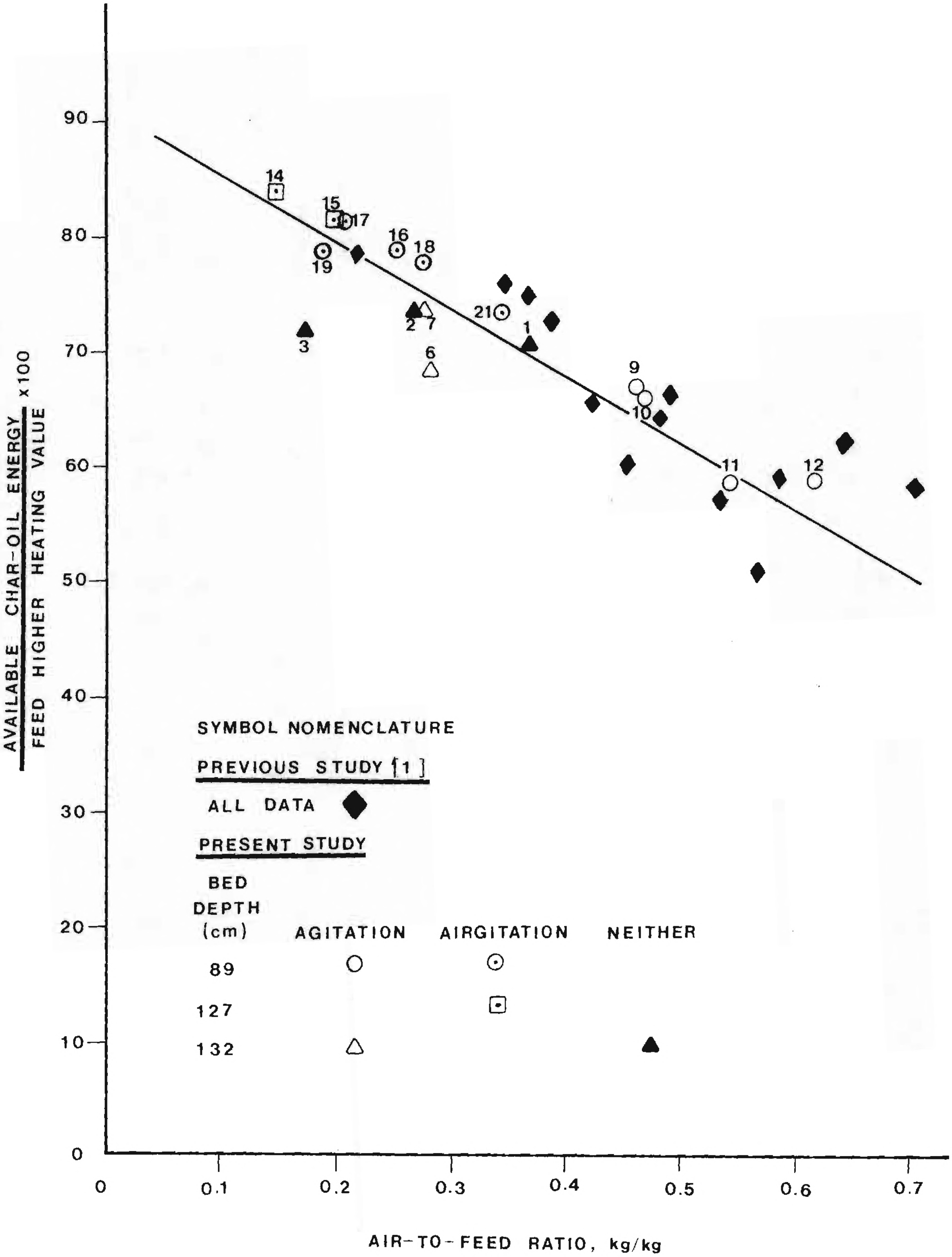


Figure 19. Percent available energy in char-oil mixture--Airgitator/parametric study/Reference 1 composite.

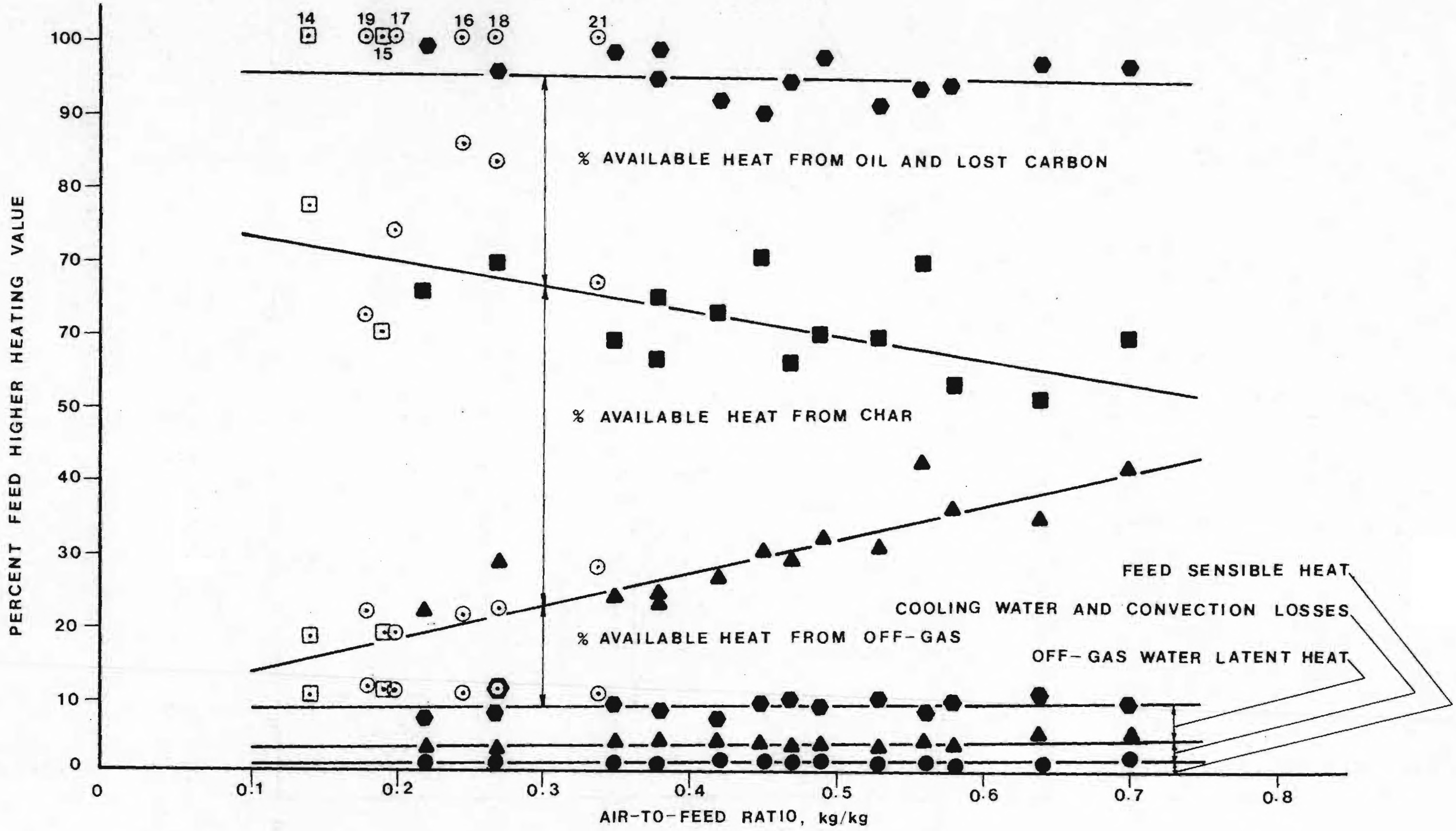


Figure 20. Energy breakdown of pyrolysis products--Airgitator/ Reference 1 composite.

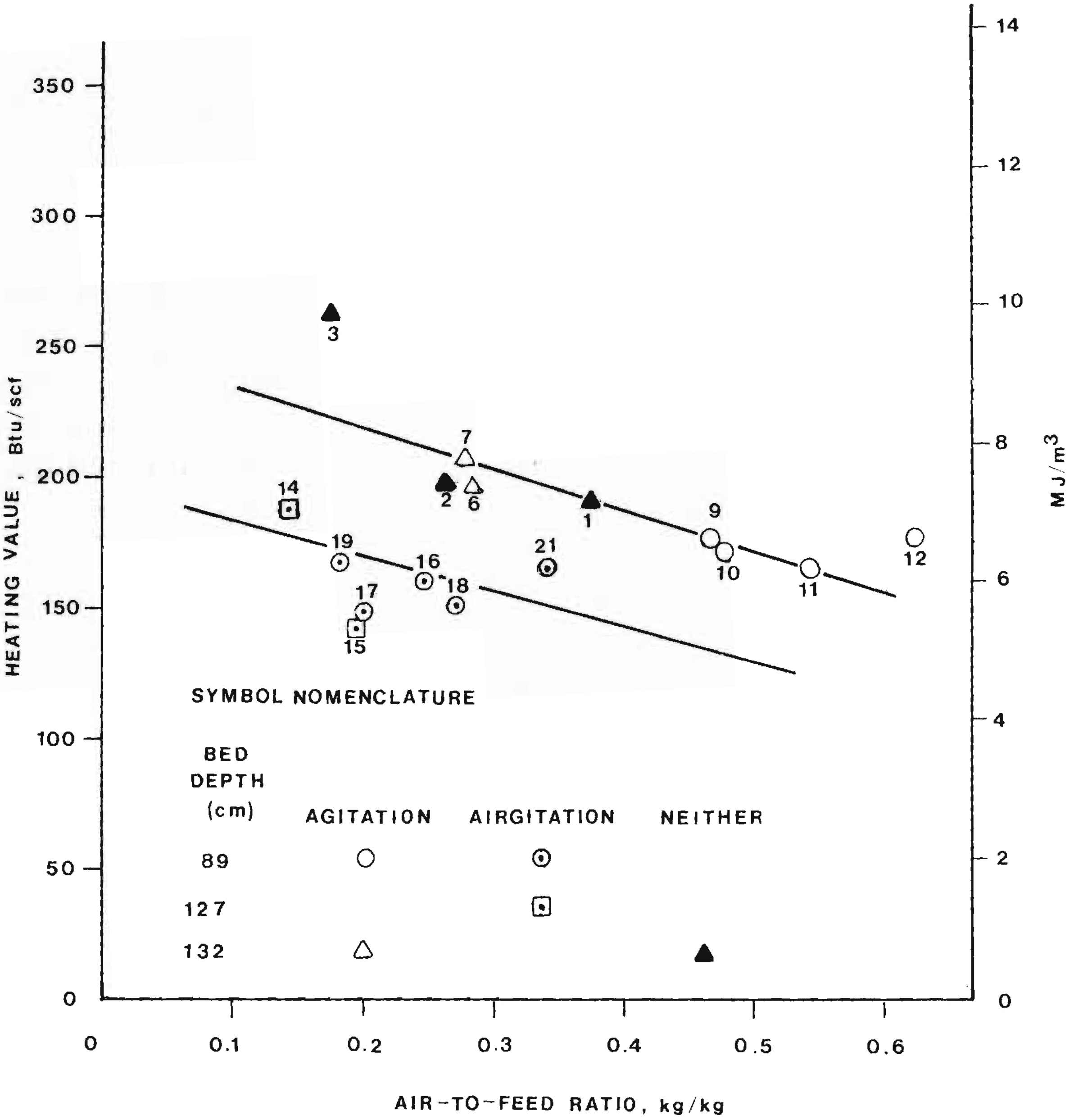


Figure 21. Heating value of noncondensible gas--Airgitator study.

SECTION 6

PERFORMANCE STUDY OF SPARK-IGNITION ENGINE FUELED WITH SIMULATED PYROLYSIS GAS

SUMMARY

The energy-conversion efficiency and self-sufficiency of a portable pyrolysis system will be enhanced if operating power can be derived from that portion of the pyrolytic off-gases which is burned in the atmosphere or otherwise not utilized. It was accordingly decided, as a first step in the development of a power system, to test a spark-ignition engine fueled with a simulated pyrolysis gas for feasibility and performance.

A 3,867-cm^3 (236-in^3), 6-cylinder, General Motors gasoline truck engine of 7.5:1 compression ratio and other familiar characteristics was used. The simulated pyrolysis gas was constituted on a volume-fraction basis as:

● Carbon Monoxide	0.24
● Hydrogen	0.12
● Methane	0.07
● Nitrogen	0.57

The higher heating value of this gas was approximately 6.71 MJ/m^3 (180 Btu/ft^3) in contrast to the 37.3 MJ/m^3 (1,000 Btu/ft^3) typical of common gaseous fuels (e.g., natural gas).

The engine ran smoothly on the low-energy fuel despite prior pessimism expressed from most sources. The wide-open-throttle output was from 60 to 65 percent of that obtained for gasoline within the operating speed range of 1,500 to 3,000 rpm. Fortuitiously, the level of power reduction is consistent with that normally recommended for continuous operation of small industrial engines. The risk of operating above-rate power is thus eliminated along with any need to increase power by supercharging or other means.

Manual control of the fuel delivery for optimum performance was necessary since no automatic metering valve is commercially available for such unusual fuel. The need is thus foreseen to develop an appropriate delivery-pressure control system to compensate for variations in gas composition and load characteristics.

The overall successful experience with simulated pyrolysis gas increases the likelihood that actual process gas can be used to fuel a spark-ignition engine.

BASIC TEST EQUIPMENT

The General Motors truck engine utilized in these tests is located in the School of Mechanical Engineering and is rated at 8.58 kW (115 hp) at 3,700 4pm. (See Figure 22.) The distributor spark-advance was manually controlled, and inlet air flow was monitored by a Meriam 50MC2-4PF laminar-flow element and a manometer. An Impco CA-300A mixer for dual-fuel operation was employed for its convertibility to gasoline (Figure 23). Modification was necessary to the extent of eliminating the internal metering by removal of the Impco gas valve assembly which had been calibrated for 37.3-MJ/m^3 (1,000-Btu/ft^3) fuel rather than for the 6.71-MJ/m^3 (180-Btu/ft^3) gas of interest. Load control was accomplished by means of a Taylor Model D-31, 179-kW (240-hp) water dynamometer (Figure 22).

GASEOUS FUEL SYSTEM

Fuel was manifolded from four size-1A gas bottles initially at 12.4 MPa (1,800 psig); each set of bottles provided fuel for 10-15 minutes of running-time at wide-open throttle. (See Figure 24.) A high-volume Matheson Gas Products Model 3052350 regulating valve delivered the fuel at approximately 138 kPa (20 psig), through a 1.91-cm (0.75-in) O.D. copper tube, to a succession of elements (Figure 25) consisting of:

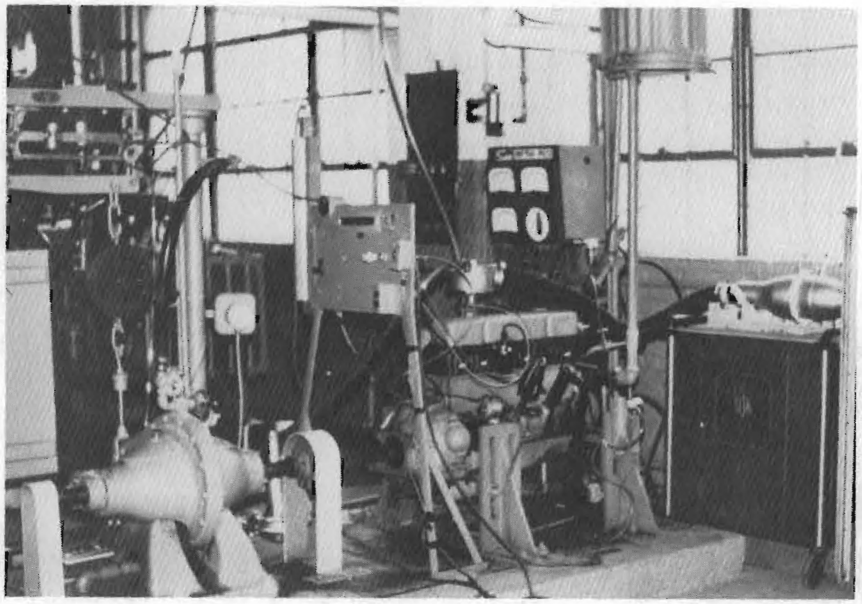


Figure 22. Overview of GM truck engine.

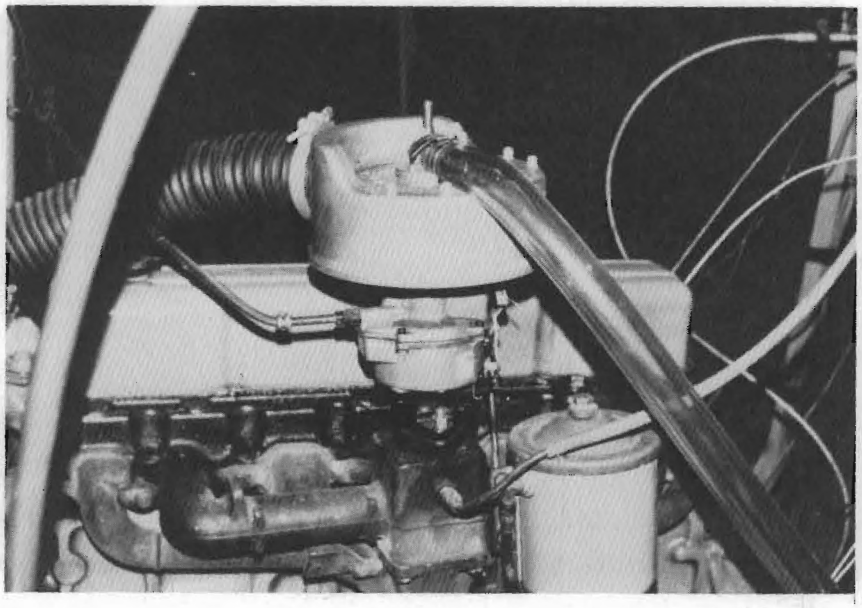


Figure 23. Impco CA-300A mixer.

