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GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION

PROJECT INITIATION

Date: April 15, 1975

Project Title: Development of a Prototype System for Pyrolysis of Agricultural Wastes into Fuels and Other Products

Project No.: B-446

Project Director: Dr. John W. Tatom

Sponsor: Environmental Protection Agency

Agreement Period: From 5/1/75 Until 11/30/75

Type Agreement: Grant No. R803430-01-0

Amount:
73,770 EPA
3,883 GIT (E-______-______)
77,653

Reports Required: Quarterly Progress Reports; Final Report

Sponsor Contact Person:

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Senior Mechanical Engineer
Solid & Hazardous Waste Research Laboratory
Environmental Protection Agency
National Environmental Research Center
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Other Sue Corbin
Bonnie Wettlaufer

RA-3 (3-75)

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OFFICE OF CONTRACT ADMINISTRATION

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SPONSORED PROJECT TERMINATION

Date: 8/16/78

Project Title: Development of a Prototype System for Pyrolysis of Agricultural Wastes into Fuels and Other Products.

Project No: B-446

Project Director: Dr. ~~John W. Tatom~~ K. Purdy

Sponsor: Environmental Protection Agency

Effective Termination Date: 4/30/77

Clearance of Accounting Charges: 8/31/78

Grant/Contract Closeout Actions Remaining:

X Final Invoice ~~and Closing Documents~~

X Final Fiscal Report

X Final Report of Inventions

_ Govt. Property Inventory & Related Certificate

_ Classified Material Certificate

_ Other ______

Assigned to: Technology & Development Laboratory (School/Laboratory)

COPIES TO:

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Division Chief (EES)
School/Laboratory Director
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Project File (OCA)
Project Code (GTRI)
Other ______

CA–4 (3/76)

B446

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

July 12, 1975

Mr. Don Oberacker
Municipal Environmental Research Laboratory
Office of Air, Land, and Water Use
Environmental Protection Agency
26 St. Clair Street
Cincinnati, Ohio 45268

Dear Don:

Enclosed please find the quarterly progress report for the period May 1, 1975 through August 1, 1975 under Grant R803403-01-0. If you have any questions please call me at (404) 894-3709.

Yours sincerely,

John W. Tatom
Project Director

JWT/edh

Enclosure (As stated)

QUARTERLY PROGRESS REPORT

GRANT R803403-01-0

"Development of a Prototype System for Pyrolysis of Agricultural Wastes into Fuels and Other Products"

For Period May 1, 1975-August 1, 1975

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

1.0 Discussion of Work Accomplished

During this reporting period, the following work was accomplished:

1) One hundred fifty tons of peanut hulls were transported from Cordele, Georgia to a storage site at the EES.

2) Seven tests, plus two shakedown tests were conducted using peanut hulls and sawdust as the feed material. A preliminary summary of these test results is shown in Table 1. A typical laboratory analysis of the products from one of these tests is presented in Table 2.

3) The integrated agitator/process air supply system has been designed and fabricated.

4) An unexpected result of the testing has been the low oil yields. Since previous tests have indicated that maximum bed depth provides greater oil yields, the tests have been conducted at near the maximum possible with the pyrolysis unit. Also to produce maximum char yields the air/feed ratio has been kept to a minimum. The result has been very low off-gas temperature (170-210°F) and apparently a large amount of oil condensation in the upper bed. This oil has subsequently been pyrolyzed as it moves downward with the production of large amounts of gas over that normally produced. It appears that the optimum bed depth for maximum oil production is considerably less than that used in these first tests.

5) Another result has been the relative unimportance of agitation on increased throughput. This is perhaps because both the sawdust and the peanut hulls are relatively free flowing materials, in constrast to feeds such as cotton gin trash.

2.0 Problems Encountered and Remedial Action

1) During the initial shakedown test with peanut hulls, the off-gas cyclone became clogged. Apparently the relatively large fraction of fine particulate material in the hulls led to a significant quantity of feed being transported from the convertor in the off-gas stream. Corrective action involved the design, fabrication, and installation of a scraping device which continuously removes any solid material follecting on the inner cyclone surfaces. After this action no further problems with the cyclone were encountered.

2) During the planned 16 hour endurance run a power failure occurred in the electrical system about twelve hours into the test. Since the run was going exceptionally smoothly at the time of the power failure and since little purpose would be gained in repeating the test, it is believed that this run essentially satisfies the wishes of the EPA for an endurance run and unless otherwise notified, the EES plans to substitute this 12 hour run for the originally planned 16 hour test.

3.0 Travel and Visits

During the reporting period, Mr. Don Oberacker from the EPA Cincinatti Laboratories together with two local EPA representatives visited the EES and observed one of the shakedown runs.

4.0 Discussion of Future Work

The principal activity of the next quarter will be the installation and test of the first generation integrated agitator/process air supply system. As part of these tests a study to determine the optimum bed depth will be made and further tests of the effects of agitation on throughput will be conducted. In addition, a reciprocating type agitator will be tested and a second generation integrated agitator/process air system will be designed and tested.

Table 1

Test Summary

Test No.	Feed	Feed Rate lb/hr	Total Feed lb	Char Yield %	Oil Yield %	Air/Feed	Test Lengths (hours)	Agitation
1	Peanut Hulls	1315	5262	20.7	3.9	.348	4	No
2	Peanut Hulls	898	3593	22.9	8.5	.256	4	No
3	Pine Sawdust	1569	4708	25.3	5.7	.163	3	No
4	Pine Sawdust	1022	3067	24.9	7.0	.251	3	Yes
5	Peanut Hulls	1183	14196	21.7	4.7	.271	12	Yes
6	Peanut Hulls	1109	3326	30	7.2	.264	3	Yes
7	Peanut Hulls	1096	3838	28.8	7.9	.228	3.5	Yes

TABLE 2

Laboratory Analysis--Test 6

	Percent by Volume							
	TEST 1				TEST 2			
Gas	Inter-grated	Grab 1 4:30 pm	Grab 2 4:45 pm	Grab 3 5:30 pm	Inter-grated	Grab 1 6:15 pm	Grab 2 6:45 pm	Grab 3 7:00 pm
O_2	4.88	3.00	3.57	3.28	3.89		3.92	3.27
N_2	49.60	42.90	46.30	44.60	48.90		51.10	48.40
CO	6.02	8.11	8.08	8.87	6.29		10.10	10.60
CO_2	16.8	20.90	18.30	17.70	20.30		18.80	19.80
H_2	11.40	14.30	13.70	13.00	11.40	12.50	7.79	7.38
CH_4	6.54	8.19	7.83	7.08	6.94	8.49	4.86	5.94
C_2	.47	.56	.53	.49	.51	.60	.51	.48
C_3	.59	.74	.69	.65	.57	.69	.50	.47
C_4	.17	.16	.18	.17	.20	.23	.19	.17
Total	96.50	98.90	99.20	95.60	99.00	-	97.80	96.50

Sample	Char 890	Oil 891
Percent Moisture	0.6	51.1
Percent Total Ash	9.8	-
Percent Carbon	73.6	57.6
Percent Hydrogen	1.8	8.6
Percent Nitrogen	2.7	6.5
Heating Values		
1st BTU/#	12976	19764
2nd BTU/#	12859	10758
Avg. BTU/#	12828	10761

B-446

ENGINEERING EXPERIMENT STATION

GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

November 10, 1975

Mr. Don Oberacker
Municipal Environmental Research Laboratory
Office of Air, Land, and Water Use
Environmental Protection Agency
26 St. Clair Street
Cincinnati, Ohio 45268

Dear Don:

Enclosed please find the quarterly progress report for the period August 1, 1975 through November 1, 1975 under Grant R803430-01-0. If you have any questions please call me at (404) 894-3709.

Yours Sincerely,

John W. Tatom
Project Director

JWT:sm

Enclosure (As stated)

QUARTERLY PROGRESS REPORT

GRANT R803430-01-0

"Development of a Prototype System for Pyrolysis of Agricultural Wastes into Fuels and Other Products"

For Period August 1, 1975-November 1, 1975

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia

1.0 Discussion of Work Accomplished

During this reporting period, the following work was accomplished:

(1) The integrated mechanical agitation system - process air supply system ("Airgitator") was designed, fabricated, operated, then modified and finally successfully tested.

(2) The test program was completed and the modified "Airgitator operated without incident for three tests and a total of more than 16 hours. A summary of the preliminary test results is presented in Table 1.

(3) Preliminary analyses of the test data has been made and while some corrections remain to be applied, present indications are that the available energy in the char-oil mix is very consistent with the earlier test results with wood waste obtained in the smaller pyrolysis unit (Blue II) from the RTP funded study. Figure 1 illustrates these preliminary analyses. If further analysis verifies these early results, this figure will take on special significance, since it indicates that the effects on product yields of changing feed material, pyrolysis unit scale, air tube geometry and bed depth and the use of agitation are all secondary compared to the effects of air/feed. In other words, this figure may be the definitive basis for predicting product yields for all feeds and all unit scales.