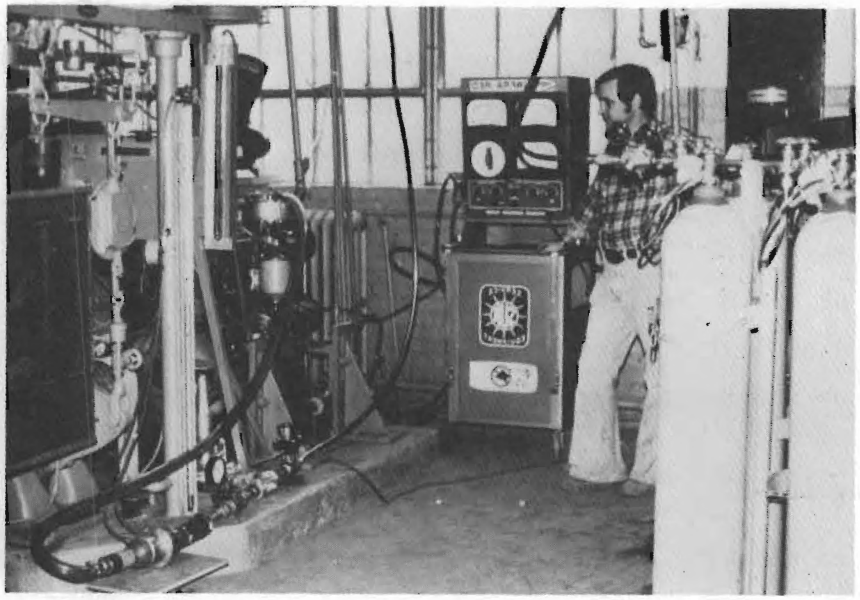


Figure 24. Overview of gaseous fuel system.

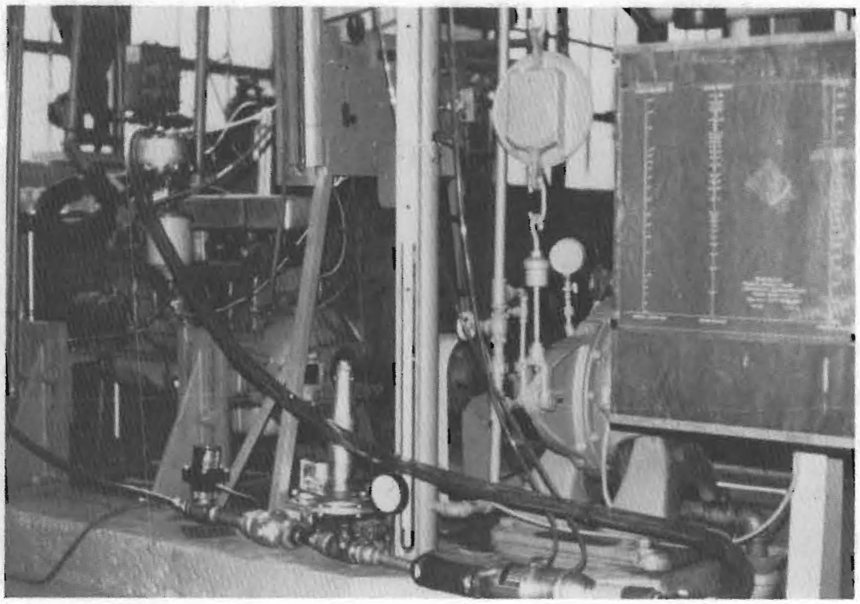


Figure 25. Gaseous fuel metering system.

- A Gould Type Q2 general-purpose, solenoid-operated shut-off valve;
- A Rockwell Model 243-8 HP pressure regulator with variable delivery pressure ranges from 300 Pa (12 inches of water) to 45 kPa (6.5 psig);
- A 3.8-cm (1.5-inch) diameter butterfly valve;
- A 100-kPa (15-psig) pressure gage; and
- A Meriam 50MC2-2S laminar-flow element.

Gas delivery rate to the Impco mixer was principally controlled by the manual setting of the Rockwell pressure regulator. All components were selected in accordance with the need to deliver the low-energy gas at approximately four times the normal volume flow rate required for any given power level.

PROCEDURE

The engine was started on gasoline for convenience and for conservation of the simulated pyrolysis gas. Upon reaching a stable operating condition at a fast idle speed of 1,200 to 1,500 rpm, the gasoline delivery was interrupte by the solenoid cut-off valve in the gasoline fuel line. Operation continued for up to one minute because of the gasoline present in the carburetor fuel bowl. At the first sign of hesitation the solenoid and butterfly valves in the simulated pyrolysis gas fuel line were opened. It was also necessary at this instant to open the throttle further to let the engine breath more of this less energetic air-fuel mixture. Reestablishment of smooth engine output usually followed with minimal stumble or stalling.

The throttle was then advanced to wide-open operation and the dynamometer load was adjusted to produce the desired operating speed. Fuel delivery pressure was then manually adjusted for maximum power at the desired engine speed, necessitating minor adjustments of the dynamometer load. Also, the spark advance was adjusted for maximum power at the desired engine speed, necessitating further minor adjustments of the dynamometer load and the fuel delivery pressure.

RESULTS

Optimum performance under specific conditions was as given in Table 5. Using data for the brake power output of the engine at specific engine speeds, as given by the smoothed presentation of these data in Figure 26, the de-rated brake power output of the engine operating on simulated pyrolysis gas, as compared with gasoline, is given in Table 6. Defining the brake de-rating factor as the ratio of the brake power output of the engine when fueled with simulated pyrolysis gas to that when it is fueled with gasoline, the brake de-rating factor varies between 0.60 and 0.65 (Table 6, Figure 26).

TABLE 5. OPTIMUM ENGINE PERFORMANCE

Fuel	Speed (rpm)	Brake Power* (kW)	Torque (N·m)	Spark Advance (degrees)
Gasoline	1,490	31.4	201	18
Gasoline	2,000	42.5	203	23
Gasoline	2,500	50.8	194	27
Gasoline	3,000	59.7	190	40
SPG[+]	1,525	21.2	133	30
SPG	2,025	25.2	119	35
SPG	2,525	31.5	119	40
SPG	3,000	37.1	118	40[‡]

* Brake power is the net power output of the engine
\+ Simulated pyrolysis gas
‡ Optimum spark advance was not determined

Stable operation of the engine beyond 3,000 rpm was not possible, in part because the maximum delivery rate of the chosen pressure regulator was being reached, and apparently because the maximum flow that could be stably accommodated by the modified Impco CA-300A gas inlet was also being exceeded. The expensiveness of the SPG and the limited interest in higher speeds mitigated against further modifications of the inlet gas-flow capacity.

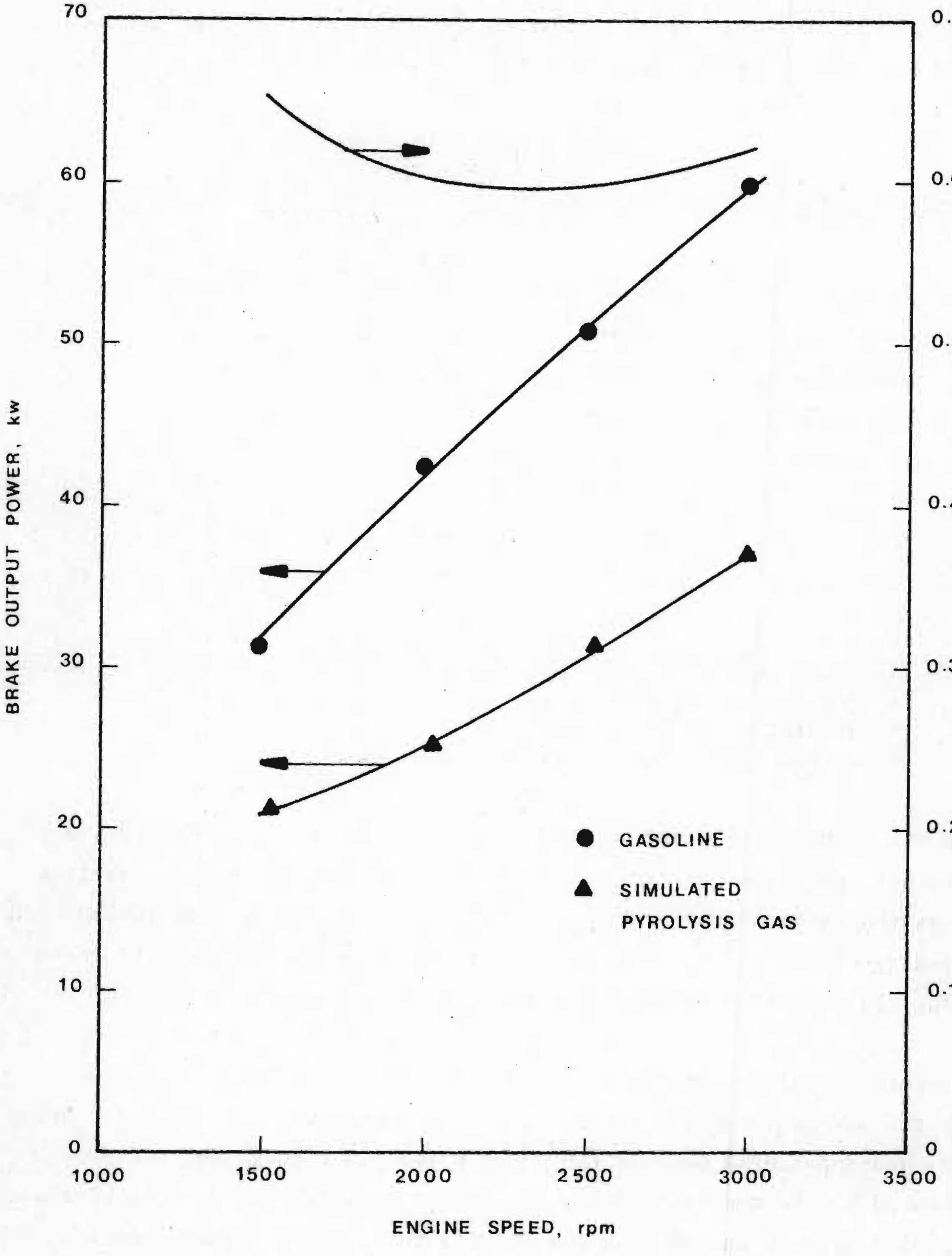


Figure 26. Wide-open-throttle performance of General Motors truck engine for gasoline and simulated pyrolysis gas.

TABLE 6. BRAKE DE-RATING FACTOR--SPG*/GASOLINE

Speed (rpm)	Gasoline (kW)	SPG (kW)	Brake De-rating Factor (SPG/Gasoline)
1,500	32.1	20.9	0.65
2,000	42.0	25.2	0.60
2,500	51.3	30.7	0.60
3,000	59.7	37.1	0.62

* Simulated pyrolysis gas.

Brake power output correction factors for atmospheric conditions were not applied to these data because the operating conditions were consistently in a range for which such corrections would have been minimal in comparison to the data tolerance.

DISCUSSION OF RESULTS

The objectives of this exploratory study were (1) to determine whether it is possible to run a spark-ignition engine on simulated pyrolysis gas and (2) to determine the brake de-rating factor in case stable operation is possible. Not only did the engine run smoothly on this "low-energy" fuel, despite prior pessimism expressed from most sources, but also the brake de-rating factor was found to be ideal for placing an intermittent-duty engine into continuous duty--the brake de-rating factor was about 0.6 over the normal engine-speed range.

The "low-energy" nature of this type of fuel warrants further comment. Low-Btu pyrolysis gas typically has a higher heating value of about 180 Btu per cubic foot of gas, whereas natural gas has one of about 1,000 Btu per cubic foot of gas and gasoline (C_8H_{18}) has one of about 6,000 Btu per cubic foot of gas. On the surface, it might appear that such pyrolysis gas is energy-deficient when compared with natural gas and gasoline. That this is not the case is evident from study of the data of Table 3. Since a spark-ignition engine operating at wide-open throttle breathes a given volume of a near Stoichiometric air-fuel mixture at approximately atmospheric pressure and temperature, the only fair way to compare these fuels is on the basis of the heating value of a given volume of Stoichiometric mixture of the fuel and air. The last two columns in Table 7 show that gasoline provides the most energetic mixture and pyrolysis gas the least. However, when pyrolysis gas is compared with gasoline and then with natural gas, it is seen that its indicated de-rating factor is about 0.72 for gasoline and about 0.80 for natural gas, when the indicated de-rating factor is defined as the ratio of the lower heating value of the pyrolysis gas per cubic meter of mixture to that of the reference fuel. From this it can be concluded that pyrolysis gas from a partial oxidation process is a practical fuel substitute for either natural gas or gasoline for a spark-ignition engine.

TABLE 7. HEATING VALUES OF STOICHIOMETRIC MIXTURES

Fuel	Phase	HHV* (MJ/kg)+	LHV‡ (MJ/kg)	Air-Fuel Ratio (kg/kg)§	HHV (MJ/m^3)#	LHV (MJ/m^3)
Gasoline	Gas	48.258	44.789	15.15	3.705	3.439
Natural Gas	Gas	55.501	50.014	17.27	3.445	3.101
Pyrolysis Gas	Gas	6.855	6.373	1.84	2.661	2.474

* Higher heating value.
\+ Energy per kg of fuel.
‡ Lower heating value.
§ Mass of air per kg of fuel.
# Energy per m^3 of mixture of fuel and Stoichiometric air at 1 atm and 25°C.

The indicated de-rating factor of 0.72 is the upper limit of what might have been expected for the GM truck engine tested. When it is noted that the friction power requirement of the engine is essentially independent of the fuel being used, it is clear that the brake power output of the less energetic air-fuel mixture will be proportionately less than that of the more energetic air-fuel mixture, the lower limit being the case where the air-fuel mixture is only energetic enough to supply the friction power and the effective brake de-rating factor is zero.

An approximate analysis of the brake de-rating factor is presented in Appendix D. Using the relationship derived for the brake de-rating factor in terms of the indicated de-rating factor and the friction power of the engine tested (Equation (D-4), page 125), the brake de-rating factor for this engine fueled with natural gas instead of gasoline was computed; the results, together with the experimentally determined brake de-rating factors for simulated pyrolysis gas, are presented in Table 8. The engine brake power when running on SPG was about 70 percent of that computed for running on natural gas (Table D-3, page 128).

TABLE 8. BRAKE DE-RATING FACTORS

Speed (rpm)	Brake De-rating Factor* (Natural Gas/Gasoline)	Brake De-rating Factor+ (SPG‡/Gasoline)
1,500	0.88	0.65
2,000	0.86	0.60
2,500	0.86	0.60
3,000	0.86	0.62

* Computed (See Table D-2, page 127).
\+ Experimental (See Table 6).
‡ Simulated pyrolysis gas.

From these observations it may be concluded that "low-Btu" pyrolysis gas should serve as an acceptable substitute for either gasoline or natural gas as a fuel for a spark-ignition engine. The brake de-rating factor of about 60 percent is ideal for using an SI engine designed for intermittent duty as a continuous-duty power source.

SECTION 7

PERC COMBUSTION AND EMISSION STUDY OF PYROLYSIS CHAR AND OIL

SUMMARY

The combustion and handling characteristics of char from pyrolyzed wood wastes were determined in a 227 kg/hr (500 lbm/hr) pulverized-coal-fired (PCF) combustion test facility, and as a slurry with No. 6 fuel oil in a 981 kW (100 HP) oil-fired boiler. In the PCF combustor, tests were also run with a 50-50 blend of Pittsburgh-seam, high-volatile coal with a high-volatile pyrolytic char, as well as with a low-volatile pyrolytic char. Stable combustion could be maintained with a secondary air-preheat temperature of 316°C (600°F), the temperature generally used when firing coal, at a carbon combustion efficiency of 97.3 to 98.6 percent. With the low nitrogen content of the char, nitrogen oxide emissions were very much lower than those obtained from coal (0.25 compared to 0.80 lbm $NO_2/10^6$ Btu) at the same firing conditions. The NO_x emissions obtained with the 50-50 blends appeared to be an average of the values obtained for the fuels separately. Similarly, SO_2 emissions were low with the char alone (0.18 lbm $SO_2/10^6$ Btu), and with the blends were an average of the values obtained with the fuels separately.

A 60-40 blend of pulverized char and char-oil, combined with No. 6 fuel oil to produce a slurry containing 30 percent char, performed well in a 981 kW (100 HP) oil-fired firetube boiler modified to fire coal-oil slurries. Excellent flame stability was experienced, and the carbon-combustion efficiency was similar to that obtained with No. 6 fuel-oil and coal-oil slurry. Nitrogen oxide emissions were significantly lower than those obtained when firing coal-oil slurry, and SO_2 emissions were about 50 percent lower. Some fouling of the small ports in the burner nozzle occurred as a

result of the accumulation of small fibers passing through the filter screen.

INTRODUCTION

Combustion and emissions tests with chars from pyrolyzed wood wastes were conducted in both a 227 kg/hr (500 lbm/hr) pulverized fuel combustion test facility and a 981 kW (100 HP) oil-fired boiler modified to fire coal-oil slurries at the Pittsburgh Energy Research Center of the U. S. Energy Research and Development Administration, in cooperation with the Industrial Environmental Research Laboratory of EPA.

A considerable amount of work concerned with the combustion of low-volatile char produced as a by-product in coal conversion processes had been performed earlier at the Pittsburgh Energy Research Center [9, 10]. Tests revealed that a low-volatile (5 percent) char such as that produced in the COED process could be successfully burned in a dry-bottom, water-walled PCF combustor by preheating the pulverized-char/primary air mixture to 232°C (450°F), or by using an auxiliary fuel (such as natural gas or coal) to provide flame stability.

PULVERIZED SOLID FUEL COMBUSTION/EMISSION STUDY

Description of Facility

The solid-fuel combustion tests were conducted in an experimental, pulverized-coal-fired furnace designed to simulate the performance of an industrial steam-generating unit used in commercial power generating plants. The wall-fired, dry-bottom furnace was capable of burning 227 kg (500 lbm) of coal per hour, with an exit gas temperature of 1,093°C (2,000°F). Heat release rate was about 670 MJ/hr-m^3 (18,000 Btu/hr-ft^3). A photograph of the furnace is shown in Figure 27. The furnace had water-cooled walls with refractory applied in the burner zone to provide flame stability by preventing excessive heat transfer to the walls in the vicinity of the burner, and to obtain an exit gas temperature of 1,093°C (2,000°F).

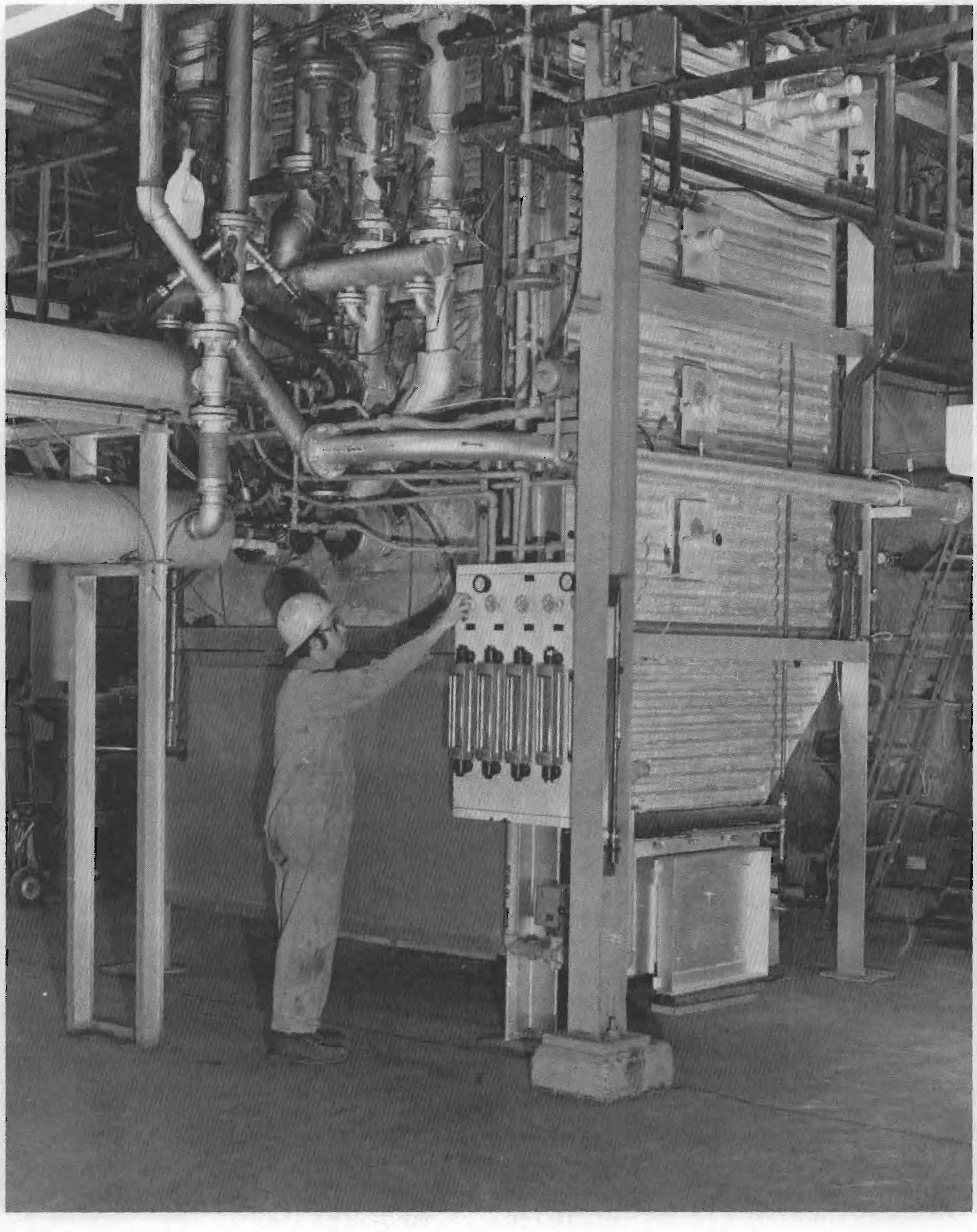


Figure 27. View of 227 kg/hr (500 lbm/hr) pulverized coal-fired furnace.

Coal was burned in a direct-fired system through four burners in the front wall of the 2.13-m (7-ft) wide, 3.66-m (12-ft) high and 1.52-m (5-ft) deep rectangular furnace. A simplified flow sheet of the combustion system is shown in Figure 28. Provision was made to preheat secondary air and to vary distribution of combustion air between the primary and secondary air streams. Variations in coal feed rate can result in pockets deficient in either fuel or oxygen, producing fluctuations in the fuel-air ratio. Consequently, a recycle loop was provided in the primary air-coal transport line to obtain a more uniform coal feed rate to the burners. Figure 29 shows the principal components of the combustion train in half section. Combustion products exited the furnace at 1,093°C (2,000°F); flowed through the convective heat-transfer section where the gas temperature was lowered to 538°C (1,000°F); through the air heater for preheating the secondary air; then through a baghouse filter. The cross-section of a multifuel burner is shown in Figure 30. The flame profile could be continuously varied from a short, bushy pattern to a relatively long, narrow pattern by adjustment of swirl induced in the secondary-air stream.

Operation of Facility

The four front-wall burners were designed to fire natural gas and/or pulverized solid fuel. Prior to each test period, the experimental furnace was fired with natural gas to preheat the refractory and to provide a source of preheat for the secondary air. During the preheat period, combustion air flows were established, and secondary-air swirl adjustments were made to provide flames that were attached to the burners, but not drawn into the burner tubes or impinging on the side walls. Preheating was continued until the secondary-air temperature was about 288°C (550°F). Natural gas flow was then reduced by 50 percent, and pulverized char, char-coal blend, or coal feed was started at a rate of 113 kg/hr (250 lbm/hr). With the oxygen content of the flue gas used as a monitoring guide, the natural gas to each burner was decreased as the solid fuel rate was increased to maintain a constant oxygen level in the flue gas.

Natural gas fed to each burner was then gradually decreased to the minimum amount necessary to produce stable flames, as determined by visual

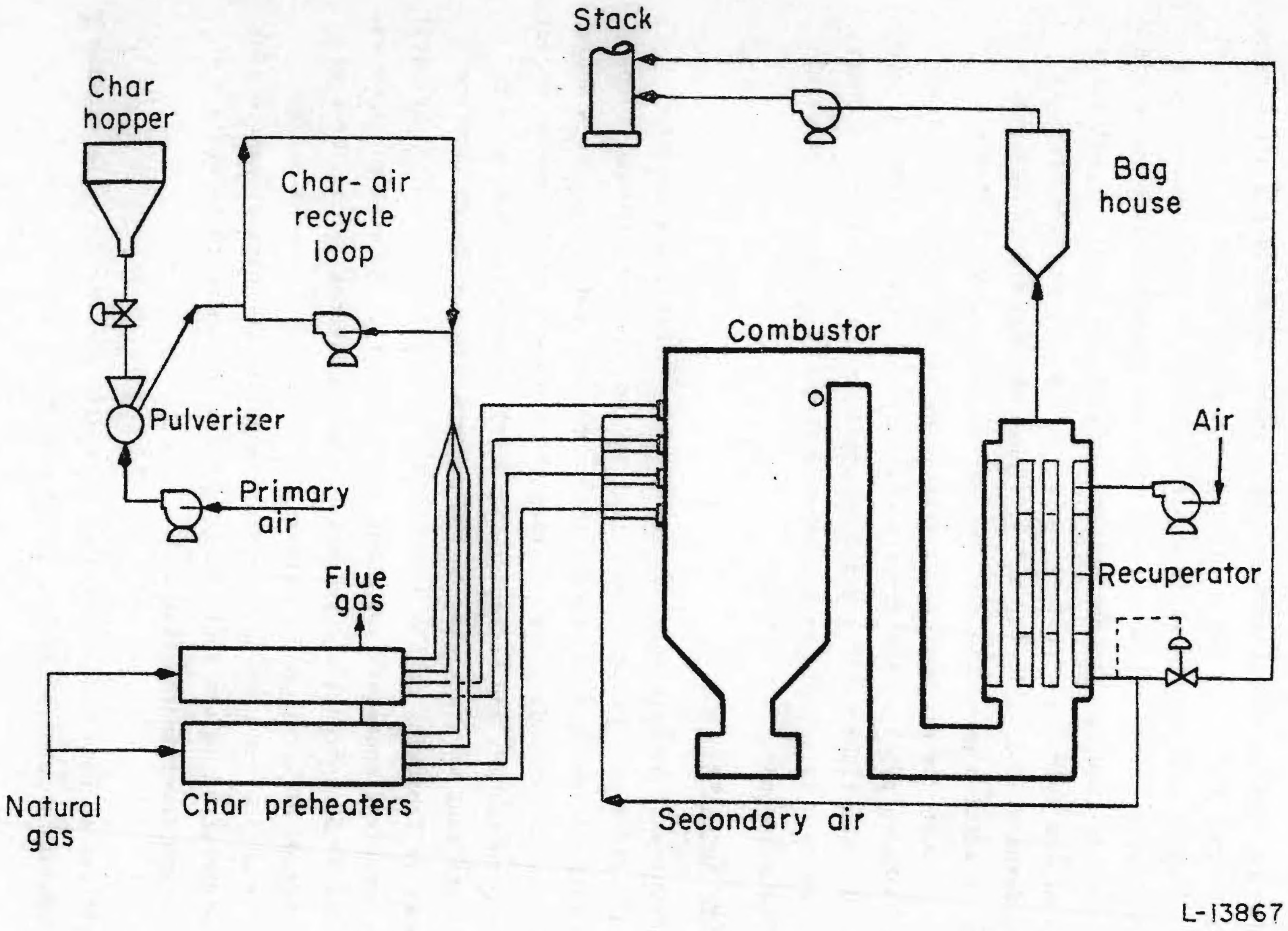


Figure 28. Schematic of 227 kg/hr (500 lbm/hr) pulverized-coal-fired furnace.

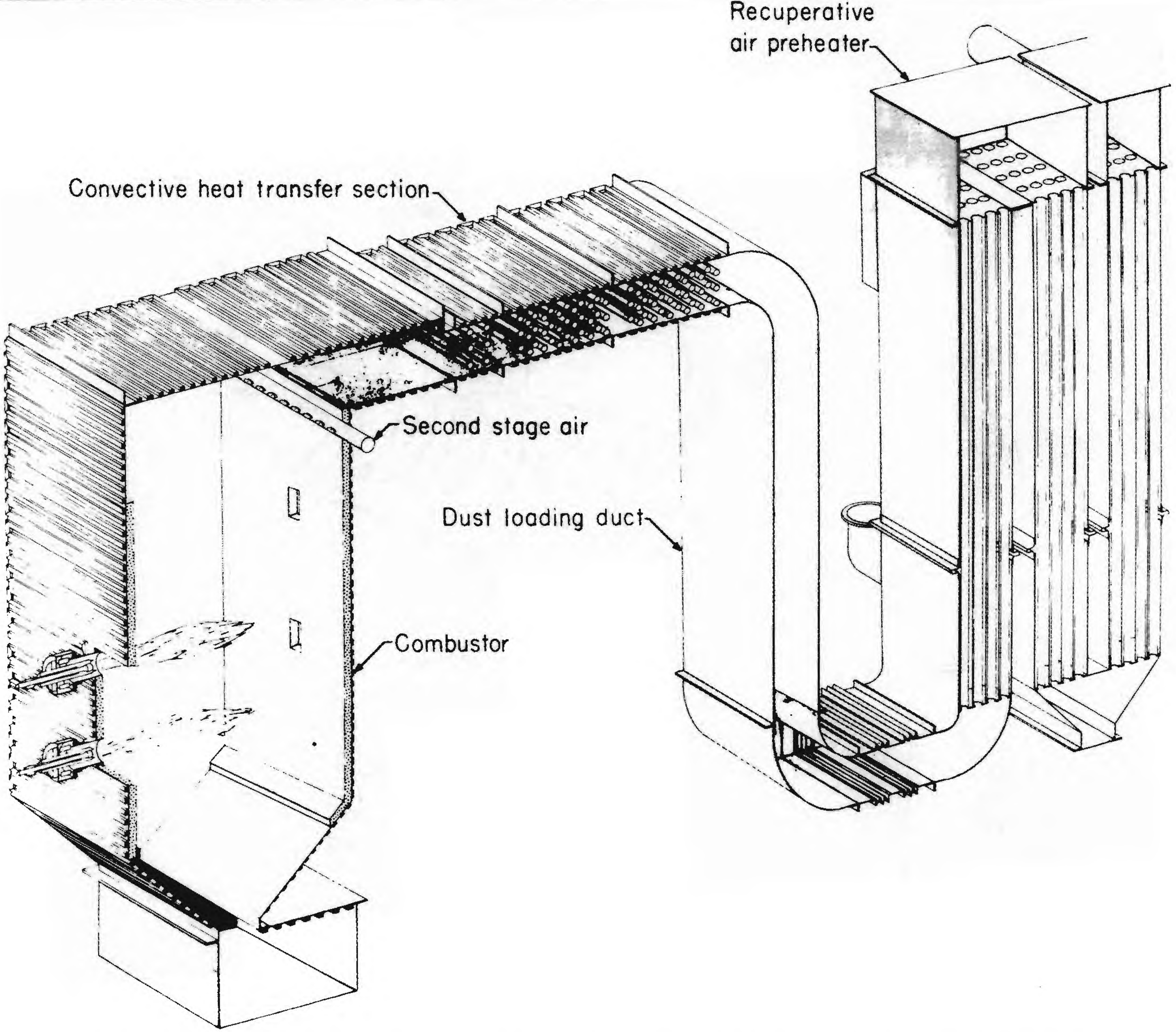


Figure 29. Half-section view of principal components of the combustion system.

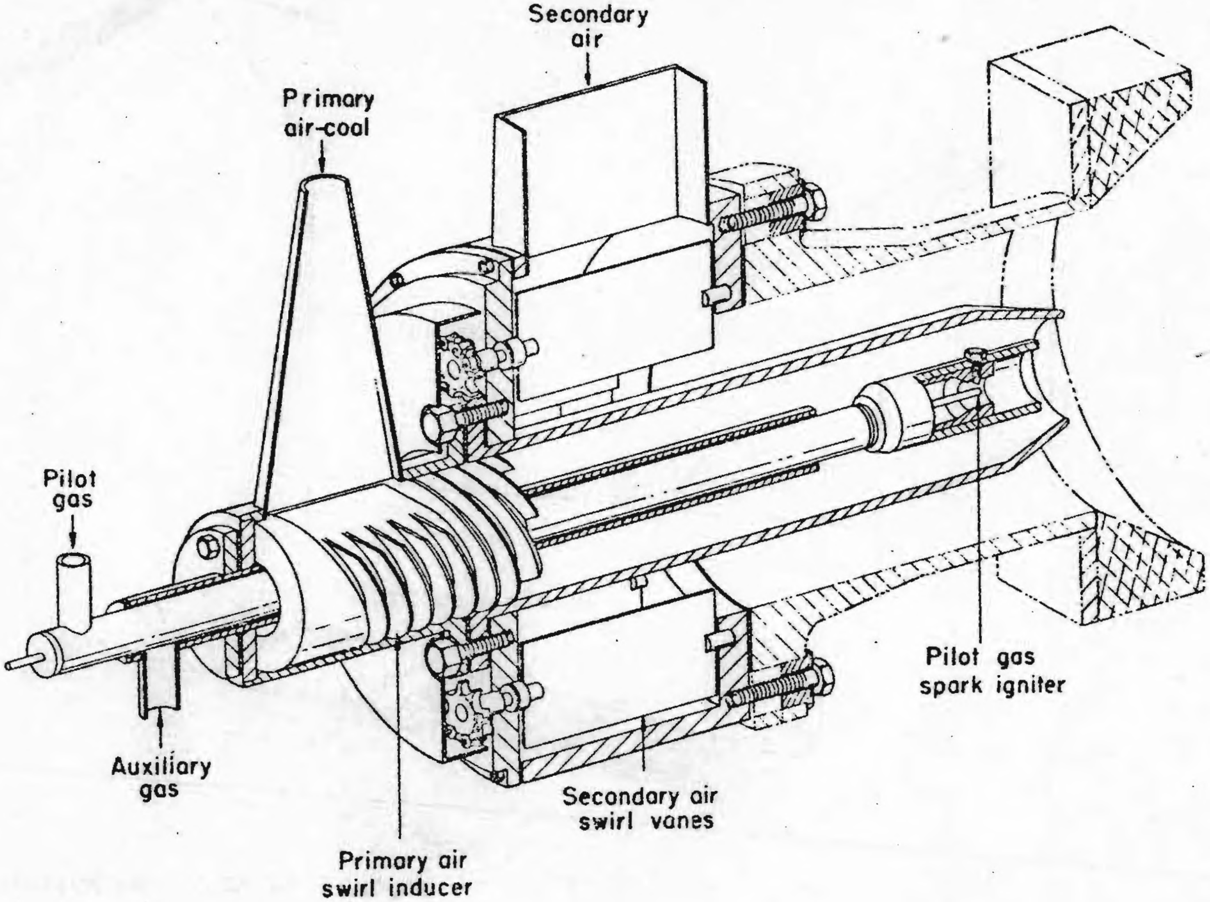


Figure 30. Multifuel burner assembly.

observation. In the present study, auxiliary gas was not required to maintain stable flames with the char-coal blend or the high-volatile char alone. After the stabilizing gas flow was eliminated, final adjustments were made on the flow of char or char-coal blends, and on secondary air to provide the desired excess-air level for the test period.