2.0 Problems Encountered and Remedial Action

(1) During the initial checkout of this "Airgitator", a failure in the drive system occurred due to unexpected torque loads. It was determined that because of the close approach to the unit walls of the end of the "Airgitator" a local binding due to packing of the feed occurred with the resulting overloads. The problem was remedied by trimming and

TABLE I

TEST SUMMARY

Test Number	Feed	Feed Rate lb/hr	% Char Yield	% Oil Yield	Air/Feed	Bed Depth	Agitation	Airgitation
1	Peanut Hulls	1316	20.7	3.9	.348	52	No	No
2	Peanut Hulls	898	22.9	8.5	.256	52	No	No
3	Pine Sawdust	1569	25.3	5.7	.163	52	No	No
4	Pine Sawdust	1022	24.9	7.0	.251	52	Yes	No
5	Peanut Hulls	1090	28.8	7.9	.227	52	Yes	No
6	Peanut Hulls	1107	30.3	7.2	.264	52	Yes	No
7	Peanut Hulls	1103	21.8	4.7	.258	52	Yes	No
8	CHECK OUT "AIRGITATOR"							Yes
9	Peanut Hulls	900	31.1	16.1	.356	36	Yes	No
10	Peanut Hulls	1105	19.4	4.53	.361	36	Yes	No
11	Peanut Hulls	1257	21.0	23.4	.419	36	Yes	No
12	Peanut Hulls	1038	22.1	17.8	.476	36	Yes	No
13	CHECK OUT MODIFIED "AIRGITATOR"							
14	Peanut Hulls	1150	38.6	3.8	.13	54	No	Yes
15	Peanut Hulls	762	26.5	26.8	.18	54	No	Yes

TOTAL OPERATING TIME = 119.5 hours

TOTAL FEED PROCESSED = 95,510 pounds

shaping the end of the Airgitator and by strengthening the drive mechanism.

(2) Another problem associated with the Airgitator also arose. This difficulty was associated with the relatively high velocity process air exiting through holes in the horizontal portion of the system. This air tended to entrain fine feed particles, some of which passed through the cyclone. In two separate occasions fire in the off-gas system occurred as a result of these fines. The remedial action was simple; e.g., the unit was lowered deeper in the porous bed which then tended to filter out the fines. A more permanent solution would be to enlarge the present holes and perhaps design the unit as T-shaped rather than L-shaped.

3. Travel and Visits

During the reporting period Mr. Don Oberacker and a representative from Poland visited the EES. Drs. Jim Knight and John Tatom made a presentation concerning project progress in Cincinnati on September 19.

4. Discussion of Future Work

The principal activity of the remaining time within the grant period will be the preparation of the final report.

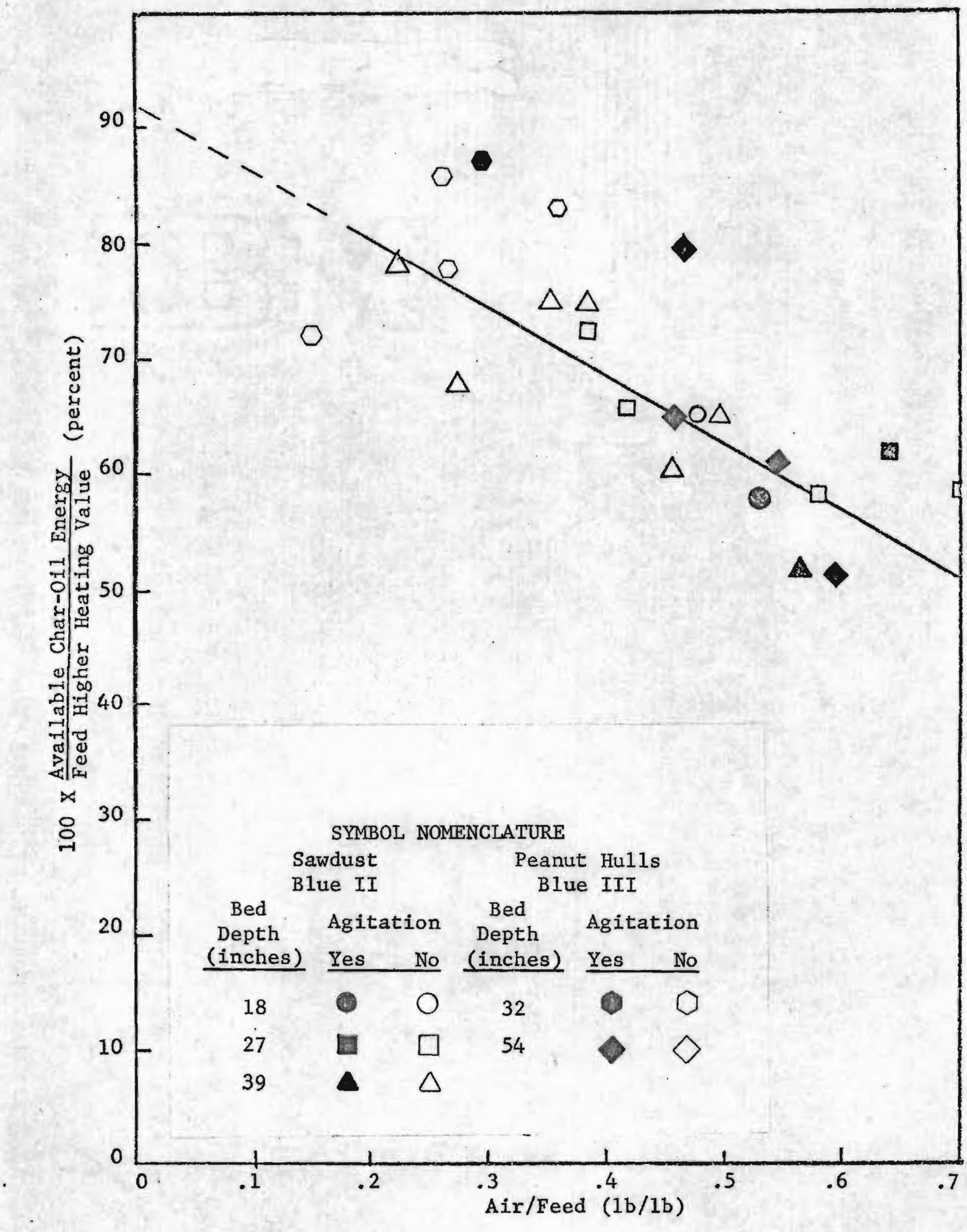


Figure 1
Percent Available
Energy in Char-Oil Mixture

B-446

ENGINEERING EXPERIMENT STATION
GEORGIA INSTITUTE OF TECHNOLOGY • ATLANTA, GEORGIA 30332

October 5, 1976

Dr. Walter W. Liberick, Jr.
Industrial Environmental Research Laboratory
Environmental Protection Agency
Cincinnati, OH 45268

Subject: Quarterly Letter Progress Report for the Quarter Ending September 30, 1976. Project B-446

Dear Dr. Liberick:

The following is a summary of the progress for each of the three main tasks.

Task 1 - Further Studies of the Potential of Process-Air-Mechanical Agitation System Integration

During this first quarter the process-air-mechanical agitator for the pyrolysis system was modified in two ways.

(1) A new simplified coupling which permits the introduction of the process-air and cooling water to the rotating agitator was designed and fabricated.

(2) The air discharge holes in the bottom of the agitator were enlarged.

These modifications were made primarily to increase the amount of process-air which could be introduced into the pyrolysis reactor through the rotating agitator.

The modified process-air-mechanical agitator was installed in the reactor and six test runs were scheduled to determine the operational characteristics of the pyrolysis system with this type of process-air introduction. The material used for these tests was dried pine sawdust which had to be substituted for the originally proposed peanut hulls since peanut hulls were no longer available when the program go-ahead was received. The six scheduled tests using the integrated process-air-mechanical stirrer were completed and samples of the feed material, char, oil and off-gas for each test have been analyzed.

Data reduction is in progress and the results of the mass and heat balances should be completed and reported in the next progress report.

Task 2 - Low-BTU Gas Engine Study

A small (approximately 100 horsepower) instrumented spark-ignition gasoline engine has been selected to determine the power available using a synthetic gas mixture which is typical of low-BTU pyrolysis gas. The engine has been fitted with a dual (pyrolysis gas/gasoline) carburetor. The synthetic low-BTU gas mixture has been received along with the necessary manifold and regulators to supply the engine with the gas. The present plan is to establish base-line data operating the engine on gasoline and then switch to the low-BTU gas for comparison.

Task 3 - Char-Oil Combustion Characteristics Tests

Arrangements have been made to obtain two tons of "high-volatile" char, one ton of "low-volatile" char and two drums (110 gallons) of pyrolysis oil from the Tech-Air Cordele facility. The ton of "low-volatile" char has been shipped to the ERDA Pittsburgh Energy Research Center and the two drums of pyrolysis oil should be shipped by October 8, 1976. Due to major component changes at the Cordele facility, it will not be possible to ship the two tons of "high-volatile" char before October 15, 1976.

Thiefed samples from seven drums of the "low-volatile" char, selected randomly from the 29 drums of Cordele char obtained for the EPA/ERDA combustion and emission tests, were analyzed for moisture and volatile matter content by the standard ASTM technique and the so-called Parr technique. For these seven drums, the average moisture content on a dry mass basis, is 3.80% (ASTM) or 4.03% (Parr) and the average volatile matter content, on a dry mass basis, is 6.25% (ASTM) or 4.78% (Parr). One of these seven drums (Drum No. 12) was retained for future reference.

As more definitive data from these three tasks are obtained, I will send them to you.

Sincerely,

Kenneth R. Purdy
Principal Research Engineer

KRP:bc

DEVELOPMENT OF A PROTOTYPE SYSTEM FOR PYROLYSIS OF AGRICULTURAL WASTES INTO FUELS AND OTHER PRODUCTS

A REPORT TO
MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO

Under Grant R 803430-01-0

October 1976

By
ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

Principal Authors

J. W. Tatom   A. R. Colcord

DEVELOPMENT OF A PROTOTYPE SYSTEM FOR PYROLYSIS OF AGRICULTURAL WASTES INTO FUELS AND OTHER PRODUCTS

A REPORT TO
MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO

Under Grant R 803430-01-0

October 1976

By
ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

Principal Authors

J. W. Tatom   A. R. Colcord

ABSTRACT

An experimental study of the performance of the one tonne/hr pyrolytic convertor located at the Georgia Tech Engineering Experiment Station has been conducted. Peanut hulls were used as the feed in a series of thirteen tests. In addition, two tests were conducted using sawdust. The objects of the test program were to determine the effects of scale, feed material, mechanical agitation, air/feed and bed depth on the product yields of the EES pyrolytic convertor. Also investigated was the performance of an integrated mechanical agitation-air supply system (AIRGITATOR) designed to improve the throughput of the unit.