A base combustion test was first conducted with the Pittsburgh-seam coal used later for blending with both the low- and high-volatile char. The firing rate with the coal was 227 kg/hr (500 lbm/hr); the firing rate with the char and the char-coal blends was adjusted to give a heat rate equivalent to 227 kg of coal per hour (500 lbm/hr). Combustion tests were conducted with a high-volatile char alone and 50-50 blends by weight of coal with both the high-volatile and low-volatile chars. The coal-char blends were prepared in a "V" type blender with 25 mm (1/4-inch) X 0 crushed coal and the char as received. The char and coal-char blend were transferred into and from the blender with a vacuum transfer system to avoid a dust nuisance. Each 91 kg (200 lbm) coal-char charge was blended for about an hour; the relatively small fluctuations in the oxygen level during the combustion tests indicated the coal and char were well-blended. Proximate and ultimate analyses of the coal, chars, and the coal-char blends are given in Table 9.

Combustion tests were conducted by firing the chars blended with an equal weight of Pittsburgh seam coal before the high-volatile char was fired alone. Stable flames could be maintained in all tests with a secondary-air preheat of 316°C (600°F), the temperature generally employed when firing coal. Experimental results of the combustion tests are given in Table 10.

Discussion of Results

As shown in Table 9, both the nitrogen and sulfur content of the chars were very low (0.1 percent). As expected, the NO_x and SO_x emissions were very low (0.25 lbm NO_2 and 0.18 lbm $SO_2/10^6$ Btu) in the test in which the high-volatile char was fired along. The NO_x emissions obtained with the 50-50 (by weight) coal-char blends were an average of the values obtained for the fuels fired separately. Similarly, the SO_2 emissions obtained with the blends were a weighted average of the SO_2 emissions obtained from the fuels

TABLE 9. TYPICAL ANALYSES OF PITTSBURGH COAL, CHARS AND CHAR/COAL BLENDS

Data	Units	Pittsburgh Coal	High-Volatile Char	Low-Volatile Char	High-Volatile-Char/Coal Blend	Low-Volatile-Char/Coal Blend
Proximate (As Received)						
Moisture	kg/kg	0.020	0.015	0.052	0.019	0.017
Volatile Matter	kg/kg	0.377	0.280	0.025	0.353	0.226
Fixed Carbon	kg/kg	0.533	0.558	0.853	0.536	0.687
Ash	kg/kg	0.070	0.147	0.070	0.092	0.070
Ultimate (As Received)						
Hydrogen	kg/kg	0.053	0.031	0.011	0.044	0.032
Carbon	kg/kg	0.749	0.675	0.856	0.723	0.816
Nitrogen	kg/kg	0.015	0.001	0.001	0.008	0.010
Sulfur	kg/kg	0.019	0.001	0.001	0.010	0.009
Oxygen	kg/kg	0.095	0.145	0.061	0.123	0.063
Ash	kg/kg	0.070	0.147	0.070	0.092	0.070
Higher Heating Value	MJ/kg	31.26	25.45	29.53	28.81	31.07
Initial Deformation Temp.	°C	1,166	1,432	1,143	1,143	--
Softening Temperature	°C	1,193	1,460	1,171	1,171	--
Fluid Temperature	°C	1,332	1,493	1,227	1,349	--

TABLE 10. EXPERIMENTAL RESULTS OF COMBUSTION TESTS WITH PULVERIZED COAL, CHAR AND CHAR/COAL BLENDS

Data	Units	Pittsburgh Coal*	High-Volatile Char	High-Volatile-Char/Coal Blend	Low-Volatile-Char/Coal Blend	Low-Volatile-Char/Coal Blend
Test Number	--	1	5	4	2	3
Fineness	% thru 200 Mesh	76.7	67.5	75.6	70.5	71.1
NO_x Emission	kg $NO_2/10^6$ kJ	0.34	0.11	0.24	0.22	0.23
SO_2 Emission	kg $SO_2/10^6$ kJ	1.04	0.08	0.66	0.53	0.57
CO Emission	kg $CO/10^6$ kg	10	10	10	50	70
Carbon Combustion Efficiency	%	99.1	97.3	98.6	96.1	98.6
Furnace Outlet Temperature	°C	1,082	1,038	1,054	1,066	1,093
Excess Air	%	20	20	20	20	20
Secondary-Air Preheat Temperature	°C	316	316	316	343	316

*Firing rate of 227 kg/hr; char and char/coal blends fired at heat rate equivalent to 227 kg of coal per hour.

separately. In the low-volatile char-coal blend in which the heating value of the char was slightly lower than that of the coal, the SO_2 emissions (1.23 lbm/10^6 Btu) would meet emissions regulations in most air regions in the U.S. Since the heating value of the high-volatile char was considerably lower than that of the coal and low-volatile char because of its higher ash and oxygen content, a greater proportion of high-volatile char would be required in the blend to meet SO_2 emission regulations.

The carbon-combustion efficiency of 98.6 percent obtained with the 50-50 high-volatile-char/coal blend, and the second test with the blend of low-volatile char and coal compared favorably with the value of 99.1 percent obtained in the coal reference test. The lower values of 96.1 and 97.3 percent, obtained in the initial test with the blend of low-volatile char and coal and for the high-volatile char alone, is attributed to the higher percentage of oversized particles. Analyses of the various fuels given in Table 11 show that the oversize (on 100 mesh) was 16.3 and 19.3 percent for the tests in which the combustion efficiencies were somewhat low, whereas the oversize was 9.5 and 10.4 percent in the blend tests in which the combustion efficiencies were satisfactory. The oversize in the pulverized coal was only 3.9 percent. The large fraction of oversize experienced is partially attributed to the deterioration of the hammers in the impact pulverizing mill due to the erosive nature of the char. Photographs of the impact rotor disc and the hammers (Figures 31 and 32) show the erosion that was experienced during 15 to 20 hours of operation. Most of the erosion was probably due to the design of the pulverizer, in which an inventory of char covered the impact rotor disc rotating at 3600 rpm. Erosion would probably be nil in the large, slowly-turning roller or ball mills used in large industrial boilers. The large amount of oversize could also be partially attributed to carry-over of light, flake-like chips of the char, which had an average bulk density of about 320 kg/m^3 (20 lbm/ft^3). Despite the relatively low bulk density, 320 kg/m^3 (20 lbm/ft^3) compared with about 721 kg/m^3 (45 lbm/ft^3) for coal, the char flowed freely from the bunker and in transfer lines.

TABLE 11. SIEVE ANALYSES OF PULVERIZED COAL, CHAR AND CHAR/COAL BLENDS

Data	Units	Pittsburgh Coal	High-Volatile Char	High-Volatile-Char/Coal Blend	Low-Volatile-Char/Coal Blend	Low-Volatile-Char/Coal Blend
Test Number	--	1	5	4	2	3
On Sieve 100	Weight %	3.9	19.3	9.5	16.3	10.4
On Sieve 150	Weight %	6.7	5.1	5.8	5.0	5.4
On Sieve 200	Weight %	12.5	8.1	8.9	8.2	13.1
On Sieve 325	Weight %	74.7	3.3	33.3	16.5	17.2
Thru Sieve 325	Weight %	2.0	64.2	42.3	54.0	53.9
Thru Sieve 200	Weight %	76.7	67.5	75.6	70.5	71.1

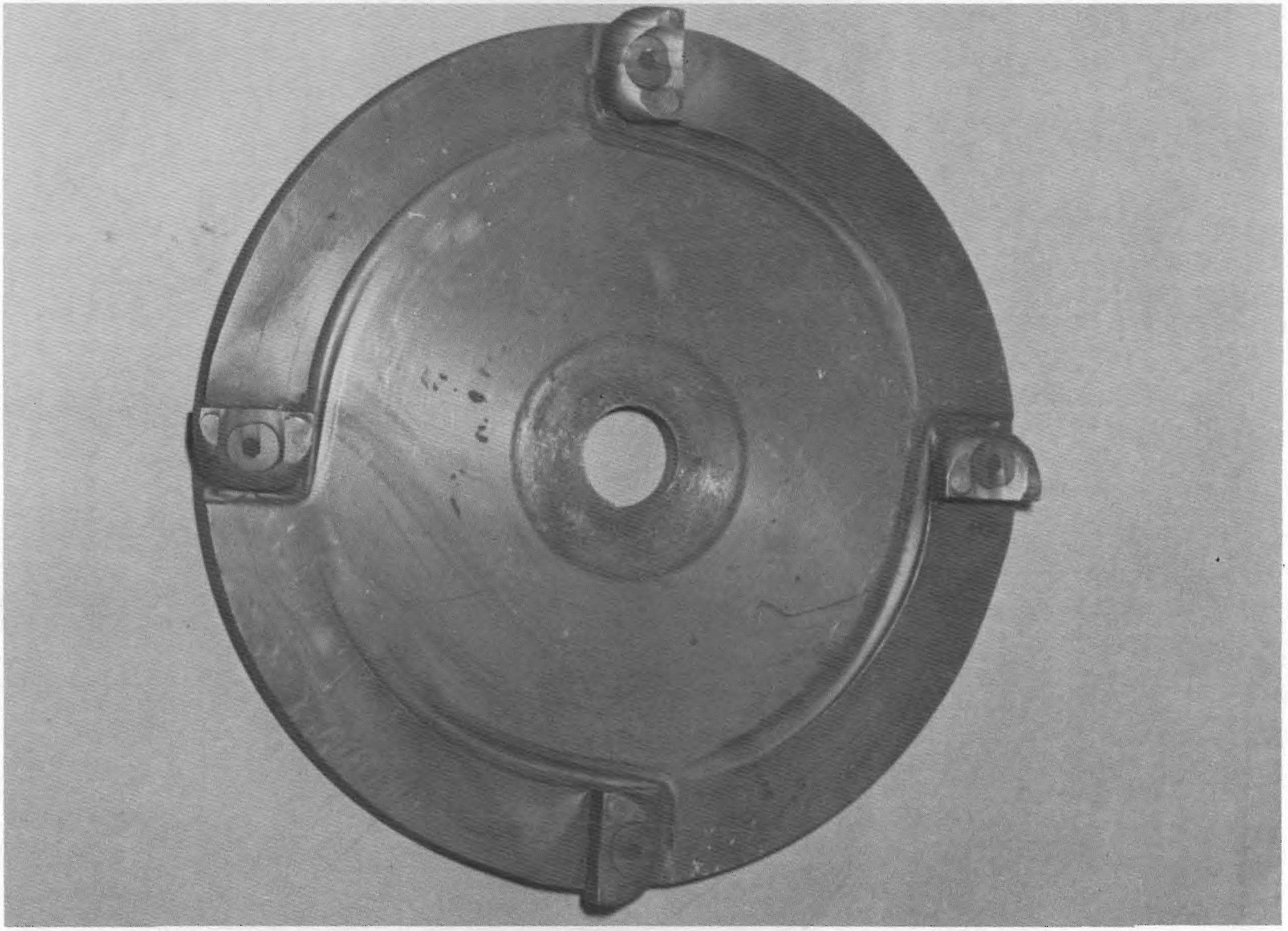


Figure 31. Worn impact rotor disc and hammers after char pulverization.

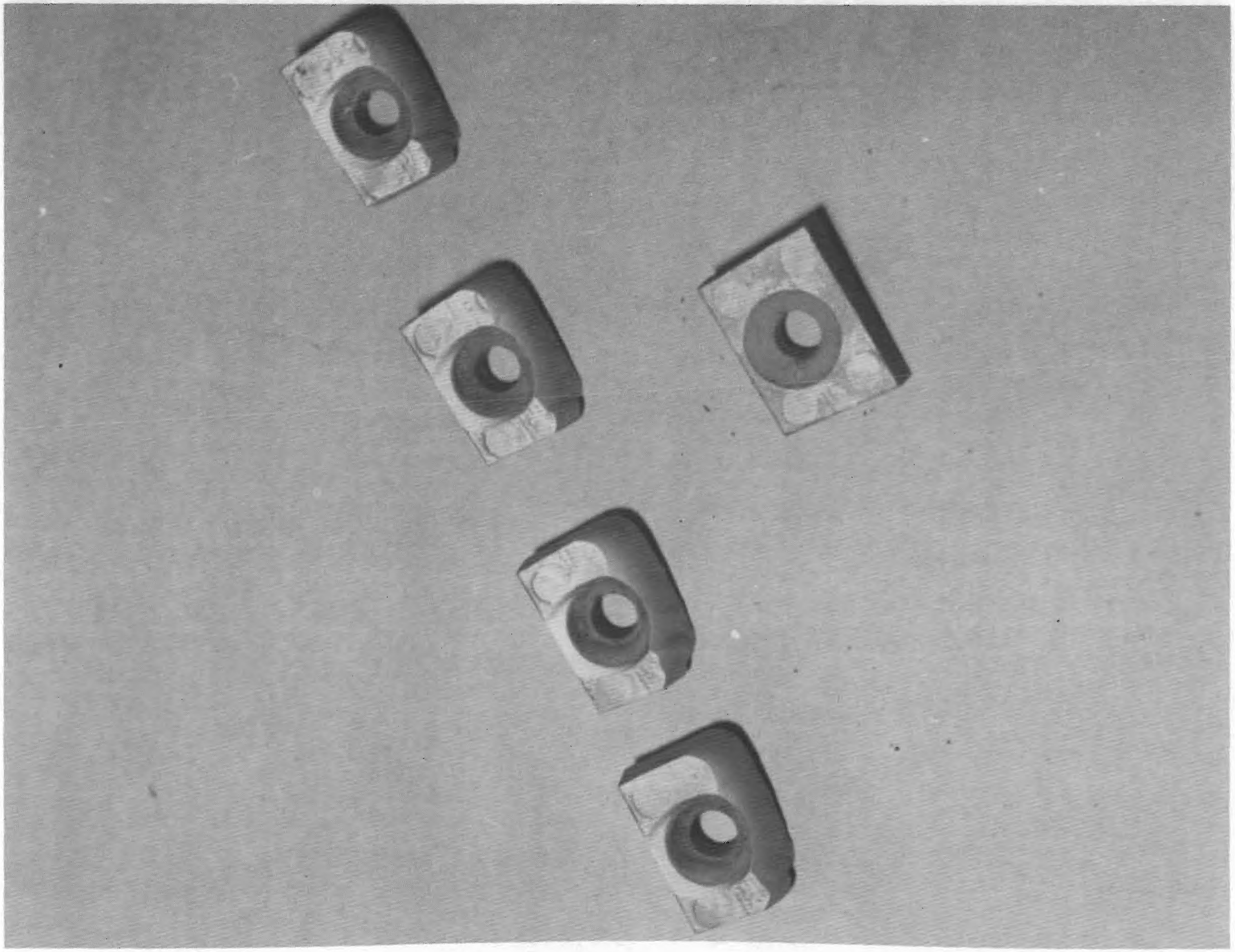


Figure 32. View of hammers before and after pulverization of char.

CHAR-OIL SLURRY COMBUSTION/EMISSION STUDY

Description of Facility

A 60-40 blend of low-volatile char and pyrolysis oil combined with No. 6 fuel oil to produce a slurry containing 30 percent char was fired in a 981 kW (100 HP) oil-fired, package firetube boiler modified to include a slurry preparation and feed system. A photograph of the boiler used for the slurry combustion studies is shown in Figure 33. A different view of the boiler and some of the auxiliary equipment is shown in Figure 34. Two No. 6 fuel-oil storage tanks appear in the background, and some of the pumps and the char-oil slurry mixing and feed tanks are in the foreground. A simplifie flow diagram is shown in Figure 35. On the left are two steam-heated storage tanks holding 26.5 m^3 (7,000 gallons) of No. 6 fuel oil. On the right is a mixing tank, equipped with a stirrer and recirculation pump, in which finely pulverized char or coal is added and slurried with oil. Following the mixing tank is the feed tank, a feed pump, and then the oil-fired boiler. A more detailed description of the slurry combustion facility was repored earlier [1].

Discussion of Results

The analysis of the char-oil slurry appears in Table 12, as well as analyses of No. 6 fuel oil and a slurry of pulverized coal and No. 6 fuel oil. Inspection reveals that nitrogen and sulfur concentrations in the char-oil slurry are about one-half the concentration in the coal-oil slurry. The results of a combustion test with the char-oil slurry appear in Table 13, with results from a No. 6 fuel oil and a coal-oil combustion test shown for comparison.

Excellent flame stability was experienced in all tests. The loss from carbon in the stack experienced with the char-oil slurry was about the same as that obtained with No. 6 fuel oil, and both were substantially lower than that obtained with the coal-oil slurry. Nitrogen oxide emissions were also lower than those obtained when firing coal-oil slurry; the SO_2 emissions were proportionate to the concentration of sulfur in the slurry, and about 50 percent lower than those with the coal-oil mixture. Some fouling of the sma

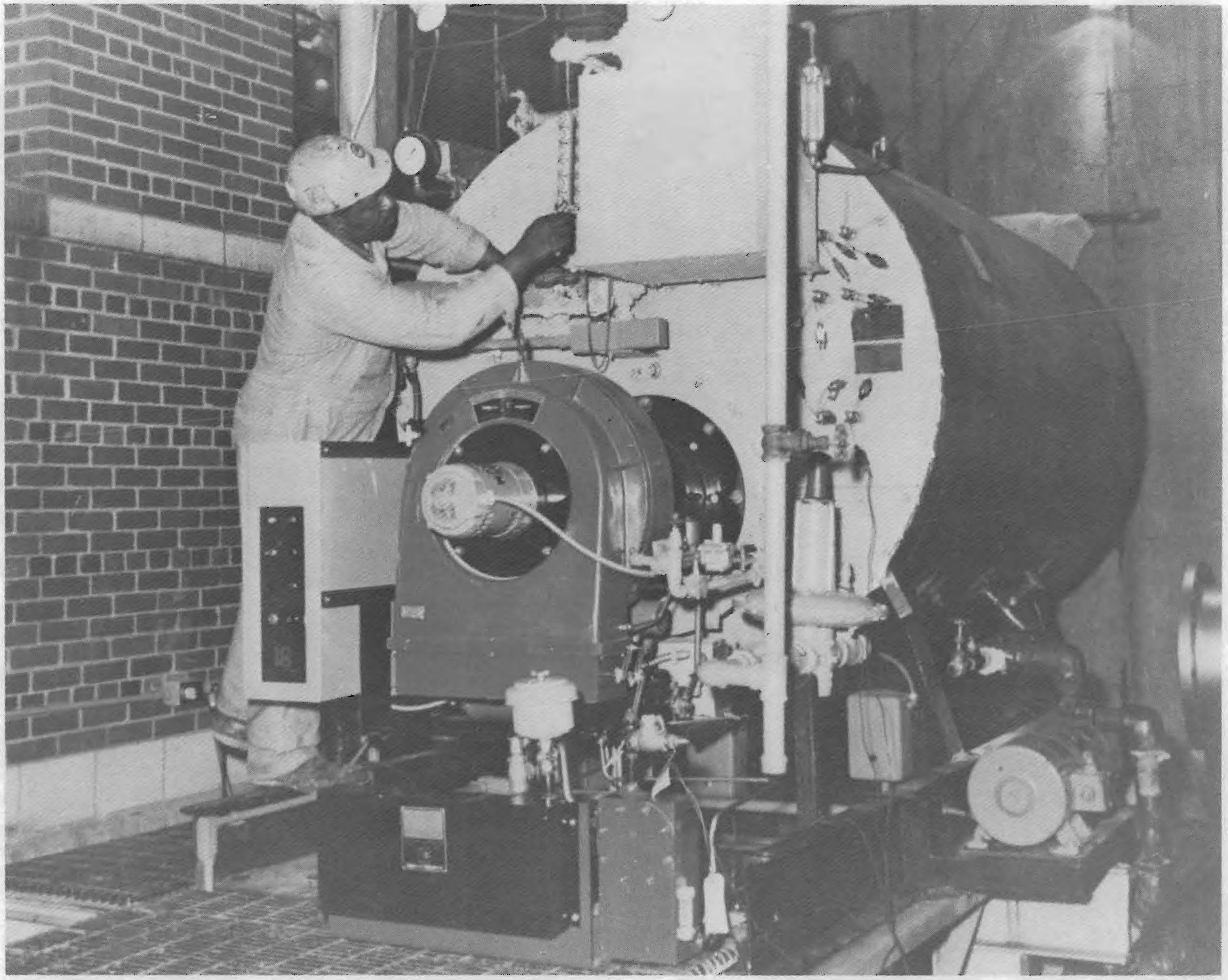


Figure 33. View of 981 kW (100 HP) Firetube boiler used for coal-oil slurry combustion studies.

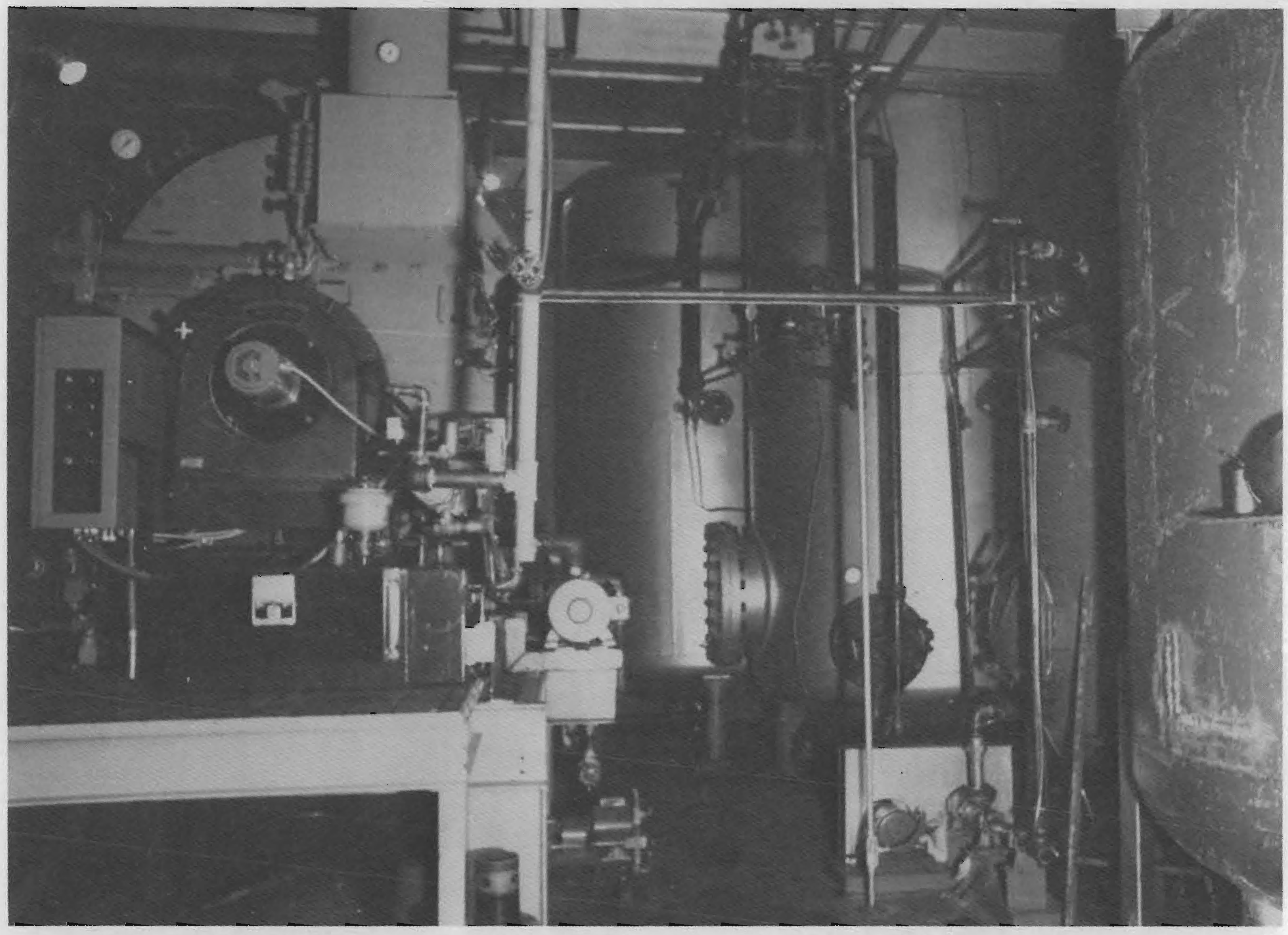


Figure 34. View of boiler, No. 6 fuel oil storage tanks, and slurry mixing and slurry mixing and feed tanks.

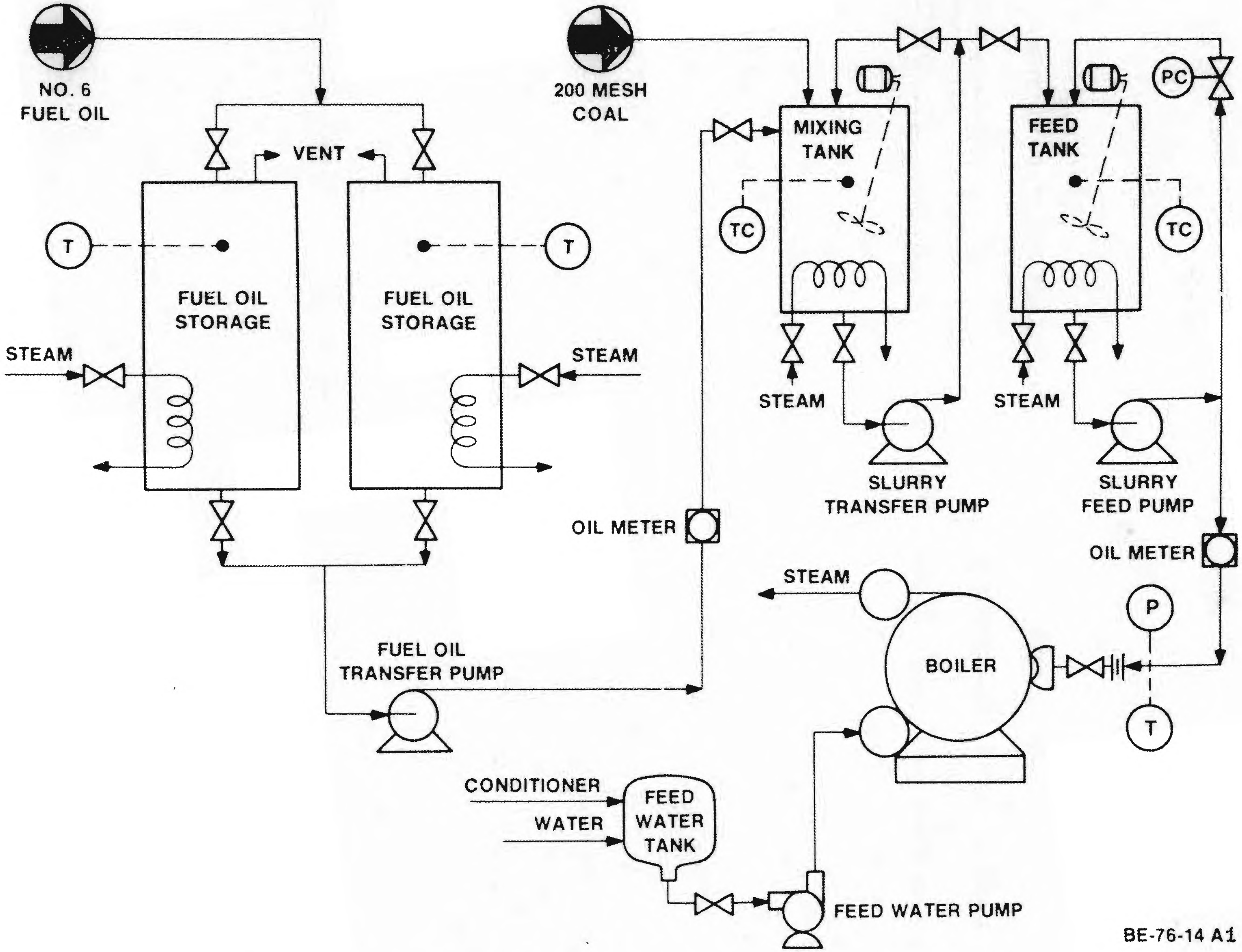


Figure 35. Simplified flow diagram of the 981 kW (100 HP) coal-oil slurry and char-oil slurry combustion test facility.

TABLE 12. TYPICAL ANALYSES OF OIL, COAL-OIL SLURRY AND CHAR-OIL SLURRY

Data	Units	Number 6 Fuel Oil	20% Coal-Oil Slurry	30% Char-Oil Slurry
Ultimate Analysis				
Hydrogen	kg/kg	0.122	0.108	0.093
Carbon	kg/kg	0.855	0.835	0.846
Nitrogen	kg/kg	0.002	0.005	0.003
Oxygen	kg/kg	0.001	0.020	0.041
Sulfur	kg/kg	0.008	0.010	0.005
Ash	kg/kg	0.000	0.018	0.013
Higher Heating Value	MJ/kg	44.12	41.55	39.94
Viscosity @ 60°C	$N.s/m^2$	0.082	0.105	0.225

Table 13. OPERATING CONDITIONS FOR SELECTED PERIODS WITH NO. 6 FUEL OIL, COAL-OIL SLURRY AND CHAR-OIL SLURRY

Data	Units	Number 6 Fuel Oil	20% Coal-Oil Slurry	30% Char-Oil Slurry
Solids Concentration	Weight %	0	20	30
Fineness	% thru 200 Mesh	-	95	92.4
Steam Pressure	kN/m^2	848	855	827
Fuel Pressure @ Burner	kN/m^2	117	131	166
Atomizing-Air Pressure	kN/m^2	124	131	172
Fuel Temperature				
At Hold Tank	°C	49	47	56
At Burner	°C	94	94	98
Flue Gas Analysis				
Oxygen	Vol. %	4.8	4.3	4.4
Carbon Dioxide	Vol. %	11.4	11.5	11.8
Carbon Monoxide	mg/kg	50	81	-
NO_x	mg/kg	223	273	235
Sulfur Dioxide	mg/kg	551	523	265
Steam Flow Rate	kg/hr	1,529	1,592	1,588
Fuel Flow Rate	kg/hr	100.4	104.1	114.3
Excess Air	Vol. %	27.1	23.8	23.0
Dust Loadings	kg/hr	0.54	1.72	1.49
Carbon in Fly Ash	Weight %	46.4	49.9	29.3
Loss From Carbon in Stack	Weight %	0.2	0.6	0.3
Fuel Heating Value	MJ/kg	44.12	41.63	39.94

ports in the burner nozzle occurred as a result of accumulation of small fibers that passed through the filter screen. The problem was alleviated by a slight modification of the nozzle. Plugging would not be a problem in larger industrial boilers in which the burner ports are proportionately larger.

The low sulfur and nitrogen content of the char makes it an ideal fuel to mix with either coal or oil to conserve our dwindling oil supply. When slurried with oil and burned in an oil-fired boiler, the only pollution abatement device required would be a baghouse for particulate control. The low-sulfur content of the char would also permit the firing of oils higher in sulfur content without violating SO_2 emission standards. If a new industrial coal-fired boiler was installed to completely eliminate the use of oil, the requirement for a sulfur emission control system could be eliminated by blending the coal with the low-sulfur char to meet SO_2 emission regulations. This is an especially attractive feature for the smaller industrial boilers for which a flue gas desulfurization system would be disproportionately cumbersome and expensive. The suppression of NO_x emissions due to the low nitrogen content of the char makes it doubly attractive.

CONCLUSIONS

1. Stable combustion and satisfactory combustion efficiency could be maintained in the 227 kg/hr (500 lbm/hr) pulverized-coal-fired, water-wall combustor with high-volatile char alone, or with 50-50 blends of high- or low-volatile char and coal.

2. Excellent flame stability was experienced and carbon combustion efficiency was equal to that obtained with No. 6 fuel oil, when pulverized char was mixed with oil and fired as a slurry in an oil-fired boiler.

3. The low sulfur and nitrogen content of the char makes it an attractive fuel to mix with either high-sulfur coal or oil to extend oil supplies and to meet SO_2 and NO_x emission regulations without emission control devices other than a baghouse or electrostatic precipitator for particular control.

REFERENCES

1. Tatom, J. W., A. R. Colcord, J. A. Knight, L. W. Elston, and P. H. Har-oz, "Utilization of Agricultural Forestry and Silvicultural Waste for the Production of Clean Fuels," Final Report under EPA Contract 68-02-1485, Engineering Experiment Station, Georgia Tech, Atlanta, Georgia, September 1976.

2. Tatom, J. W., A. R. Colcord, J. A. Knight, L. W. Elston, and P. H. Har-oz, "A Mobile Pyrolytic System - Agricultural and Forestry Wastes into Clean Fuels," Proceedings 1975 Agricultural Waste Management Conference published as Energy Agricultural and Waste Management, Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan.

3. Tatom, J. W., A. R. Colcord, J. A. Knight, L. W. Elston, and P. H. Har-oz, "Parametric Study for a Pyrolytic System for Production of Clean Fuels from Agricultural and Forestry Wastes," Proceedings Tenth Intersociety Energy Conversion Engineering Conference, published by Institute of Electrical and Electronics, Inc., New York, N. Y.

4. Tatom, J. W., A. R. Colcord, J. A. Knight, L. W. Elston, and P. H. Har-oz, "Clean Fuels from Agricultural and Forestry Wastes - The Mobile Pyrolysis Concept, 1974 A.S.M.E. Winter Annual Meeting, paper no. 75 - WA/HT - 47.

5. Everett, Kevin, "Playing Ball with the Big Boys; Has Mobile Pyrolysis Come of Age?" unpublished paper, Florida Resource Recovery Council, December 1975.

6. Long, J. R. M., "Coal-in-Oil Fuel Study," Final Report, January 2, 1964, Combustion Engineering, Inc.

7. Private Communication, Andrew Brown, General Motors.

8. Private Communication, J. J. Demeter of the ERDA Pittsburgh Energy Research Center.

9. McCann, C. R., J. J. Demeter, A. A. Orning, and D. Bienstock, "Combustion of Pulverized Char," presented at Combustion Symposium, Div. Fuel Chemistry, ACS National Meeting, Washington, D.C., September 12-17, 1971.

10. Demeter, J. J., C. R. McCann, and D. Bienstock, "Further Studies of the Combustion of Pulverized Char and Low-Volatile Coal," presented at the Winter Annual Meeting, ASME, Detroit, Michigan, November 11-15, 1973.

11. Demeter, J. J., C. R. McCann, G. T. Bellas, J. M. Ekmann, and D. Bienstock, "Combustion of Coal-Oil Slurry in a 100 HP Firetube Boiler," PERC/RI-77/8, May 1977.