From the tests, and after comparison with earlier smaller scale work with sawdust, it appears that changing feed and scale, and the use of mechanical agitation have little influence on the product yields. Bed depth, while not affecting the total potentially available energy in the char and oil, substantially influences the relative amounts of these products. The air/feed ratio again appears to be the dominant influencing variable and data from the present study and earlier work are shown to correlate to a single curve.

The influence on system performance of the integrated mechanical agitation-air supply system, while not investigated comprehensively, appears to be very favorable. Using this system, off-gas temperatures were raised, while stable operation was maintained at very low values of air/feed.

This report is submitted in fulfillment of EES Project Number B-446 in an initial reporting period. The work was supported under Grant Number R 803430-01-0 of the Environmental Protection Agency. Work was completed in December 1975.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

Symbols	Definition	Units
h	Enthalpy	kcal/gm
HV	Heating Value	kcal/gm
L	Losses (see equation 2)	kcal
M	Mass	gm
w	Weight Fraction	gm/gm

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

ACKNOWLEDGEMENTS

This effort was supported by the Municipal Environmental Research Laboratory of the Environmental Protection Agency under Grant R 803430-01-0. We wish to express our appreciation to Mr. Donald A. Oberacker of MERL for his many contributions and suggestions. And a note of thanks is offered to Ms. Beth Lanier for her invaluable assistance in the preparation of this document.

SECTION I

CONCLUSIONS

From the results of this work the following conclusions can be drawn:

- The effects of the air/feed ratio on product energy yields appears to be dominant; changing scale and feed material, and the effects of mechanical agitation are of minor importance compared with air/feed.
- The available energy in the char-oil mixture appears from the results of this and earlier work to be a single function of air/feed; all the data correlated to a common curve.
- While the total energy in the char-oil mixture is a function only of air/feed, the relative amounts of char and oil can be changed significantly by varying the bed depth.
- The processing of peanut hulls through the convertor presents no problems either with or without the use of mechanical agitation.
- The integrated mechanical agitation-air supply system or "AIRGITATOR", which was tested successfully, appears to offer many advantages in increased through-put, operating stability and off-gas temperature at very low values of air/feed. The ability of this system to allow continuous variation in the bed depth provides an additional, significant and attractive feature.
- The overall mass, energy, and chemical balances appear to be satisfactory; thus giving confidence to the results of the testing.

SECTION II

RECOMMENDATIONS

The results of the study further reinforce the attractiveness of the mobile pyrolytic convertor concept by providing additional operating data and basic understanding of the physical processes at work. However, while the design, fabrication and test of the complete mobile system can be initiated in the very near future, several technical studies should be made before this final phase begins. These include:

(1) an investigation of the operating and ignition characteristics and derating required of a modified gasoline engine operating on the low heating value gas.

(2) a study of the burning characteristics of the char-oil mixture in various combinations with coal and petroleum oil.

(3) further development and test of the integrated mechanical agitation-air supply system (AIRGITATOR) evaluated in the current work.

When these studies have been completed, successfully, the design, fabrication and test of the full-scale mobile pyrolysis converter itself should be initiated. Upon successful operation of this component the complete mobile system should be designed and constructed.

SECTION III

INTRODUCTION

GENERAL

This report describes an experimental program designed to improve the technology required for the development of a mobile pyrolysis system for conversion of agricultural and forestry wastes at the site of their production into a clean and easily transportable fuel. The program involves a series of tests using peanut hulls, primarily, as the feed in the one tonne/hr Georgia Tech Engineering Experiment Station (EES) pyrolytic convertor pilot plant and is 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 lb/hr) EES pilot plant.

RATIONALE FOR MOBILE PYROLYSIS CONCEPT

Agricultural wastes, while representing a huge potential source of energy for the U. S., have certain adverse characteristics which have limited their use as fuels in the past and which must be dealt with in any successful energy conversion system. These characteristics include the facts that:

- Agricultural waste (organic matter) is typically quite wet, containing 30 to 70 percent water and therefore relatively low in heating value per pound.
- Since these materials would be scattered all over the countryside, the transportation costs per kcal to large thermal conversion plants would be very high.
- Because of the water content of these raw materials, the use of existing thermal conversion equipment is doubtful, at least at its rated capacity. Most likely new or modified facilities would 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 there is a serious conversion penalty using these as-received, wet materials.)

- 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, not continuously. Thus a steady supply of fuel from these wastes is not available and also it is impractical to tie-up capital 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. While initially the waste producer may be spending two to five dollars per tonne of raw wastes for disposal, he may hesitate or refuse in a long term contract to give away, or perhaps pay a disposal charge for his wastes. And clearly, once a facility for waste utilization has been constructed, the waste producer, upon termination of the original contract, has the waste utilizer in an uncomfortable economic position.

One solution to these problems is to utilize a mobile pyrolysis system that could be transported to the site of the 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 weight reduction and the associated transportation costs thereby affected would be very substantial. A further benefit to be derived is that since the system is portable it would provide greater leverage for 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 forestry 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.

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 the pyrolysis occurs 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 pounds) of a powered char-oil fuel, similar to coal, with a heating value of 6.00 to 9.00 kcal/gm (11,000-13,000 Btu/lb.) Thus, depending upon the feed moisture content, the energy available for use at the central thermal conversion plant could be 75 to 80 percent of that theoretically available from the original dry waste; and, using a boiler conversion efficiency of 80 to 85 percent, the overall steam-side efficiency of the process could be 65 to 70 percent. Hence the percent of useable energy could be as large and perhaps larger than 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. It could be blended with cheaper high sulfur coal to produce an additional economic advantage.

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

(1) The application of the mobile pyrolysis concept to large barges* moving on the thousands of miles of inland and intercoastal waterways appears to have great promise. This would not only permit an increase in the scale of the mobile system but would also allow its application to the municipal waste of smaller communities which presently cannot individually justify or afford a large, economical waste conversion system, but which in groups could successfully operate such a system.

(2) The char-oil fuel produced by the mobile pyrolysis system was considered primarily in (1) 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 the ERDA, Pittsburgh Labs (8) that 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 minimum 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 as a boiler fuel.

These two considerations should have relatively little influence on the planned development program for the portable system, but strengthen significantly the justification for the portable concept with production of the char-oil fuel.

OBJECTIVES

The investigation, which was primarily experimental, had several objectives, i.e.

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

- To determine the effects of scale on pyrolytic convertor performance.
- To determine the effects of changing feed material on pyrolytic convertor performance.
- To determine the effects of mechanical agitation on pyrolytic convertor performance.
- To determine the performance of an integrated mechanical agitation-process air supply system.
- To determine the influence of air/feed and bed depth on product yields.

In the following sections a description of the study is presented.