APPENDIX A

LABORATORY PROCEDURE

The following procedures were followed in the laboratory analysis of the input feed and the pyrolysis products:

Solid Samples

Sample Preparation--The solid samples examined consisted of the dried peanut hulls or pine sawdust used as feed material for the waste converter, and chars produced by the converter. The sample size received in the laboratory ranged from one to eight liters for the peanut hulls or sawdust feeds and from one to two liters for the char products. The samples were thoroughly mixed and divided by quartering or by a riffle splitter to produce a representative one liter sample, which was passed through a Wiley Model 4 mill using a six-millimeter screen. The ground sample was again mixed and divided into approximately equal parts. One part was again passed through the Wiley Model 4 mill using a two-millimeter screen. This material was then mixed and reduced by quartering to approximately 100 grams. The 100-gram sample was then passed through a Wiley intermediate mill using 40-mesh screen, remixed, and quartered. The larger portion of the 40-mesh sample was stored in a tightly closed glass bottle for use in laboratory analysis. The remaining quarter of the material was again passed through the Wiley intermediate mill using an 80-mesh screen, remixed, and stored in a tightly-capped vial for elemental analysis.

Analytical Procedures--The following analytical procedures were used:

1. Percent Moisture in Peanut Hull or Sawdust Feeds: Duplicate 1.000-gram samples were placed in aluminum dishes and dried for one hour at 40.5°C in a forced air oven. The dried samples were cooled in a desiccator and weighed. The estimated error was ± 0.6 percent (absolute).

2. Percent Moisture and Percent Volatiles in Chars: These analyses were performed by ASTM Method D-271. The estimated error was ± 0.3 percent (absolute).

3. Percent Ash and Percent Acid-Insoluble Ash in Feeds and Chars: Duplicate 1.000-gram samples of the feed or char were weighed into tared porcelain crucibles, ignited to constant weight in a muffle furnace at 600°C, cooled in a desiccator, and reweighed. The ash was digested in a 1:3 mixture of hydrochloric acid and nitric acid for 30 minutes. The mixture was then diluted to approximately 100 ml and filtered through a Whatman No. 40 paper. After thorough washing with distilled water, the filter paper and undissolved ash were returned to the crucible used for the original ash determinations, ignited to constant weight at 600°C, cooled in a desiccator and weighed. The estimated error was ± 0.2 percent (absolute).

4. Heating Value: The heating values of the feeds and chars were determined in a Parr Plain (Isothermal Jacket) oxygen bomb calorimeter, following the procedures described on pages 33-38 of Oxygen Bomb Calorimeter and Combustion Methods, Technical Manual No. 130, Parr Instrument Company, Moline, Illinois (1960). Agreement among replicate samples was better than 2.5 percent (absolute) for the feeds and 3.5 percent (absolute) for the chars.

5. Elemental Analysis: Carbon, hydrogen and nitrogen were determined using a Perkin Elmer Model 240 Elemental Analyzer. (Oxygen was determined by difference.) The manufacturer claims a precision of ± 1.0 percent (relative for pure, crystalline materials). Because of the heterogeneous nature of the samples, loss of volatiles from the chars in the purge fraction of the analytical cycle, and the difficulty of selecting a representative three milligram sample, occasional variations as high as 15 percent (absolute) have been observed in the carbon and oxygen determination on char samples. However in most cases, the agreement was better than 6.0 percent (absolute) for carbon and oxygen in the feeds and chars. Agreement among replicate hydrogen or nitrogen determinations was better than 1.0 percent.

Oil Samples

Sample Preparation--The oil samples received in the laboratory were stored in tightly-closed glass bottles and stirred before each analysis.

Percent Moisture in Oil--The percent moisture in the oil was determined by the method of Dean and Stark. The error is believed to be ± 5.0 percent (relative), although the oil is known to begin to decompose partially with liberation of additional water at the temperature of the toluene-water azeotrope, and acetone and other water soluble compounds have been detected in the head space over stored oil samples.

Non-condensible Gas Samples

Sample Preparation--Gas samples were drawn continuously from the head space in the waste converter or from the upstream end of the condensers. The sample stream was passed through a series of water-cooled condensers, a glass-wool demister, and ice-cooled trap, a chemical drying tube, and a dry test meter to a tee in the sampling line. From the tee the major portion of the sample was exhausted to the atmosphere through a vane-type pump. A smaller portion of the stream was led from the tee through a tubing pump and a wet test meter into a 96-liter "Saran" gas collection bag. The flow rate in the gas streams was held constant throughout the sampling periods. At the end of the test, the waters and oils from the condenser train were measured and the gas collection bag was closed and returned to the laboratory for analysis.

Analysis of Noncondensible Gas Samples--The gases were mixed by kneading the sample collection bag, and their concentrations were determined by gas chromatography. Oxygen and nitrogen were determined in a Perkin Elmer Model 990 Gas Chromatograph using helium carrier gas, a Molecular Sieve 5A column, and a thermal conductivity detector. Hydrogen was determined in a similar manner using argon as the carrier gas. Carbon monoxide, methane and carbon dioxide were determined in the same instrument using helium carrier gas and an activated carbon column. Hydrocarbons containing two or more carbon atoms were determined in a Perkin Elmer Model 154 instrument using helium carrier gas, a Perkin Elmer "R" column, and a flame ionization detector. The estimated error was ± 5.0 percent (relative).

APPENDIX B

LABORATORY DATA

Listed in the following pages are the results of the laboratory analysis described in Sections 4 and 5 for the feed, char, oil and off-gases. It should be noted that the CHNO analysis and the heating values for the oils are for the indicated moisture content. Thus, the results for dry oil in Tables 2 and 4 have been corrected for this moisture. The CHNO analysis and heating values for the feed and char are on a dry basis.

TABLE B-1. LABORATORY ANALYSIS FOR TEST 1

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent Composition[‡]
Water	Percent	4.4	8.3	11.9	N_2	44.37
Ash	Percent	3.4	10.9	-	CO	16.88
					CO_2	15.78
Acid-Insoluble Ash	Percent	-	-	-	H_2	16.17
Carbon	Percent	48.6	75.1	57.0	CH_4	4.60
Hydrogen	Percent	6.0	2.6	7.6	C_2H_6	0.52
Nitrogen	Percent	1.7	2.5	3.5	C_2H_4	0.72
Oxygen[§]	Percent	40.3	8.9	31.9	C_3H_8	0.13
Heating Value	MJ/kg	19.46	25.45	29.12	C_3H_6	0.24
					C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-2. LABORATORY ANALYSIS FOR TEST 2

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	4.3	0.3	33.2	N_2	47.1
Ash	Percent	2.3	10.0	-	CO	14.5
Acid-Insoluble Ash	Percent	-	-	-	CO_2	19.9
					H_2	11.1
Carbon	Percent	47.0	82.9	55.5	CH_4	5.52
Hydrogen	Percent	5.8	1.8	7.6	C_2H_6	0.63
Nitrogen	Percent	2.0	2.1	3.1	C_2H_4	0.90
Oxygen[§]	Percent	42.9	3.2	33.8	C_3H_8	0.14
Heating Value	MJ/kg	18.40	29.75	22.17	C_3H_6	0.27
					C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-3. LABORATORY ANALYSIS FOR TEST 3

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	5.0	4.6	21.1	N_2	33.8
Ash	Percent	1.2	6.5	-	CO	18.2
					CO_2	24.0
Acid-Insoluble Ash	Percent	-	-	-	H_2	12.5
Carbon	Percent	45.8	84.4	60.6	CH_4	9.5
Hydrogen	Percent	5.4	1.7	7.7	C_2H_6	0.6
Nitrogen	Percent	0.0	1.0	1.3	C_2H_4	0.9
Oxygen[§]	Percent	47.6	6.4	30.4	C_3H_8	0.1
Heating Value	MJ/kg	19.12	30.73	23.97	C_3H_6	0.3
					C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-4. LABORATORY ANALYSIS FOR TEST 6

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas Non-Condensible Components	Off-Gas Percent Composition[‡]
Water	Percent	4.6	2.7	17.9	N_2	41.1
Ash	Percent	2.3	6.5	-	CO	9.8
					CO_2	22.4
Acid-Insoluble Ash	Percent	-	-	-	H_2	18.7
Carbon	Percent	47.3	72.4	60.1	CH_4	6.7
Hydrogen	Percent	5.7	1.7	8.6	C_2H_6	0.6
Nitrogen	Percent	1.2	2.9	2.4	C_2H_4	-
Oxygen[§]	Percent	43.5	16.5	28.9	C_3H_8	0.6
Heating Value	MJ/kg	18.99	31.59	No Fire	C_3H_6	-
					C_4H_{10}	-

---

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-5. LABORATORY ANALYSIS FOR TEST 7

					Off-Gas	
Element	Units	Feed	Char[*]	Oil[+]	Non-Condensible Components	Percent[‡] Composition
Water	Percent	4.6	0.6	16.1	N_2	41.9
Ash	Percent	2.3	9.8	-	CO	24.51
					CO_2	8.14
Acid-Insoluble Ash	Percent	-	-	-	H_2	15.07
Carbon	Percent	47.3	73.6	57.6	CH_4	8.91
Hydrogen	Percent	5.7	1.8	8.6	C_2H_6	0.65
Nitrogen	Percent	1.2	2.7	6.5	C_2H_4	-
Oxygen[§]	Percent	43.5	12.1	27.3	C_3H_8	0.78
Heating Value	MJ/kg	18.99	29.82	25.01	C_3H_6	-
					C_4H_{10}	-

---

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-6. LABORATORY ANALYSIS FOR TEST 9

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas Non-Condensible Components	Off-Gas Percent[‡] Composition
Water	Percent	22.3	0.6	20.3	N_2	45.32
Ash	Percent	4.6	9.8	–	CO	19.89
					CO_2	15.36
Acid-Insoluble Ash	Percent	1.4	-	–	H_2	6.14
Carbon	Percent	48.3	73.6	56.9	CH_4	5.67
Hydrogen	Percent	5.9	1.8	8.7	C_2H_6	0.66
Nitrogen	Percent	1.2	2.7	1.1	C_2H_4	0.52
Oxygen[§]	Percent	40.0	12.1	33.3	C_3H_8	0.13
Heating Value	MJ/kg	20.39	28.04	27.54	C_3H_6	0.20
					C_4H_{10}	–

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-7. LABORATORY ANALYSIS FOR TEST 10

					Off-Gas	
Element	Units	Feed	Char[*]	Oil[+]	Non-Condensible Components	Percent[‡] Composition
Water	Percent	22.3	1.5	26.1	N_2	53.26
Ash	Percent	4.6	13.6	-	CO	17.03
Acid-Insoluble Ash	Percent	1.4	4.4	-	CO_2	11.31
					H_2	12.84
Carbon	Percent	48.3	74.8	53.6	CH_4	4.40
Hydrogen	Percent	5.9	1.5	9.1	C_2H_6	0.41
Nitrogen	Percent	1.2	0.8	1.1	C_2H_4	0.50
Oxygen[§]	Percent	40.0	10.3	36.2	C_3H_8	0.09
Heating Value	MJ/kg	20.39	27.77	26.18	C_3H_6	0.18
					C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-8. LABORATORY ANALYSIS FOR TEST 11

					Off-Gas	
Element	Units	Feed	Char[*]	Oil[+]	Non-Condensible Components	Percent[‡] Composition
Water	Percent	22.3	3.2	28.6	N_2	46.98
Ash	Percent	4.6	17.0	-	CO	17.91
					CO_2	18.18
Acid-Insoluble Ash	Percent	1.4	-	-	H_2	11.13
Carbon	Percent	48.4	77.8	51.5	CH_4	4.63
Hydrogen	Percent	5.9	1.3	8.9	C_2H_6	0.41
Nitrogen	Percent	1.2	0.8	1.1	C_2H_4	0.53
Oxygen[§]	Percent	39.9	3.1	38.5	C_3H_8	0.09
					C_3H_6	0.16
Heating Value	MJ/kg	20.39	27.60	24.34	C_4H_{10}	—

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-9. LABORATORY ANALYSIS FOR TEST 12

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent Composition[‡]
Water	Percent	22.3	1.2	34.0	N_2	46.88
Ash	Percent	4.6	20.1	-	CO	21.86
					CO_2	16.36
Acid-Insoluble Ash	Percent	1.4	-	-	H_2	8.72
Carbon	Percent	48.3	77.3	47.0	CH_4	4.84
Hydrogen	Percent	5.9	0.9	8.7	C_2H_6	0.43
Nitrogen	Percent	1.2	1.1	1.1	C_2H_4	0.63
Oxygen[§]	Percent	40.0	0.6	43.2	C_3H_8	0.09
Heating Value	MJ/kg	19.97	25.22	25.59	C_3H_6	0.19
					C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-10. LABORATORY ANALYSIS FOR TEST 14

					Off-Gas	
Element	Units	Feed	Char[*]	Oil[+]	Non-Condensible Components	Percent[‡] Composition
Water	Percent	6.1	1.2	14.7	N_2	40.3
Ash	Percent	2.8	7.1	-	CO	23.2
					CO_2	19.3
Acid-Insoluble Ash	Percent	0.5	1.0	-	H_2	9.84
Volatiles	Percent	-	12.2	-	CH_4	6.03
Carbon	Percent	50.6	78.5	60.0	C_2H_6	1.0
Hydrogen	Percent	6.1	1.8	8.2	C_2H_4	-
Nitrogen	Percent	0.7	1.1	1.0	C_3H_8	0.1
Oxygen[§]	Percent	39.8	11.5	30.8	C_3H_6	0.1
Heating Value	MJ/kg	19.78	29.12	26.28	C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-11. LABORATORY ANALYSIS FOR TEST 15

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	6.1	0.9	18.1	N_2	47.0
Ash	Percent	2.8	10.2	-	CO	11.1
					CO_2	26.1
Acid-Insoluble Ash	Percent	0.5	3.0	-	H_2	0.5
Volatiles	Percent	-	11.0	-	CH_4	3.33
Carbon	Percent	50.6	78.7	56.8	C_2H_6	0.99
Hydrogen	Percent	6.1	1.4	6.3	C_2H_4	-
Nitrogen	Percent	0.7	0.7	1.0	C_3H_8	0.20
Oxygen[§]	Percent	39.8	9.0	35.9	C_3H_6	0.13
Heating Value	MJ/kg	19.78	23.92	24.34	C_4H_{10}	-

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-12. LABORATORY ANALYSIS FOR TEST 16

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent Composition[‡]
Water	Percent	7.2	3.7	50.4	N_2	46.4
Ash	Percent	0.9	3.3	-	CO	17.9
					CO_2	23.9
Acid-Insoluble Ash	Percent	0.6	1.7	-	H_2	3.99
Carbon	Percent	47.3	75.0	45.4	CH_4	6.26
Hydrogen	Percent	6.0	3.6	8.1	C_2H_6	1.04
Nitrogen	Percent	0.1	0.0	0.3	C_2H_4	-
Oxygen[§]	Percent	45.7	18.1	46.2	C_3H_8	0.38
Heating Value	MJ/kg	18.48	27.95	18.81	C_3H_6	-
					C_4H_{10}	0.08

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-13. LABORATORY ANALYSIS FOR TEST 17

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	4.7	2.0	44.9	N_2	46.5
Ash	Percent	0.8	2.7	-	CO	18.5
					CO_2	25.7
Acid-Insoluble Ash	Percent	0.5	1.1	-	H_2	2.19
Carbon	Percent	48.3	72.7	39.7	CH_4	5.91
Hydrogen	Percent	6.0	3.7	6.6	C_2H_6	0.85
Nitrogen	Percent	0.4	0.0	0.6	C_2H_4	-
Oxygen[§]	Percent	44.5	20.9	53.1	C_3H_8	0.29
Heating Value	MJ/kg	18.55	27.43	14.41	C_3H_6	-
					C_4H_{10}	0.01

---

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-14. LABORATORY ANALYSIS FOR TEST 18

					Off-Gas	
Element	Units	Feed	Char*	Oil+	Non-Condensible Components	Percent‡ Composition
Water	Percent	4.8	1.7	25.6	N_2	48.1
Ash	Percent	2.9	4.4	-	CO	19.9
Acid-Insoluble Ash	Percent	0.9	1.5	-	CO_2	21.2
					H_2	4.3
Carbon	Percent	45.9	73.9	45.7	CH_4	5.2
Hydrogen	Percent	5.8	3.6	7.1	C_2H_6	0.86
Nitrogen	Percent	0.4	0.1	0.5	C_2H_4	-
Oxygen §	Percent	45.0	18.0	46.7	C_3H_8	0.26
Heating Value	MJ/kg	18.23	27.84	20.45	C_3H_6	-
					C_4H_{10}	0.02

* The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

+ The CHNO analysis and heating values are based on oil with the indicated moisture content.

‡ Note that this is the volume, not the weight composition.

§ Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-15. LABORATORY ANALYSIS FOR TEST 19

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	3.5	1.7	12.4	N_2	37.4
Ash	Percent	2.0	2.8	-	CO	20.5
					CO_2	31.2
Acid-Insoluble Ash	Percent	0.8	1.6	-	H_2	2.65
Carbon	Percent	48.0	81.2	53.6	CH_4	6.84
Hydrogen	Percent	5.9	2.9	6.8	C_2H_6	1.00
Nitrogen	Percent	0.0	0.5	0.8	C_2H_4	-
Oxygen[§]	Percent	44.1	12.6	38.8	C_3H_8	0.34
Heating Value	MJ/kg	18.46	31.30	22.56	C_3H_6	-
					C_4H_{10}	0.03

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-16. LABORATORY ANALYSIS FOR TEST 20

Element	Units	Feed	Char*	Oil+	Off-Gas: Non-Condensible Components	Off-Gas: Percent‡ Composition
Water	Percent	6.0	1.2	21.2	N_2	36.2
Ash	Percent	2.1	2.9	-	CO	21.3
Acid-Insoluble Ash	Percent	1.1	1.6	-	CO_2	21.5
					H_2	10.9
Carbon	Percent	47.1	85.6	48.1	CH_4	8.4
Hydrogen	Percent	5.9	2.0	7.2	C_2H_6	1.4
Nitrogen	Percent	0.3	0.7	0.8	C_2H_4	-
Oxygen§	Percent	44.6	8.8	43.9	C_3H_8	0.32
Heating Value	MJ/kg	18.01	32.01	21.75	C_3H_6	-
					C_4H_{10}	0.02

---

* The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

+ The CHNO analysis and heating values are based on oil with the indicated moisture content.

‡ Note that this is the volume, not the weight composition.

§ Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

TABLE B-17. LABORATORY ANALYSIS FOR TEST 21

Element	Units	Feed	Char[*]	Oil[+]	Off-Gas	
					Non-Condensible Components	Percent[‡] Composition
Water	Percent	7.6	1.5	5.1	N_2	43.1
Ash	Percent	1.1	2.7	-	CO	20.7
					CO_2	26.9
Acid-Insoluble Ash	Percent	0.6	1.2	-	H_2	2.67
Carbon	Percent	47.7	82.7	56.5	CH_4	4.46
Hydrogen	Percent	5.9	2.8	6.3	C_2H_6	0.93
Nitrogen	Percent	0.1	0.3	1.0	C_2H_4	-
Oxygen[§]	Percent	45.2	11.5	36.2	C_3H_8	1.25
Heating Value	MJ/kg	18.15	31.68	25.13	C_3H_6	-
					C_4H_{10}	0.03

[*] The volatile component of the char probably contains very little water and is primarily gaseous hydrocarbons.

[+] The CHNO analysis and heating values are based on oil with the indicated moisture content.

[‡] Note that this is the volume, not the weight composition.

[§] Oxygen computed; $O_2 = 1 - N_2 - C - H_2$.

APPENDIX C

LISTING OF DATA REDUCTION COMPUTER PROGRAM

Presented in this section are listings and sample calculations illustrating the use of the data analysis computer program.*

To demonstrate the sample computer output, in Run Number 4 (Test 1) the nominal laboratory CHNO and heating values for the input feed and products (see Table B-1) are listed below:

	N_2	C	H_2	O_2	HV
Gas	0.485	0.191	0.021	0.303	6.29
Char	0.025	0.751	0.026	0.089	25.45
Feed	0.017	0.486	0.061	0.437	19.46
Air	0.770	0	0	0.230	0

From the testing, the char yield was 21.7 kg per 100 kg dry feed; the measured amount of air per 100 kg of dry feed was 36.4 kg, and the amount of the moisture in the feed was 4.6 kg per 100 kg dry feed. The energy losses (1) were estimated at 57.0 MJ (54,000 Btu) for each 45.36 kg (100 lbm) of feed (or about 7 percent of the energy of the feed).

In the computation procedure, which involved an iterative approach, initial values for w_{no} and HV_o were chosen and equations 1-8 were solved approximately.

Then variations of ± 10 percent of each of the coefficients in the eight equations were made, and the resulting values of each of the eight unknowns

---

*Note: All calculations within these two programs were made using the English system of units and conversion to metric units was made during report preparation.

were determined. Using these results, the measured versus the computed values of the oil composition could be compared. The results of this procedure are presented as part of the SENSAN OUTPUT.

Comparison of the computed versus the measured oil composition shows the following results:

Element	Measured	Computed	Percent Difference
C	0.657	0.837	+ 27.4
H	0.071	0.0344	- 51.5
O	0.242	0.185	- 23.6
N	0.04	- 0.056	--

Not only was the difference between the values for C, H and O substantial, but the computed value for N was physically impossible. Clearly, significant inconsistencies between the measured and the computed results were present using the nominal values of the coefficients.

From a study of the effect of variations in the values of the coefficients on the deviation between the measured and computed oil composition, it was determined that the carbon content of the char and the carbon content of the feed have a major influence on the results. Thus, the least-squares program made a search for that combination of w_{cf} and w_{cch}, within bounds of ± 10 percent of the nominal values, which minimizes the square root of the sum of the squares of the difference between the computed and measured values of w_{co}, w_{oo}, w_{ho} and w_{no}.

The results of this computation are presented in the ITERAT OUTPUT. Study of the table shows that the measured versus the computed values of C, H, N, and O for the oil are as follows:

Element	Measured	Computed	Percent Difference
C	0.657	0.654	+ 0.45
H	0.071	0.043	- 39
O	0.242	0.268	+ 10.7
N	0.04	0.034	- 15

Thus, with the slightly modified values of w_{cf} (+ 6%) and w_{cch} (+ 4%), all the results are put into a much better overall agreement than is possible from the direct computation of the first eight equations, and with only minor variations in M_g, M_o, M_w and HV.

SENSAN OUTPUT

```
RUN NUMBER 4

            N2              C              H2              O2             HV

GAS       .485            .191           .021            .303           2704
CHAR      .025            .751           .026            .089           10950
WATER      0              0              .110            .890           1140
FEED      .017            .486           .061            .437           8372
AIR       .770            0               0              .230           0
OIL INITIAL VALUES:       WNO = .041                     HVO = 13713
TOTAL WEIGHT:             CHAR= 21.7                     FEED= 100
                          AIR = 36.4                     MOISTURE= 4.6
                          ENERGY LOSSES= 54000

HV=HEATING VALUE
HVO=HEATING VALUE OF THE OIL
WNO=WT. FRAC. OF N2 IN OIL


NOMINAL W( 1 )= .485
+10% OF NOM W( 1 )= .5335
MG= 52.706 MO= 26.0201 MW= 40.5739 HVO= 13497.7
WCO= .854587 WHO= .018134 WOO= 8.27837E-2 WNO= 4.44951E-2
-10% OF NOM W( 1 )= .4365
MG= 64.557 MO= 24.5459 MW= 30.1971 HVO= 15199.4
WCO= .813696 WHO= 5.55865E-2 WOO= .317711 WNO=-.186994


NOMINAL W( 2 )= .191
+10% OF NOM W( 2 )= .2101
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 13599.9
WCO= .793084 WHO= .034429 WOO= .184997 WNO=-1.25098E-2
-10% OF NOM W( 2 )= .1719
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14867.5
WCO= .880508 WHO= .034429 WOO= .184997 WNO=-9.99336E-2


NOMINAL W( 3 )= .021
+10% OF NOM W( 3 )= .0231
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 13940.5
WCO= .836796 WHO= .029623 WOO= .184997 WNO=-5.14157E-2
-10% OF NOM W( 3 )= .0199
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14526.9
WCO= .836796 WHO= .039235 WOO= .184997 WNO=-6.10277E-2


NOMINAL W( 4 )= .303
+10% OF NOM W( 4 )= .3333
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .115653 WNO= 1.31222E-2
-10% OF NOM W( 4 )= .2727
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .254341 WNO=-.125566


NOMINAL W( 5 )= 2704
+10% OF NOM W( 5 )= 2974.4
MG= 58.1395 MO= 24.0938 MW= 37.0667 HVO= 14640.1
WCO= .879837 WHO= 3.08601E-2 WOO= .150624 WNO=-6.13207E-2
-10% OF NOM W( 5 )= 2433.6
MG= 57.9262 MO= 26.6165 MW= 34.7572 HVO= 13867.2
WCO= .797977 WHO= 3.76478E-2 WOO= .215958 WNO=-5.16229E-2
```

```
NOMINAL W( 6 )= .025
+10% OF NOM W( 6 )= .0275
MG= 57.9196 MO= 25.3716 MW= 36.0098 HVO= 14217.7
WCO= .837193 WHO= 3.40743E-2 WOO= .182772 WNO=-5.40296E-2
-10% OF NOM W( 6 )= .0225
MG= 58.1457 MO= 25.3434 MW= 35.8108 HVO= 14249.7
WCO= .836408 WHO= .034784 WOO= .187224 WNO=-5.84162E-2


NOMINAL W( 7 )= .751
+10% OF NOM W( 7 )= .8261
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 13301.8
WCO= .772528 WHO= .034429 WOO= .184997 WNO= 8.04605E-3
-10% OF NOM W( 7 )= .6759
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 15165.6
WCO= .901064 WHO= .034429 WOO= .184997 WNO=-.120489


NOMINAL W( 8 )= .026
+10% OF NOM W( 8 )= .0286
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14098.
WCO= .836796 WHO= .032204 WOO= .184997 WNO=-5.39967E-2
-10% OF NOM W( 8 )= .0234
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14369.4
WCO= .836796 WHO= 3.66539E-2 WOO= .184997 WNO=-5.84467E-2


NOMINAL W( 9 )= .089
+10% OF NOM W( 9 )= .0979
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .17738 WNO=-4.86054E-2
-10% OF NOM W( 9 )= .0801
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .192613 WNO=-.063838


NOMINAL W( 10 )= 10950
+10% OF NOM W( 10 )= 12045
MG= 58.1941 MO= 23.4475 MW= 37.6583 HVO= 14864.9
WCO= .903644 WHO= .028886 WOO= .131611 WNO=-6.41411E-2
-10% OF NOM W( 10 )= 9855
MG= 57.8712 MO= 27.2675 MW= 34.1613 HVO= 13691.
WCO= .779313 WHO= 3.91954E-2 WOO= .230903 WNO=-4.94118E-2


NOMINAL W( 11 )= 0
+10% OF NOM W( 11 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
-10% OF NOM W( 11 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2


NOMINAL W( 12 )= 0
+10% OF NOM W( 12 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
-10% OF NOM W( 12 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
```

```
NCMINAL W( 13 )= .11
+10% OF NCM W( 13 )= .121
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 13405.2
WCO= .836796 WHO= 2.08469E-2 WOO= .184997 WNO=-4.26396E-2
-10% OF NOM W( 13 )= .099
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 15062.2
WCO= .836796 WHO= 4.80111E-2 WOO= .184997 WNO=-6.98038E-2


NOMINAL W( 14 )= .89
+10% OF NOM W( 14 )= .979
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= 7.51051E-2 WNO= 5.36698E-2
-10% OF NOM W( 14 )= .801
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .294838 WNO=-.166113


NCMINAL W( 15 )= 1140
+10% OF NOM W( 15 )= 1254
MG= 58.0607 MO= 25.0257 MW= 36.2136 HVO= 14336.5
WCO= .847678 WHO= 3.35267E-2 WOO= .176306 WNO=-5.75109E-2
-10% OF NOM W( 15 )= 1026
MG= 58.0051 MO= 25.6838 MW= 35.6111 HVO= 14135.3
WCO= .82637 WHO= 3.52935E-2 WOO= .193323 WNO=-5.49865E-2


NCMINAL W( 16 )= .017
+10% OF NCM W( 16 )= .0187
MG= 58.3869 MO= 25.3134 MW= 35.5997 HVO= 14284.
WCO= .83558 WHO= 3.55429E-2 WOO= .191984 WNO=-6.31068E-2
-10% OF NOM W( 16 )= .0153
MG= 57.6784 MO= 25.4016 MW= 36.22 HVO= 14183.6
WCO= .838008 WHO= 3.33189E-2 WOO= .178034 WNO=-4.93606E-2


NOMINAL W( 17 )= .486
+10% OF NOM W( 17 )= .5346
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 17012.8
WCO= 1.02846 WHO= .034429 WOO= .184997 WNO=-.247881
-10% OF NOM W( 17 )= .4374
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 11454.7
WCO= .645137 WHO= .034429 WOO= .184997 WNO= .135438


NOMINAL W( 18 )= .061
+10% OF NOM W( 18 )= .0671
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 15701.1
WCO= .836796 WHO= .058485 WOO= .184997 WNO=-8.02777E-2
-10% OF NOM W( 18 )= .0549
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 12766.3
WCO= .836796 WHO= .010373 WOO= .184997 WNO=-3.21657E-2


NCMINAL W( 19 )= .437
+10% OF NOM W( 19 )= .4807
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .357332 WNO=-.228557
-10% OF NOM W( 19 )= .3933
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= 1.26611E-2 WNO= .116114
```

```
NOMINAL W( 20 )= 8372
+10% OF NOM W( 20 )= 9209.2
MG= 57.4638 MO= 1[illegible].047 MW= 29.7492 HVO= 12608.6
WCO= .664634 WHC= 4.47003E-2 WOO= .322447 WNO=-3.58318E-2
-10% OF NOM W( 20 )= 7534.8
MG= 58.6015 MO= 18.528 MW= 42.0704 HVO= 17032.9
WCO= 1.13326 WHC= 9.84649E-3 WOO=-5.17633E-2 WNO=-9.13436E-2


NOMINAL W( 21 )= .77
+10% OF NOM W( 21 )= .847
MG= 63.873 MO= 24.671 MW= 30.796 HVO= 15086.2
WCO= .816189 WHO= 5.33032E-2 WCO= .303399 WNO=-.172891
-10% OF NOM W( 21 )= .693
MG= 52.1923 MO= 25.094 MW= 41.0237 HVO= 13423.7
WCO= .856255 WHC= 1.66061E-2 WOO= 7.31996E-2 WNO= .053939


NCMINAL W( 22 )= 0
+10% OF NOM W( 22 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
-10% OF NOM W( 22 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2


NCMINAL W( 23 )= 0
+10% OF NOM W( 23 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
-10% OF NOM W( 23 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2


NOMINAL W( 24 )= .23
+10% OF NOM W( 24 )= .253
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .218013 WNO=-8.92376E-2
-10% OF NOM W( 24 )= .207
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .151981 WNO=-2.32058E-2


NCMINAL W( 25 )= 0
+10% OF NCM W( 25 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2
-10% OF NOM W( 25 )= 0
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14233.7
WCO= .836796 WHO= .034429 WOO= .184997 WNO=-5.62217E-2


NCMINAL W( 26 )= .041
+10% OF NOM W( 26 )= .0451
MG= 57.8158 MO= 25.3845 MW= 36.0997 HVO= 14203.
WCO= .837539 WHO= 3.37489E-2 WOO= .180731 WNO=-5.20184E-2
-10% OF NOM W( 26 )= .0369
MG= 58.2491 MO= 25.3306 MW= 35.7203 HVO= 14264.4
WCO= .836054 WHO= .035109 WOO= .189262 WNO=-.060425


NCMINAL W( 27 )= 13713
```

```
+10% OF NOM W( 27 )= 15084.3
MG= 58.2455 MO= 22.8399 MW= 38.2146 HVO= 15087.8
WCO= .827253 WHO= 2.69284E-2 WOO= .112757 WNO=-6.69381E-2
-10% OF NOM W( 27 )= 12341.7
MG= 57.7671 MO= 23.4988 MW= 33.0341 HVO= 13379.6
WCO= .746339 WHO= 4.19296E-2 WOO= .257237 WNO=-4.55053E-2


NOMINAL W( 28 )= 21.7
+10% OF NOM W( 28 )= 23.87
MG= 58.0643 MO= 23.6604 MW= 35.4653 HVO= 14248.1
WCO= .827633 WHO= 3.68315E-2 WOO= .204677 WNO=-7.31918E-2
-10% OF NOM W( 28 )= 19.53
MG= 58.0011 MO= 27.0546 MW= 36.4144 HVO= 14221.1
WCO= .844766 WHO= 3.23279E-2 WOO= .164287 WNO=-4.13806E-2


NOMINAL W( 29 )= 100
+10% OF NOM W( 29 )= 110
MG= 57.8955 MO= 31.1266 MW= 40.2779 HVO= 14131.2
WCO= .838681 WHO= 3.23011E-2 WOO= .167542 WNO=-3.85237E-2
-10% OF NOM W( 29 )= 90
MG= 58.1598 MO= 19.5884 MW= 31.5417 HVO= 14396.5
WCO= .833801 WHO= 3.78103E-2 WOO= .212733 WNO=-8.43444E-2


NOMINAL W( 30 )= 36.4
+10% OF NOM W( 30 )= 40.04
MG= 63.9012 MO= 24.2975 MW= 34.7413 HVO= 14199.1
WCO= .827172 WHO= 3.61491E-2 WOO= .197143 WNO=-6.04633E-2
-10% OF NOM W( 30 )= 32.76
MG= 52.1641 MO= 26.4176 MW= 37.0784 HVO= 14265.6
WCO= .845648 WHO= 3.28469E-2 WOO= .173825 WNO=-5.23205E-2


NOMINAL W( 31 )= 4.6
+10% OF NOM W( 31 )= 5.06
MG= 58.0362 MO= 25.3154 MW= 36.4084 HVO= 14246.6
WCO= .838163 WHO= 3.43157E-2 WOO= .183905 WNO=-5.63836E-2
-10% OF NOM W( 31 )= 4.14
MG= 58.0291 MO= 25.3997 MW= 35.4112 HVO= 14220.9
WCO= .835434 WHO= 3.45413E-2 WOO= .186084 WNO=-5.60604E-2


NOMINAL W( 32 )= 54000
+10% OF NOM W( 32 )= 59400
MG= 58.0634 MO= 24.9234 MW= 36.3072 HVO= 14368.7
WCO= .851088 WHO= 3.32439E-2 WOO= .173583 WNO=-5.79149E-2
-10% OF NOM W( 32 )= 48600
MG= 57.996 MO= 25.7916 MW= 35.5125 HVO= 14103.3
WCO= .822985 WHO= 3.55742E-2 WOO= .196026 WNO=-5.45855E-2
```

ITERAT OUTPUT

```
RUN NUMBER 4


             N2             C             H2             O2             HV

GAS        .495           .191          .021           .303           2704
CHAR       .025           .751          .026           .089           10950
WATER       0              0            .110           .890           1140
FEED       .017           .486          .061           .437           8372
AIR        .770            0             0             .230           0

OIL INITIAL VALUES:   WNO = .041          HVO = 13713
TOTAL WEIGHT:         CHAR= 21.7          FEED= 100
                      AIR = 36.4          MOISTURE= 4.6
                      ENERGY LOSSES= 54000
WEIGHT FRACTIONS OF
   ELEMENTS IN OIL:   CARBON= .657         HYDROGEN= .071
                      OXYGEN= .242         NITROGEN= .04

CALCULATED VALUES ARE AS FOLLOWS:

INDICES=        NEW VALUES=
7                .72096
17               .45684
11               0
11               0
   MASSES:                 GAS = 57.7202         MOISTURE= 32.5261
                           OIL = 29.0537         HEATING VALUE IN OIL= 12118.
   WEIGHT FRACTIONS
   OF ELEMENTS IN OIL:  CARBON= .654465          HYDROGEN= 4.30859E-2
                           OXYGEN= .268373       NITROGEN= .034076
```