SECTION IV

TESTING

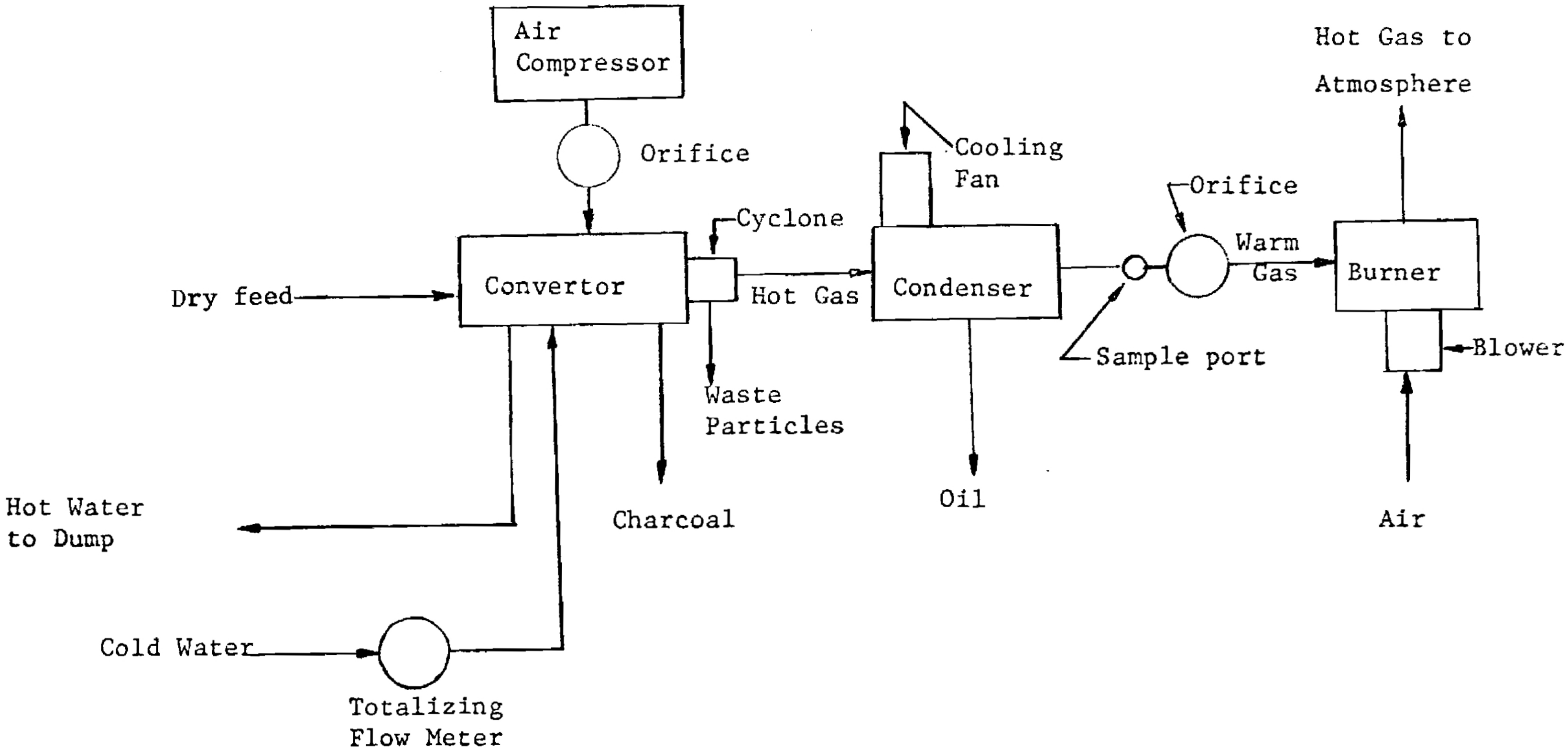
GENERAL

The 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 13 tests and sawdust was used in 2 tests, for a total of 15 tests in the complete study. All told, approximately 45.5 metric tons (50 tons) of hulls were used in the program. The tests involved investigation of the influences of scale, feed, air/feed, mechanical agitation and bed depth on product yields. In addition, the performance of an integrated mechanical agitation-process air system on product yields and process rates was studied. This section presents a description of the test facilities, the calibration and test procedure, the laboratory procedure, the data reduction methodology and the results of the 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 then 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 is 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 convertor 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



EES Pyrolytic Unit Process Flow Diagram

Figure 1

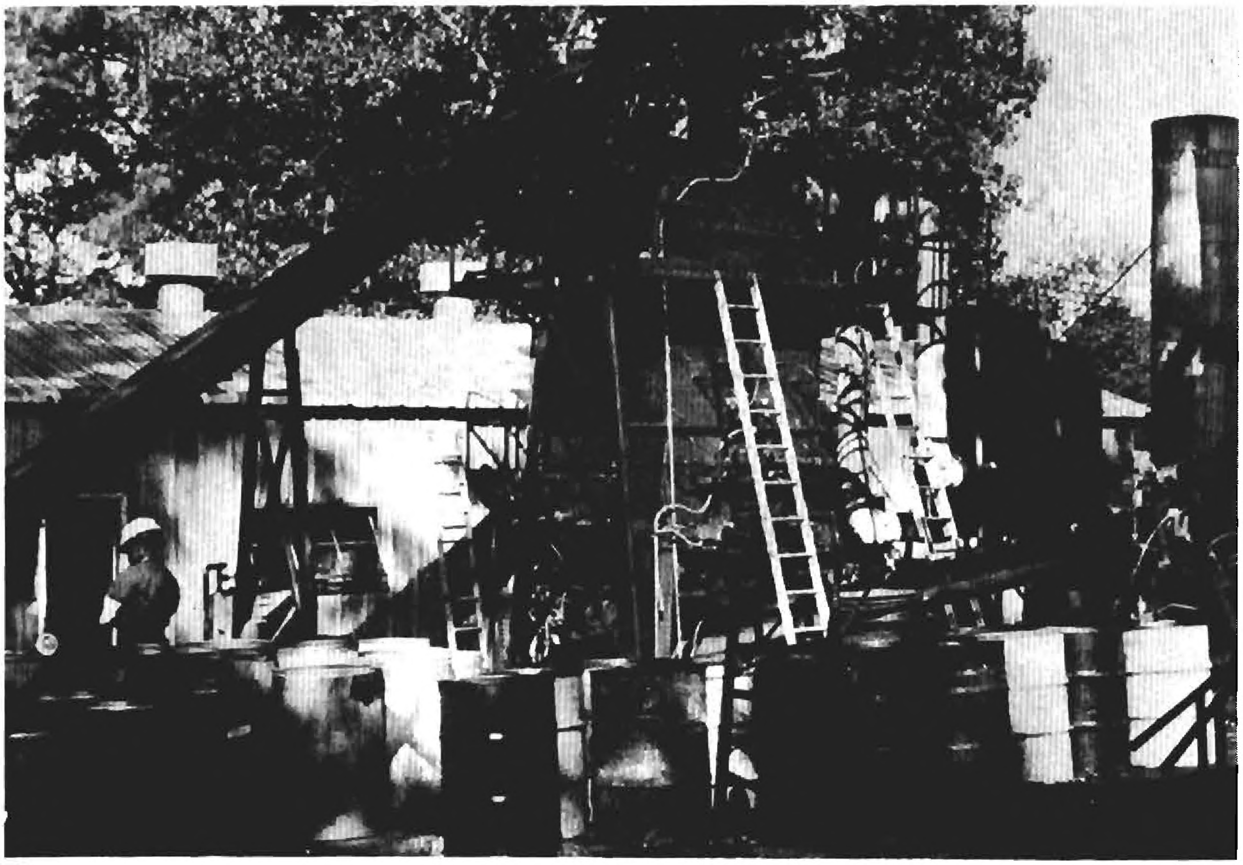


Figure 2
Fourth EES Pyrolytic Pilot Plant.

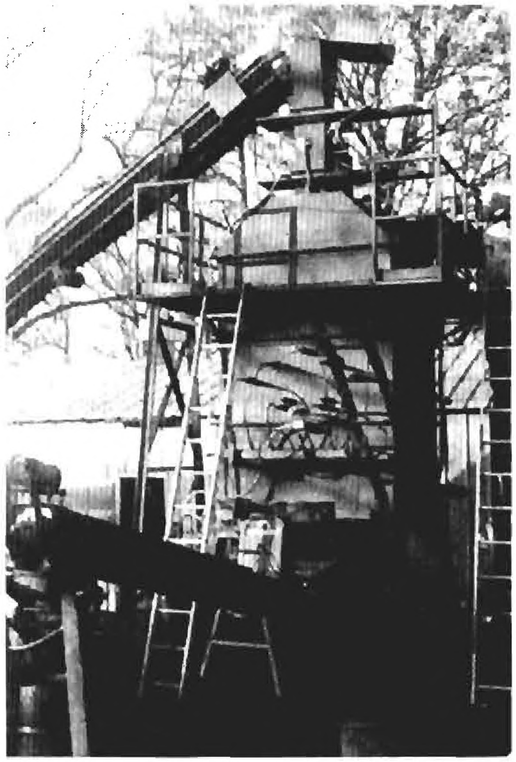


Figure 3

Close-Up View of EES Pyrolytic Converter

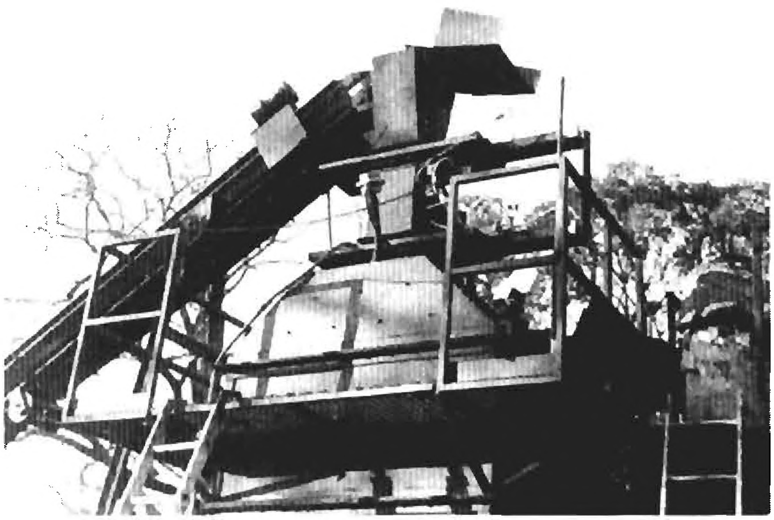


Figure 4

Close-Up View of Conveyer and Input System - EES Pyrolytic Converter

Figure 5

Close-Up view of Cyclone and Condenser System - EES Pyrolytic Converter

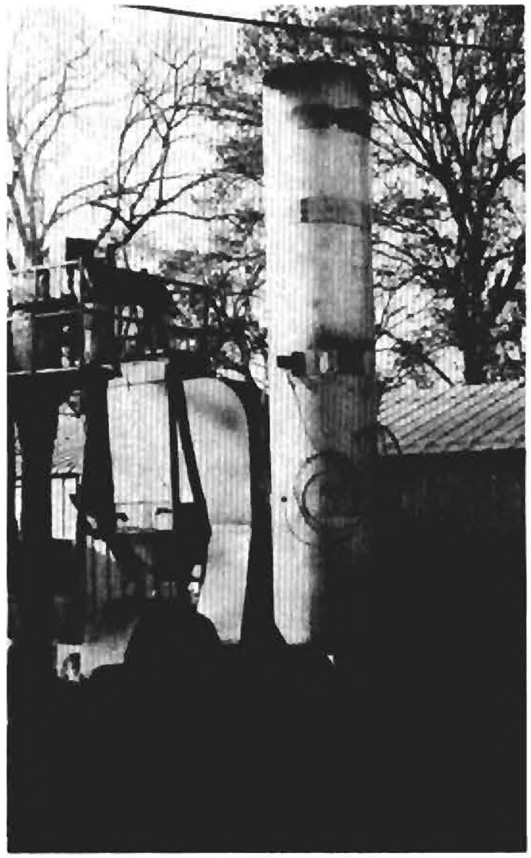


Figure 6

Close-Up View of Off-Gas Burner- EES Pyrolytic Converter 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 un-condensed oils, the water vapor, some condensed oil droplets and the non-condensible 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/feed ratio.