SENSAN LISTING

```
9 FILE #1="SENSAN"
10 FILE #4="RUN4",#5="RUN5",#6="RUN6",#10="RUN10",#11="RUN11"
11 FILE #13="RUN13",#14="RUN14",#15="RUN15",#16="RUN16",#17="RUN17"
12 FILE #18="RUN18"
20 DIM W(32),A(3,3),D(3,3),B(3),C(3),R(6),E(4),H(4),L(4),M(4),H1(4)
25 PRINT "RUN #"
26 INPUT N
30 MAT INPUT #N,W
40 PRINT "INITIAL RUN"
50 GOSUB 500
60 PRINT "MG=";R(1),"MO=";R(2),"MW=";R(3),"HVO=";H
70 PRINT "WCO=";R(4);"WHO=";R(5),"WOO=";R(6),"WNO=";W
80 PRINT "RUN?"
90 INPUT C
100 IF C=0 THEN 999
102 RESTORE #N
103 MAT INPUT #N,W
105 PRINT #1,"1"
110 PRINT #1," RUN NUMBER";N
111 PRINT #1
112 PRINT #1
113 PRINT #1,"          N2            C           H2             O2           HV'
114 PRINT #1
115 PRINT #1," GAS    ":W(1);"        ";W(2);"       ";W(3);"        ";W(4):"
116 PRINT #1," CHAR   ":W(6);"        ";W(7);"       ";W(8);"        ";W(9):"
117 PRINT #1," WATER     0            0           .110          .890         114(
118 PRINT #1," FEED   ";W(16);"        ";W(17):"        ":W(18);"       ";W(19):'
119 PRINT #1," AIR    .770            0             0           .230         0"
120 PRINT #1," OIL INITIAL VALUES:    WNO =";W(26);"             HVO =";W(27)
121 PRINT #1," TOTAL WEIGHT:          CHAR=";W(28);"             FEED=";W(29)
122 PRINT #1,"                        AIR =";W(30);"             MOISTURE=";W(31
123 PRINT #1,"                        ENERGY LOSSES=";W(32)
125 PRINT #1
130 PRINT #1," HV=HEATING VALUE"," "
131 PRINT #1," HVO=HEATING VALUE OF THE OIL"
132 PRINT #1," WNO=WT. FRAC. OF N2 IN OIL"
133 PRINT #1
134 PRINT #1
150 PRINT "INPUT %"
160 INPUT P
170 P=P*.01
190 FOR I=1 TO 32
195 PRINT #1," NOMINAL W(";I:")=";W(I)
200 RESTORE #N
210 MAT INPUT #N,W
220 W(I)=W(I)+P*W(I)
225 PRINT #1," +10% OF NOM W(";I:")=";W(I)
230 GOSUB 500
235 GOSUB 800
240 RESTORE #N
245 MAT INPUT #N,W
250 W(I)=W(I)-P*W(I)
251 PRINT #1," -10% OF NOM W(";I:")=";W(I)
253 GOSUB 500
255 GOSUB 800
256 PRINT #1
257 PRINT #1
260 NEXT I
265 GO TO 25
400 FOR J=1 TO 10
430 GOSUB 500
440 W(27)=H
450 NEXT J
460 RETURN
```

```
500 A(1,1)=W(1)
510 A(1,2)=W(26)
520 A(1,3)=W(11)
530 A(2,1)=1
540 A(2,2)=1
550 A(2,3)=1
560 A(3,1)=W(5)
570 A(3,2)=W(27)
580 A(3,3)=W(15)
590 C(1)=W(16)*W(29)+W(21)*W(30)-W(6)*W(28)
600 C(2)=W(29)+W(30)-W(28)+W(31)
610 C(3)=W(20)*W(29)-W(32)-W(10)*W(28)
620 MAT D=INV(A)
630 MAT B=D*C
640 R(1)=B(1)
641 R(2)=B(2)
642 R(3)=B(3)
650 X=W(19)*W(29)+W(14)*W(31)
660 R(4)=(W(17)*W(29)-W(2)*R(1)-W(7)*W(28))/R(2)
670 R(5)=(W(18)*W(29)+W(13)*W(31)-W(3)*R(1)-W(8)*W(28)-W(13)*R(3))/R(2)
680 R(6)=(X+W(24)*W(30)-W(4)*R(1)-W(9)*W(28)-W(14)*R(3))/R(2)
685 W=1-R(4)-R(5)-R(6)
686 H=(14500*R(4)+61000*R(5))
690 RETURN
800 PRINT #1," MG=";R(1);"MO=";R(2);"MW=";R(3);"HVO=";H
810 PRINT #1," WCO=";R(4);"WHC=";R(5);"WOO=";R(6);"WNO=";W
820 RETURN
999 END
```

ITERAT LISTING

```
9 FILE #1="FINALLY"
10 FILE #4="RUN4",#5="RUN5",#6="RUN6",#10="RUN10",#11="RUN11",#12="RUN12"
11 FILE #13="RUN13",#14="RUN14",#15="RUN15",#16="RUN16"
12 FILE #17="RUN17",#18="RUN18"
20 DIM W(32),A(3,3),B(3,3),P(3),C(3),R(6),E(4),H(4),L(4),M(4),H1(4)
25 PRINT "RUN #"
26 INPUT N
27 RESTORE #N
30 MAT INPUT #N,W
40 MAT INPUT #N,E
41 GOSUB 900
45 V=1000000
50 K=0
55 PRINT "ENTER I"
60 INPUT S
65 M(K+1)=W(S)
70 W(S)=.9*W(S)
75 H(K+1)=S
80 PRINT "MORE CHANGES?"
85 INPUT C
90 IF C=0 THEN 105
95 K=K+1
100 GO TO 55
105 L(1)=10
110 L(2)=10
115 L(3)=10
120 L(4)=10
125 FOR L=K+2 TO 4
130 L(L)=1
132 H(L)=11
135 NEXT L
140 FOR L=1 TO L(4)
145 FOR M=1 TO L(3)
150 FOR N=1 TO L(2)
155 FOR O=1 TO L(1)
160 GOSUB 400
165 IF R(1)<0 THEN 215
166 IF R(2)<0 THEN 215
167 IF R(3)<0 THEN 215
170 IF R(4)<0 THEN 215
171 IF R(5)<0 THEN 215
172 IF R(6)<0 THEN 215
173 IF W<0 THEN 215
180 Z4=(R(4)-E(1))**2+(R(5)-E(2))**2+(R(6)-E(3))**2+(W-E(4))**2
185 IF Z4>V THEN 215
190 V=Z4
195 H1(1)=W(H(1))
200 H1(2)=W(H(2))
205 H1(3)=W(H(3))
210 H1(4)=W(H(4))
215 W(H(1))=W(H(1))+.02*M(1)
220 NEXT O
225 W(H(1))=.9*M(1)
230 W(H(2))=W(H(2))+.02*M(2)
235 NEXT N
240 W(H(2))=.9*M(2)
245 W(H(3))=W(H(3))+.02*M(3)
250 NEXT M
255 W(H(3))=.9*M(3)
260 W(H(4))=W(H(4))+.02*M(4)
265 NEXT L
270 W(H(4))=.9*M(4)
271 T=H1(1)+H1(2)+H1(3)+H1(4)
272 IF T >0 THEN 295
```

```
275 PRINT #1," NEGATIVE WEIGHT FRACTION"
280 GO TO 25
295 PRINT #1," INDICES=","NEW VALUES="
299 FOR I=1 TO 4
300 PRINT #1,H(I),H1(I)
301 NEXT I
305 W(H(1))=H1(1)
310 W(H(2))=H1(2)
315 W(H(3))=H1(3)
320 W(H(4))=H1(4)
325 GOSUB 400
330 GOSUB 800
335 GO TO 25
400 FOR J=1 TO 10
430 GOSUB 500
440 W(27)=H
450 NEXT J
460 RETURN
500 A(1,1)=W(1)
510 A(1,2)=W(26)
520 A(1,3)=W(11)
530 A(2,1)=1
540 A(2,2)=1
550 A(2,3)=1
560 A(3,1)=W(5)
570 A(3,2)=W(27)
580 A(3,3)=W(15)
590 C(1)=W(16)*W(29)+W(21)*W(30)-W(6)*W(28)
600 C(2)=W(29)+W(30)-W(28)+W(31)
610 C(3)=W(20)*W(29)-W(32)-W(10)*W(28)
620 MAT D=INV(A)
630 MAT B=D*C
640 R(1)=B(1)
641 R(2)=B(2)
642 R(3)=B(3)
650 X=W(19)*W(29)+W(14)*W(31)
660 R(4)=(W(17)*W(29)-W(2)*R(1)-W(7)*W(28))/R(2)
670 R(5)=(W(18)*W(29)+W(13)*W(31)-W(3)*R(1)-W(8)*W(28)-W(13)*R(3))/R(2)
680 R(6)=(X+W(24)*W(30)-W(4)*R(1)-W(9)*W(28)-W(14)*R(3))/R(2)
685 W=1-R(4)-R(5)-R(6)
686 H=(14500*R(4)+61000*R(5))
690 RETURN
800 PRINT #1,"    MASSES:             GAS =";R(1),"MOISTURE=":R(3)
802 PRINT #1,"                        OIL =";R(2),"HEATING VALUE IN OIL=":H
804 PRINT #1,"    WEIGHT FRACTIONS"
805 PRINT #1,"    OF ELEMENTS IN OIL: CARBON=";R(4),"HYDROGEN=";R(5)
806 PRINT #1,"                        OXYGEN=":R(6),"NITROGEN=";W
820 RETURN
900 PRINT #1,"1"
901 PRINT #1," RUN NUMBER:";N
902 PRINT #1
907 PRINT #1
910 PRINT #1,"           N2        C          H2          O2         HV"
911 PRINT #1
912 PRINT #1," GAS     ";W(1);"     ":W(2);"     ":W(3):"     ":W(4):"     ";W
913 PRINT #1," CHAR    ";W(6);"     ":W(7);"     ";W(8):"     ";W(9):"     ";W
914 PRINT #1," WATER     0          0         .110       .890       1140"
915 PRINT #1," FEED    ";W(16):"     ";W(17);"     ";W(18);"     ";W(19);"
916 PRINT #1," AIR      .770        0          0         .230       0"
917 PRINT #1
918 PRINT #1," OIL INITIAL VALUES:  WNO =";W(26);"       HVO =":W(27)
920 PRINT #1," TOTAL WEIGHT:        CHAR=";W(28);"       FEED=":W(29)
922 PRINT #1,"                      AIR =";W(30);"       MOISTURE=";W(31)
923 PRINT #1."                      ENERGY LOSSES=":W(32)
```

```
925 PRINT #1," WEIGHT FRACTIONS OF"
926 PRINT #1,"    ELEMENTS IN OIL:  CARBON=";E(1);"       HYDROGEN=";E(2)
928 PRINT #1,"                      OXYGEN=";E(3);"       NITROGEN=";E(4)
930 PRINT #1
932 PRINT #1," CALCULATED VALUES ARE AS FOLLOWS:  "
934 PRINT #1
940 RETURN
999END
```

APPENDIX D

APPROXIMATE ANALYSIS OF BRAKE DE-RATING FACTOR

This appendix contains an approximate analysis of the brake de-rating factor for an unthrottled spark-ignition (SI) engine (Otto engine). The results are intended to be a guide for predicting the de-rating of the brake output power of the SI engine due to a change in the fuel.

BASIC ASSUMPTIONS

For an unthrottled SI engine operating on the hypothetical Otto cycle with a perfect gas as the working fluid, it can be shown that the thermal efficiency depends upon the specific-heat ratio of the gas and the engine compression ratio. Furthermore, the energy available to the engine--the heat transferred to the gas at constant volume--is considered to be the lower heating value of the fuel in the air-fuel mixture. (Values for this are given in the right-hand column of Table 7, page 64, for Stoichiometric mixtures of air and gasoline, natural gas and pyrolysis gas.) Thus, for a given engine (i.e., a given compression ratio) and for Stoichiometric mixtures of two different fuels and air, if the apparent specific-heat ratios for the mixtures are practically the same,

- the thermal efficiency will be practically the same for each air-fuel mixture; and therefore,
- the ratio of the net work (indicated work) done by each gas (air-fuel mixture) will be essentially the same as the ratio of the lower heating value of the fuel in a given volume of each of the two gases (air-fuel mixtures).

BRAKE DE-RATING FACTOR

In order to develop an approximate expression for the brake de-rating factor, it is convenient to make the following definitions:

IP_{RG} = indicated power produced by the reference gas (working fluid) at a given engine speed

IR_{TG} = indicated power produced by the test gas at a given engine speed

$FP = FP_{RG} = FP_{TG}$ = friction (includes water pump, generator, etc.) power required to drive the engine at a given speed--assumed independent of gas

BP_{RG} = brake power at a given engine speed for the reference gas

BP_{TG} = brake power at a given engine speed for the test gas

IDF = indicated de-rating factor at a given engine speed IP_{TG}/IP_{RG}

BDF = brake de-rating factor at a given engine speed = BP_{TG}/BP_{RG}

Noting that

$$BP_{RG} = IP_{RG} - FP \tag{D-1}$$

$$BP_{TG} = IP_{TG} - FP \tag{D-2}$$

the brake de-rating factor becomes

$$BDF = \frac{BP_{TG}}{BP_{RG}} = \frac{IP_{TG} - FP}{IP_{RG} - FP} \tag{D-3}$$

or, upon introducing the indicated de-rating factor, Eq. (D-3) becomes

$$BDF = \frac{IDF - FP/IP_{RG}}{1 - FP/IP_{RG}} \tag{D-4}$$

If the "friction" power is known as a fraction of the indicated power of the reference gas (i.e., FP/IP_{RG}) as a function of engine speed, the brake de-rating factor depends only upon the indicated de-rating factor. Noting that the indicated de-rating factor is equal to the ratio of the rate of net work done by the test gas to that done by the reference gas which, in turn, is essentially equal to the ratio of the lower heating value of the fuel in a given volume of the test gas to that of the fuel in this given volume of the reference gas, the indicated de-rating factor may be written as

$$IDF = \frac{LHV_{TG}}{LHV_{RG}} \qquad (D-5)$$

where

LHV_{TG} = lower heating value of the fuel in a given volume of the test gas
LHV_{RG} = lower heating value of the fuel in a given volume of the reference gas

Note that IDF is independent of engine speed.

From the data of Table 7 (page 64), using a Stoichiometric mixture of gasoline and air as the reference gas and a Stoichiometric mixture of simulated pyrolysis gas and air as the test gas, the indicated de-rating factor is

$$IDF = \frac{2.474 \text{ MJ/m}^3}{3.439 \text{ MJ/m}^3} = 0.72$$

Since the brake de-rating factor has been obtained for simulated pyrolysis gas (Table 6, page 63), it is possible to compute the "friction" power fraction FP/IP_{RG} as a function of engine speed from Equation (D-4).

Solving Equation (D-4) for FP/IP_{RG} gives

$$\frac{FP}{IP_{RG}} = \frac{IDF - BDF}{1 - BDF} \qquad (D-6)$$

Computed values of FP/IP_{RG}, using the data of Table 2, are given in Table D-1

Had data existed for $FP/IP_{gasoline}$, it would have been possible to estimate the brake de-rating factor for simulated pyrolysis gas by using Equation (D-4). For example, assuming that the factors in Table D-1 are correct, the brake de-rating factors for a test gas consisting of a Stoichiometric mixture of natural gas and air and a reference gas consisting of a

TABLE D-1. FRICTION POWER FACTOR

Speed (rpm)	$FP/IP_{gasoline}$	FP (kW)
1,500	0.20	6.4
2,000	0.30	12.6
2,500	0.30	15.4
3,000	0.26	15.7

Stoichiometric mixture of gasoline and air can be computed as follows:

- From Table 3, page 47, IDF is

$$IDF = \frac{LHV_{natural\ gas}}{LHV_{gasoline}} = \frac{3.101\ MJ/m^3}{3.439\ MJ/m^3} = 0.90$$

- From Equation (D-4), the data of Table D-1, and DF = 0.90, compute BDF. (The results of these computations are given in Table D-2).

TABLE D-2. BRAKE DE-RATING FACTOR--NATURAL GAS/GASOLINE

Speed (rpm)	Brake De-rating Factor (Natural Gas/Gasoline)
1,500	0.88
2,000	0.86
2,500	0.86
3,000	0.86

Noting that the brake de-rating factor is defined by

$$BDF_{SPG/G} = \frac{BP_{SPG}}{BP_G} = \frac{BP_{simulated\ pyrolysis\ gas}}{BP_{gasoline}}$$

or

$$BDG_{NG/G} = \frac{BP_{NG}}{BP_G} = \frac{BP_{natural\ gas}}{BP_{gasoline}}$$

it is clear that

$$\mathrm{BDF}_{\mathrm{SPG/NG}} = \frac{\mathrm{BP}_{\mathrm{SPG}}}{\mathrm{BP}_{\mathrm{NG}}} = \frac{\mathrm{BDF}_{\mathrm{SPG/G}}}{\mathrm{BDF}_{\mathrm{NG/G}}}$$

Thus, comparing the simulated pyrolysis gas with natural gas, the brake de-rating factor can be obtained from the data of Table 6 (page 63) and Table D-2. The results are given in Table D-3.

TABLE D-3. BRAKE DE-RATING FACTOR--SPG/NATURAL GAS

Speed (rpm)	Brake De-rating Factor (Sim. Pyrol. Gas/Natural Gas)
1,500	0.74
2,000	0.70
2,500	0.70
3,000	0.72