The instrumentation used in the study includes:

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

The system operates at a few centimeters of water below ambient; thus any leaks present generally result in the introduction of air into the system. However, within the cavity between the sliding plates of the gate valve, the displacement of the pyrolysis gas by the input feed does result in some lost gas when the gate valve operates. As the process rate of the unit increases, the gas production increases and the 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 for 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 gate valve cycles only upon demand, not continuously; hence the gases lost through this 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 the cooling air flow. In all but the last tests the condenser was operated at about 93°C (200°F), however, to determine the influence of condenser temperature an oil yields, the condenser temperature was dropped to 77-82°C (170-180°F) in the last test. It has been observed that oil droplets are frequently carried in suspension through the off-gas system, past the draft fan and into burner. This results in some loss of oil; however, analytical techniques are 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 convertor 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 RPM.

In the latter phase of the testing, an integrated mechanical agitation-process air system (AIRGITATOR) was also tested. A schematic view of this system is shown in Figure 8. The system is driven by the same gear drive as the simpler agitator and is described in more detail in Section V.

It might 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 in the stream which make conventional instrumentation techniques impractical. Instead, analytical techniques involving nitrogen, carbon, hydrogen and oxygen balances were used to compute the flows of the various constituents which make up the off-gas stream.

CALIBRATION AND TEST PROCEDURE

Prior to the testing many elements of the system instrumentation were carefully calibrated. The accuracy of some components such as the thermocouples, however, was not checked since the required 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. However, 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 sufficiently

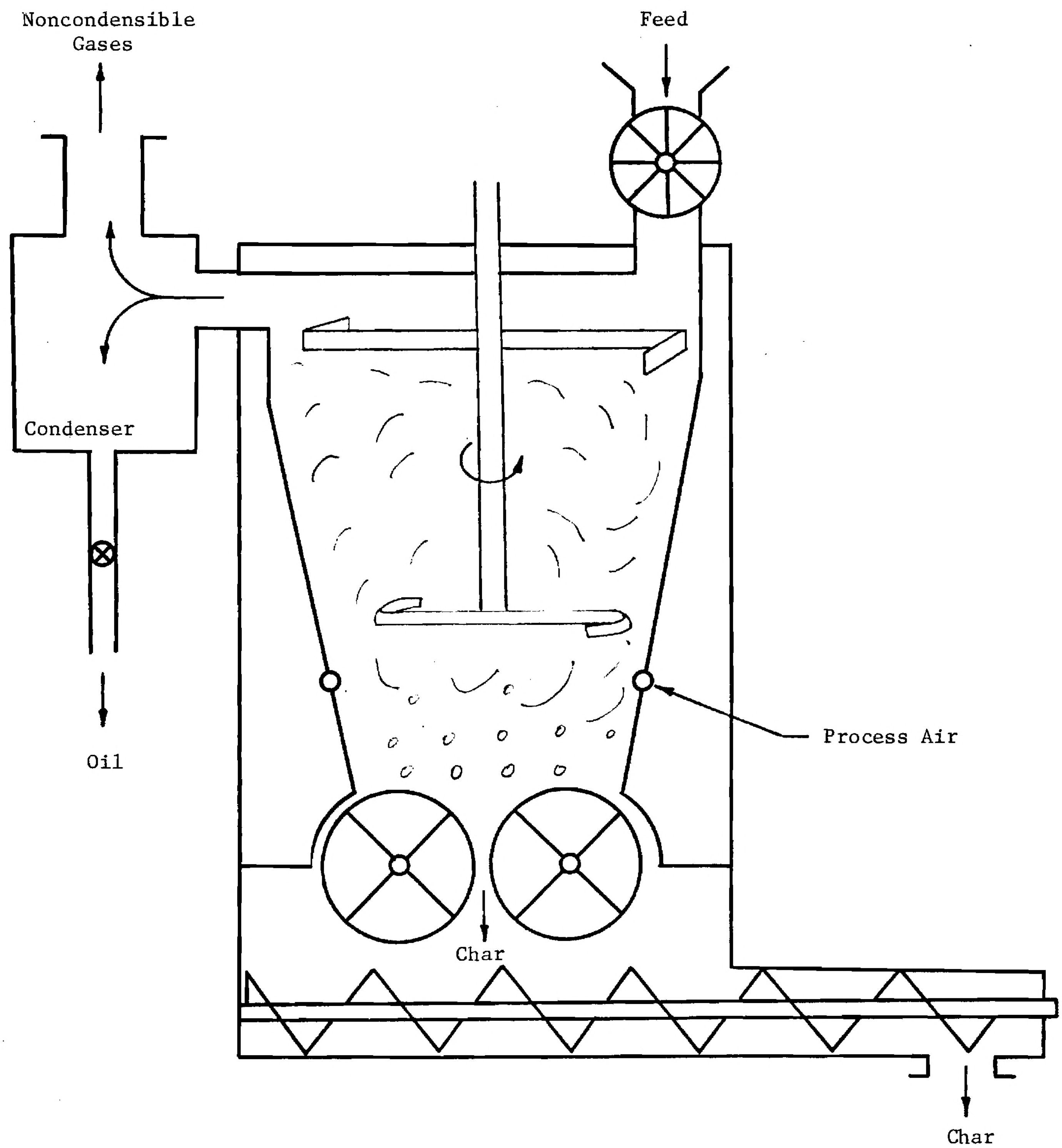


Figure 7

Schematic of EES Convertor with Rotating Agitator

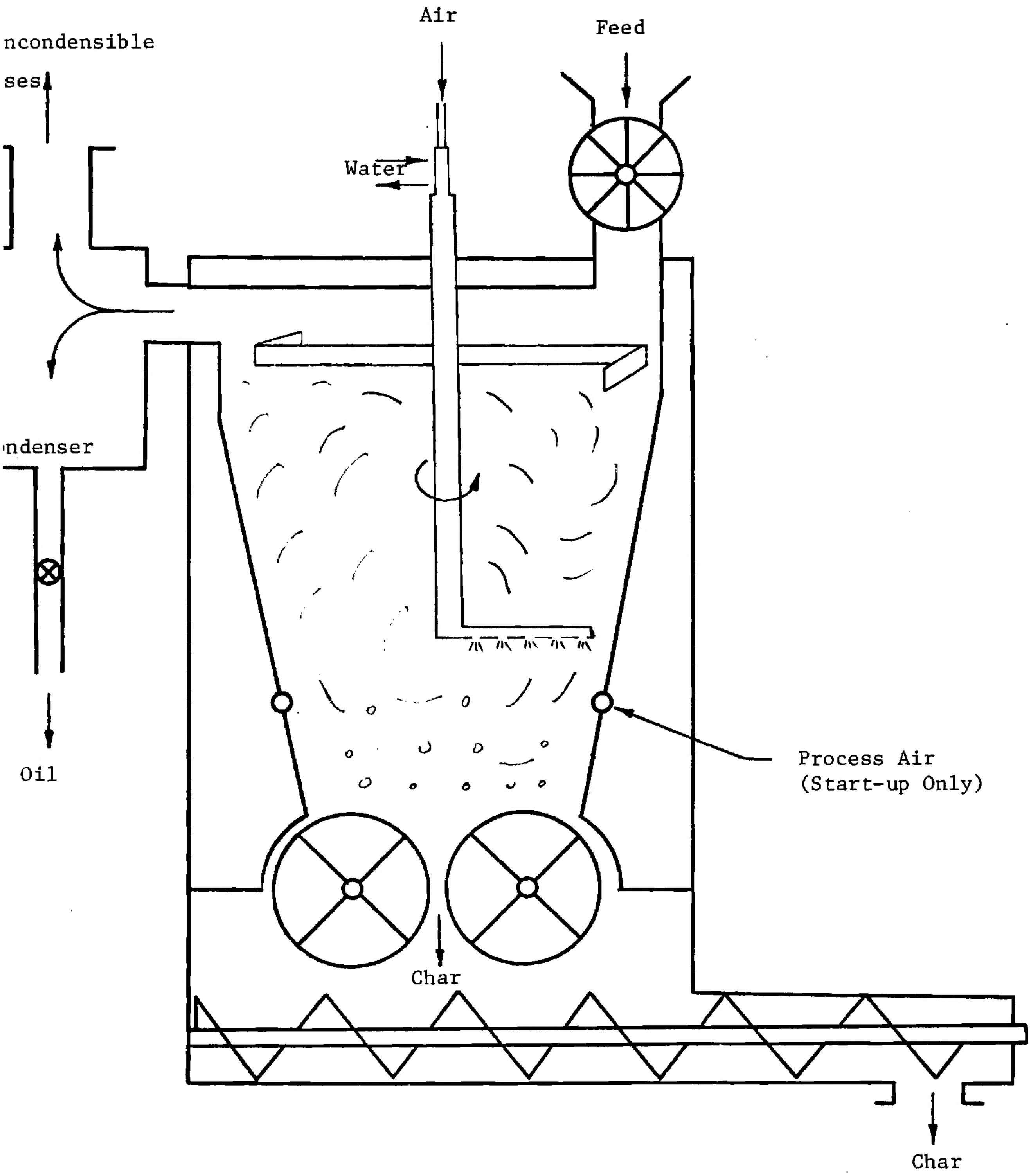


Figure 8

Schematic of EES Convertor with Integrated

Mechanical Agitation - Air Supply System

elevated the process air was introduced slowly and the element 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 operating capacity chosen for the test. Likewise, the process air feed rate was adjusted to correspond to the desired ratio of air-to-feed for the test. The system was then allowed to come to a steady-state condition, which required 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 the ability to establish a given feed process rate and given air-to-feed ratio was limited to a tolerance of plus or minus about 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-gasses was taken. Every effort was made to insure that the unit remained 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 its completion all of the char and oil produced were collected and representative samples of each obtained. The char sample was obtained by use of a grain sampler. The oil was collected in a large drum, mixed throughly and a sample of about one-half liter (one pint) taken. All of the feed grab samples were mixed and cut using a rifle splitter to obtain a composite sample of about one kilogram.

LABORATORY TESTING

The laboratory played a vital role in the determination of the feed and products characteristics and in the subsequent analysis of the data. Thus the work was checked carefully and every precaution made to insure the accuracy of the results. However, despite these efforts there are occasional instances where inconsistencies did arise. While 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 and 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. While these variations are predominantly less than one percent, the overwhelming impression is of good repeatability. The presence, expecially in the CHNO analysis, of even small inconsistencies was found to have a significant effect on the test results. Thus, while these data by ordinary standards stand up well, 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
- percent C_3 components
- percent C_4 components

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 itself 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 was 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 is 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 and 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 non-condensible 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 can be written. These equations have been solved on the computer and the calculated results 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 data into a generally consistent form. Since it must be recognized that all the data is 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 is generally consistent with earlier results (1) and shows an acceptable degree of scatter).

Analysis

The equations used in the data analysis include

Conservation of Mass:

$$*M_g + M_o + M_{ch} + M_{wo} = M_f + M_a + M_{wi} \tag{1}$$

Conservation of Energy:

$$(HV_g + h_g) M_g + (HV_o + h_o) M_o + (HV_{ch} + h_{ch}) M_{ch} + h_{wo} M_{wo} =$$
$$(HV_f + h_f) M_f + h_a M_a + h_{wi} M_{wi} - \text{[conduction and cooling water losses]}$$

*A table of Nomenclature is presented on page vi.

By establishing ambient conditions as a reference, h_f and h_a can be set to zero. Now generally the sensible and latent heat terms involving h_g, h_o, h_{ch}, and h_{wi} and the heat losses are small in comparison to the other terms. Thus 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:

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

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

Conservation of Nitrogen:

$$w_{ng} Mg + w_{no} M_o + w_{nch} M_{ch} = w_{nf} M_f + w_{ha} Ma \quad (3)$$

Conservation of Carbon:

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

Conservation of Hydrogen:

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

Conservation of Oxygen:

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

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

$$HV_o = 14,500 w_{co} + 61000 w_{ho} \quad (7)$$

The C, H, N, O analysis of the oil requires that:

$$w_{co} + w_{ho} + w_{no} + w_{oo} = 1 \quad (8)$$

Likewise the C, H, N, O analysis of the char and feed requires that:

$$w_{cch} + w_{hch} + w_{nch} + w_{och} = 1 - w_{xch} \quad (9)$$

$$w_{cf} + w_{hf} + w_{nf} + w_{of} = 1 - w_{xf} \quad (10)$$

Correspondingly, a computed C, H, N, O composition of the off-gas from the gas chromatographic results requires that:

$$w_{cg} + w_{hg} + w_{ng} + W_{og} = 1 \quad (11)$$

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

The procedure, therfore, 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_{och}, 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).

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

**The C, H, N, O composition of the oil and its heating value have been chosen as "unknowns" because it is believed there is greater uncertainty in the measured oil composition and heating value than for the feed, char or gas (which could have just as easily been used) due to the presence of water.

Once values of the eight "unknowns' are determined, a sensitivity analysis by which the effect on the computed values of the "unknowns" of individual variations in each of the 26 "known" coefficients is conducted. Those coefficients, which have a major influence on the solution, are thereby identified. Since the final object is to obtain as internally consistent a set of data as possible, the next step is a least squares procedure by which variations between the measured and computed values of w_{co}, w_{ho}, w_{no}, and w_{oo}, are minimized. This is accomplished by introduction of combinations of up to four of the major influencing coefficients and by allowing the values to vary simultaneously about their "known" value, usually within bounds of $\pm$ 10%. A least squares program then selects that combination of the major influencing coefficients while minimizes the sum of the squares of the difference between the computed and measured data. This generally results in a complete set of transformed data which is very nearly consistent internally and which represents an exact solution to the first eight equations.

In one case, Test 14, variations in the "known" coefficients of considerably more than 10% were required to bring the system of equations in a proper balance. This occurred both with the char and the feed carbon content which was adjusted significantly. However, since the modified data for this case (as seen in the next section) plots up well with all the other results, it is believed that whatever the cause of this anomaly, the applied correction is made apparently in the proper term and to the required extent.

Presented in Appendix C are listings of the computer programs for the sensitivity analysis (SENSAN) and the least squares procedure (ITERAT) developed from the analysis. Also presented are sample calculations for Test 1 (Run 4) to illustrate the output of these two programs.

TEST RESULTS

Overview of Test Conditions

The experimental program involved a series of 15 tests; 13 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 the first part of the study. Of the 15 reported tests, two were checkouts of the first generation integrated mechanical agitation-process air supply system or "AIRGITATOR", for which no quantitative data was recorded. Besides these two tests, two more were found to have defective off-gas compositions, apparently due to an air leak somewhere in the system. Thus while some data for these latter two tests were obtained, the primary basis for the results presented in this section is the 11 remaining tests.

Of the 11, ten were conducted using the hulls, and one with sawdust. There was one extended run of 12 hours using hulls (Test 7), but normally the runs lasted two to three hours, sometimes slightly more or less. In addition, two of the 11 were conducted using the "AIRGITATOR". In the 9 basic tests, the influence of mechanical agitation, changing feed material, changing bed depth and the air/feed ratio was studied. In the last two tests, the performance of the "AIRGITATOR" was evaluated at a fixed bed depth.

Table 1 presents a summary of the test conditions, along with some of the observed data from the pilot plant tests. Study of the table shows that basic agitation was involved in eight of the 15 tests conducted, while three were completed without any form of agitation. Four tests were made with the "AIRGITATOR".

TABLE I

TEST SUMMARY

Test Number[1]		Feed Rate kg/hr	Char Yield kg/kg dry feed	Oil & Aqueous Yield kg/kg dry feed	Off-Gas Yield kg/kg dry feed[2]	Air/Feed	Off-Gas Temp.[3] (°C)	Average Maximum Measured Bed Temperatures (°C)[4]	Bed (cm) Depth	Agitation	Airgitation
1	Peanut Hulls	572	21.7	.039	1.108	.364	96	649	132	No	No
2	Peanut Hulls	390	23.9	.085	.941	.265	93	732	132	No	No
3	Pine Sawdust	676	26.6	.057	.849	.172	113	760	132	No	No
4	Pine Sawdust	464	24.9	.070	.932	.251	140	732	132	Yes	No
5	Peanut Hulls	494	28.8	.079	.86	.227	86	649	132	Yes	No
6	Peanut Hulls	481	32.1	.072	.884	.277	85	716	132	Yes	No
7	Peanut Hulls	476	22.9	.047	.994	.270	88	704	132	Yes	No
8					CHECK OUT "AIRGITATOR"					No	Yes
9	Peanut Hulls	408	40.0	.161	.897	.458	78	960	89	Yes	No
10	Peanut Hulls	501	24.9	.0453	1.17	.464	88	560	89	Yes	No
11	Peanut Hulls	570	27.0	.234	1.035	.539	87	682	89	Yes	No
12	Peanut Hulls	471	28.4	.178	1.151	.613	83	787	89	Yes	No
13					CHECK OUT MODIFIED "AIRGITATOR"					No	Yes
14	Peanut Hulls	490	41.4	.035	.691	.140	174	471	127	No	Yes
15	Peanut Hulls	324	28.3	.262	.645	.190	226	471	127	No	Yes

TOTAL FEED PROCESSED = 43,400 kg

TOTAL OPERATING TIME = 119.5 hours

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

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

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

[4] The indicated temperatures correspond to the average maximum measured by the thermocouples in the lower bed of the convertor. Since the temperature of the bed varies both three dimensionally in space and also in time (due to variations in the environment near the sensing element) the quantitative significance of the specific indicated temperatures is doubtful. They are presented however for completeness and to indicate the range of temperatures encountered. Study of the data does indicate a general trend of increasing temperature with increasing air/feed, however there is considerable scatter.

Further, it is seen that testing was conducted at two bed depths, i.e. 127-132 cm (50-52 inches) and 89 cm (35 inches). The air/feed varied from 0.14 to 0.613; a range within which most operations would be found. Study of the off-gas temperatures indicates they were generally in the range of 77 to 88°C, except the two tests with sawdust which ran somewhat hotter. While not reported, the condenser thermostat temperature was usually set in the range of 93 to 99°C except in the last test where it was set at 99°C to determine the influence of condenser temperature on oil recovered.

Additional study of the table shows that the dry feed rates varied from slightly over 300 kg/hr (700 lb/hr) to nearly 700 kg/hr (1,5000 lb/hr). One puzzling result is the wide variation in the recovered oil and aqueous phases from the condenser. Reference to Appendix reveals that sometimes the water content is quite significant, and other times it is small. Apparently minor variations in the off-gas and condenser temperatures can produce significant changes in the oil yield exists, it is believed, in the form of more volatile hydrocarbons, the recovered yields (on a dry basis), with the exception of Test 15, are generally much smaller than the computed yields, as discussed in the following section.

In the course of the testing, almost 42,000 kgm (100,000 pounds) of feed were consumed and the unit was operated for a total of 119.5 hours.

Analysis of the Data

Besides the data shown in Table 1, the laboratory analysis of the feed, char, oil and non-condensible off-gas are presented in Appendix A. The data from these tables was 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. This transformed data is presented in Table 2 and is the basis for all further discussion of the testing. Shown also in the table, in parentheses, are the amounts the transformed data was changed from the original. Inspection reveals that only a minor part of the data has been modified and the changes are generally small.

While many of the modifications appear to be random, there is a rough pattern to some of the changes. For example, there appear to be relatively frequent reductions of the order of 8 percent on 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 where the carbon content of the feed and the heating value of the feed must be increased about 6 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, are 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, which 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 7.408 kcal/gm (13,335 Btu/lb). Regarding the laboratory reported

Table 2

Summary of Transformed Data

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
(Gas)												
N_2	gm/gm	.485	.530 (-8%)	.382 (-8%)	.442	.434	.517 (-8%)	.574	.478	.510 (-8%)	.396	.351
C	gm/gm	.191	.199	.258 (-2%)	.194	.201	.199	.163	.189	.199	.216	.218
H_2	gm/gm	.021	.021	.027	.028	.028	.017	.019	.017	.016	.018	.011
O_2	gm/gm	.303	.289	.364	.336	.338	.306	.244	.314	.314	.369	.422
HV	kcal/gm	1.5	1.488	1.966	1.528	1.528	1.333	1.317	1.283	1.406 (-8%)	1.322	.856
(Char)												
N_2	gm/gm	.025	.021	.011	.029	.027	.027	.008	.008	.011	.011	.007
C	gm/gm	.721 (4%)	.829	.844	.724	.795 (-8%)	.677 (8%)	.808 (-8%)	.809 (-4%)	.773	.393 (-50%)	.818 (-4%)
H_2	gm/gm	.026	.018	.017	.017	.016 (5.5%)	.018	.015	.013	.009	.018	.014
O_2	gm/gm	.089	.032	.064	.165	.121	.121	.103	.031	.089	.115	.091
HV	*kcal/gm	6.111	7.111	7.333	6.778 (10%)	7.000 (2%)	6.722	6.611	6.833	6.389	6.944	6.889
(Feed)												
N_2	gm/gm	.017	.021	.001	.012	.012	.012	.012	.012	.012	.007	.007
C	gm/gm	.457 (6%)	.462 (2%)	.450 (2%)	.445 (6%)	.473	.444 (8%)	.464 (4%)	.444 (8%)	.483	.304 (40%)	.466 (8%)
H_2	gm/gm	.061	.058	.054	.057	.057	.059	.059	.059	.059	.061	.061
O_2	gm/gm	.437	.452	.488	.457	.458	.446	.446	.446	.446	.427	.427
HV	kcal/gm	4.650	4.400	4.294 (6%)	4.539	4.628 (-2%)	4.778 (2%)	4.583 (6%)	4.389 (10%)	4.778 (2%)	4.728	4.728

*Not ash free; on dry basis

Table 2 - Continued

	Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
	WEIGHT FRACTIONS OF ELEMENTS IN OIL												
Measured	N_2	gm/gm	.040	.047	.016	.029	.078	.014	.015	.015	.017	.012	.012
Measured	C	gm/gm	.657	.831	.758	.732	.687	.737	.725	.722	.712	.703	.694
Measured	H_2	gm/gm	.071	.059	.067	.080	.081	.080	.084	.080	.075	.077	.077
Measured	O_2	gm/gm	.242	.064	.145	.158	.155	.168	.176	.182	.197	.208	.217
Computed	N_2	gm/gm	.034	.039	.024	.046	.078	.056	.028	.008	.043	.087	.111
Computed	C	gm/gm	.650	.813	.670	.723	.723	.582	.743	.691	.679	.660	.676
Computed	H_2	gm/gm	.043	.004	.001	.021	.024	.093	.013	.090	.097	.102	.106
Computed	O_2	gm/gm	.269	.144	.306	.210	.175	.270	.215	.212	.181	.152	.107
	HV	kcal/gm	6.722	6.722	5.422	6.667	6.500	7.833	6.444	8.611	8.778	8.778	9.056

Table 2 - Continued

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
MASSES												
CHAR	gm/100 gm dry Feed	21.7	23.9	26.6	32.1	22.9	40.0	24.9	27.0	28.4	41.4	28.3
FEED	100 gm dry	100	100	100	100	100	100	100	100	100	100	100
AIR	gm/100 gm dry Feed	36.4	26.5	17.2	27.7	27	45.8	46.4	53.9	61.3	14.0	19.0
MOISTURE(IN)	gm/100 gm dry Feed	4.6	4.5	5.3	4.8	4.8	28.7	28.7	28.7	28.7	6.5	6.5
OFF-GAS	gm/100 gm dry Feed	57.7	39.5	33.3	44.2	47.8	68.2	63.4	88.6	94.0	27.5	42.4
OIL	gm/100 gm dry Feed	29.1	22.8	20.7	27.9	14.0	6.49	21.4	8.45	11.3	12.4	20.9
MOISTURE(OUT)	gm/100 gm dry Feed	32.5	44.9	42.0	36.7	36.1	59.8	65.4	58.5	56.4	39.2	33.9
ENERGY LOSSES	kcal/100 gm dry Feed	30	30	30	30	30	30	30	30	30	15	30

heating values which are for the indicated moisture contents, again an average of the dry heating values is probably a more accurate value (in passing it should be noted that the uncertainity in the moisture percentage can be significant and thus the corrected heating value is also uncertain). However, upon adjusting the indicated numbers to a dry basis and after computing an average value, the result obtained is 7.906 kcal/gm which is 6.7% greater than the average of the computed results. It is believed that the justification for working with these average values is adequate, and that these two values are sufficiently in agreement to satisfy the accuracy requirements of the study.

Using the results presented in Table 2, several informative graphs can be drawn. This is done in the next six figures which correlate closely with corresponding figure in (1).

Graphical Data Presentations

Perhaps the most important results of the entire program are those plotted in Figure 9 which presents the percent available energy of the char and oil (related to the feed) as a function of the air/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 correlates to a single line. This line is identical to that reported in (1) using sawdust in a unit 1/2 the geometric scale 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 10 for which the best fit straight line is again identical to both that in Figure 9 and that from (1).

This suggests therefore, that to an acceptable engineering precision the available energy fraction of the feed in the char-oil mix is independent of unit scale, feed material, bed depth and the presence of mechanical agitation; and is a linear function only of the air/feed ratio.

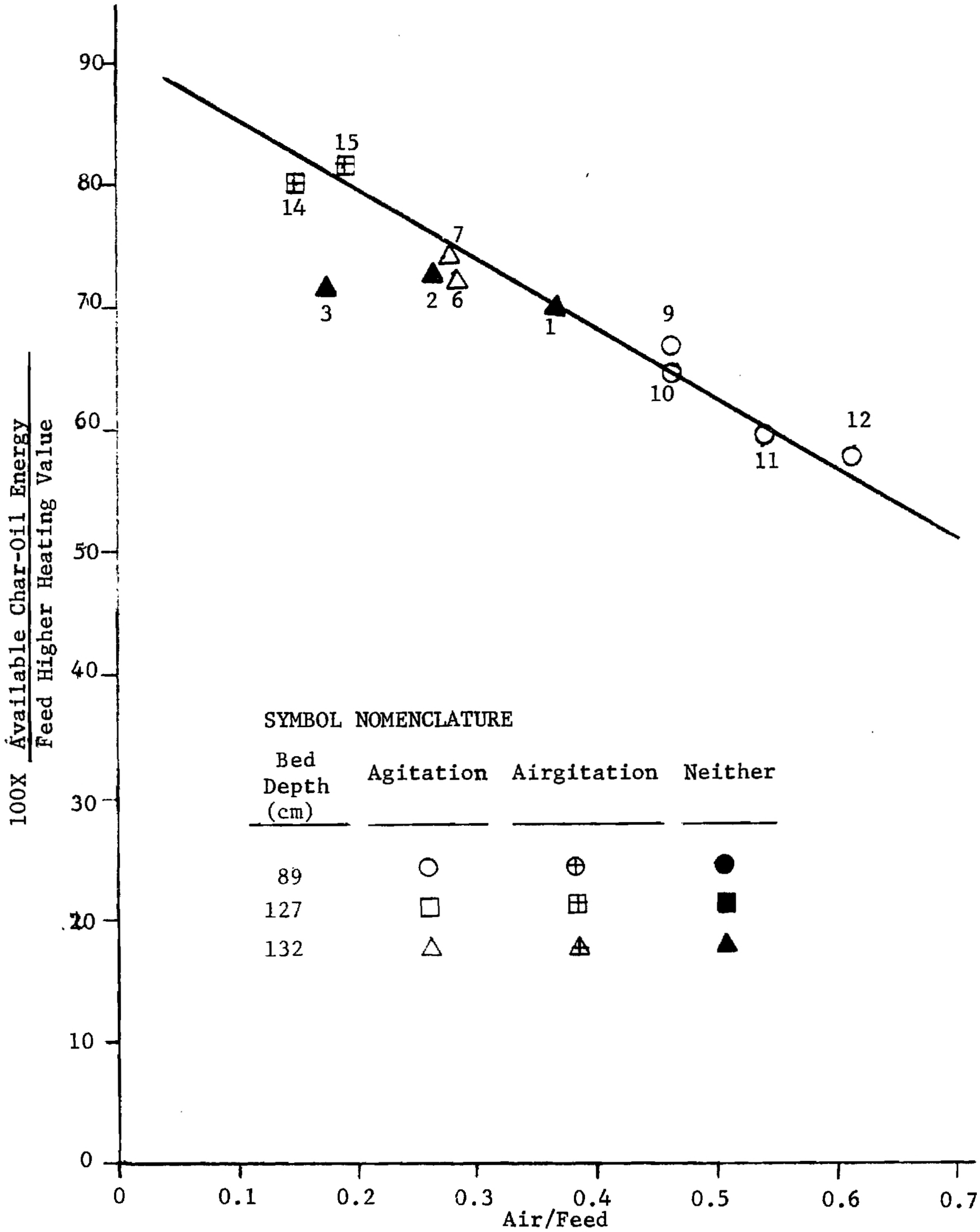

Figure 9

Percent Available Energy in Char-Oil Mixture

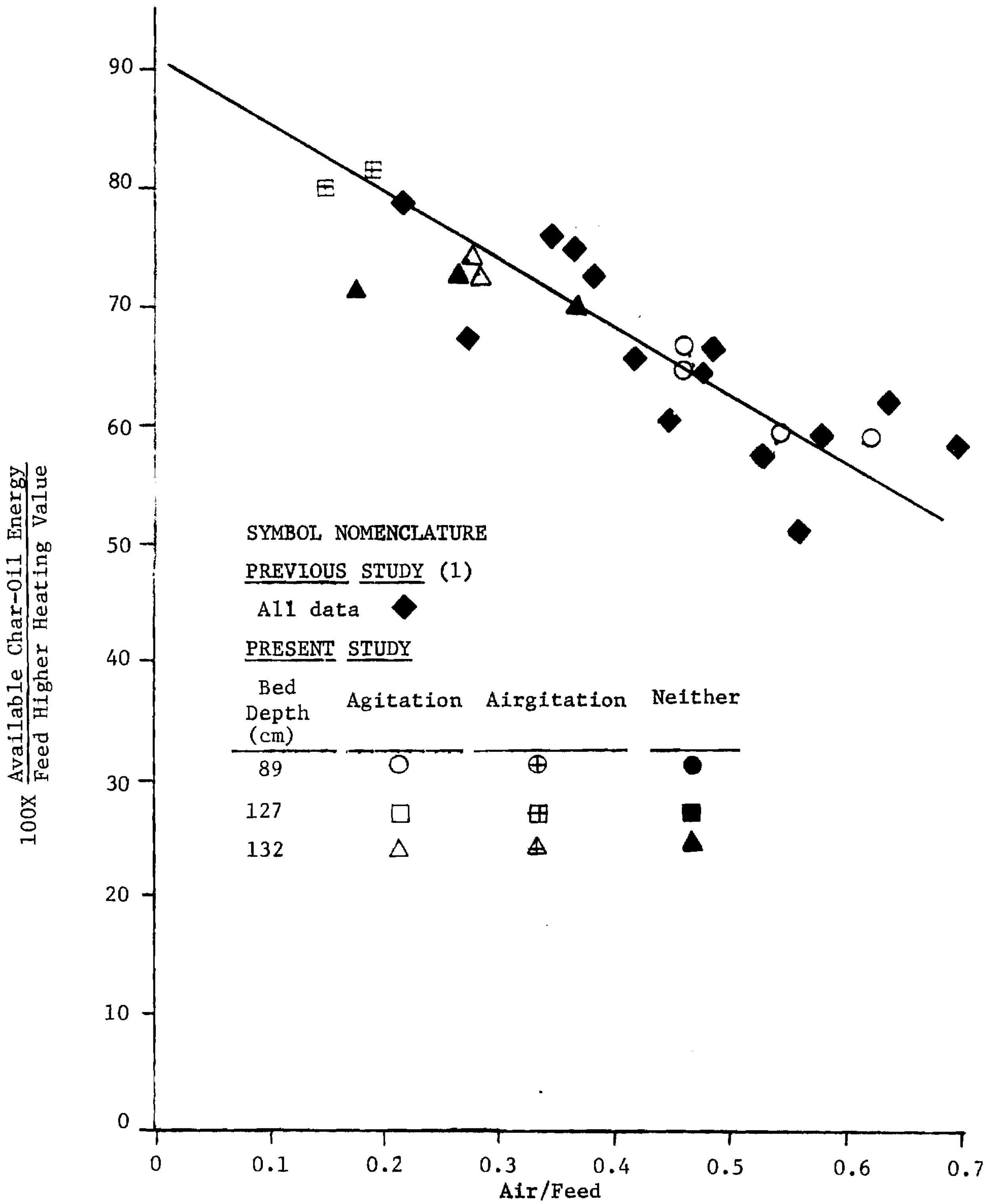

Figure 10

Percent Available Energy in Char-Oil
Mixture- Composite of all Data

Figure 11 presents an energy breakdown of the pyrolysis products as a function of the air/feed ratio. Examination of the figure reveals the relative consistency of the data and, as in Figure 9, suggests that the dominant influencing variable is the air/feed ratio. Comparison of similar results from (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 with the results from (1). And finally the combined energy in the char-oil agrees very well with the results from (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 (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/feed ratio:

In (1), the char yields linearly decreased and the oil yields linearly increased with increasing air/feed while in the present study the char yields remain practically constant and independent of air/feed, whereas the oil yields decrease with increasing air/feed. However, in (1) the pyrolysis off-gas temperatures were always in the range of 150-175°C while in the present study the off-gas temperatures using peanut hulls[+] and with the exception of Test 14 and 15[++], were in the range of 75-95°C. This difference in the off-gas

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\+ The off-gas temperatures with the sawdust were somewhat higher, but still low in comparison with the tests in (1) using sawdust.

++ Test 14 and 15 were conducted using the integrated mechanical agitation-air supply system and for reasons presently not completely understood produced relatively high off-gas temperatures at very low air/feed ratios.

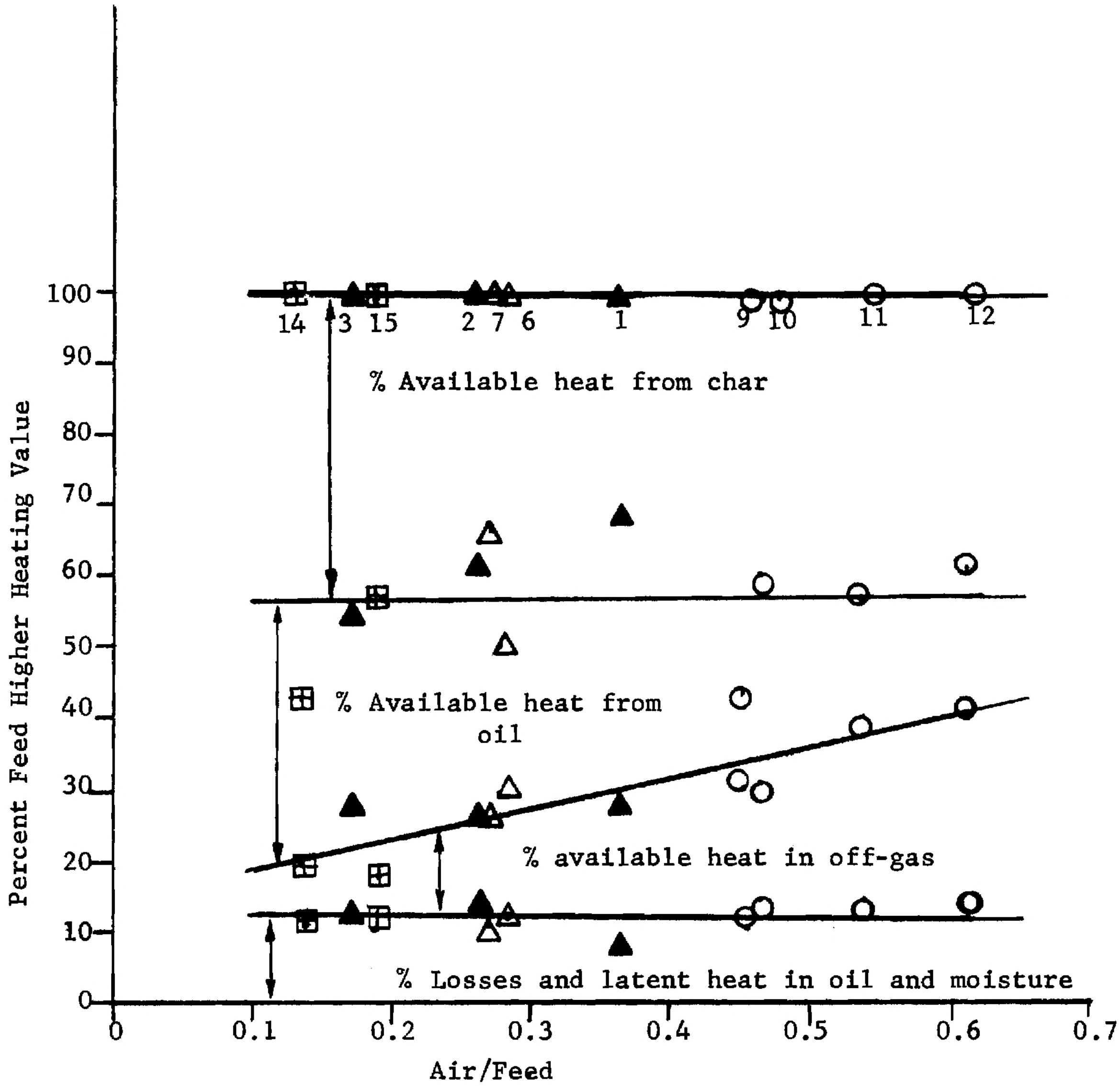

Figure 11

Energy Breakdown of Pyrolysis Products

temperature is very significant because in the latter case the higher boiling point oils are condensing in the bed. Laboratory experience has taught that when pyrolytic oils are heated, a significant degree 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 part of the original oil evaporated, while a considerable portion was converted into solid carbon. The result was the almost constant char yield and a diminishing oil yield with increasing air/feed.

The reason why the off-gas temperatures in the present study were generally so low compared with the results from (1) is because the bed depth was generally near the maximum. The results from (1), at a smaller scale, had suggested that for maximum oil yields a larger bed depth was desirable and therefore, in the present study the larger 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 a breakdown of the oily products occurs to produce 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 become unstable. All this behavior is illustrated graphically in Figure 12 which also shows the surmised operating zones for the present study and that for (1).

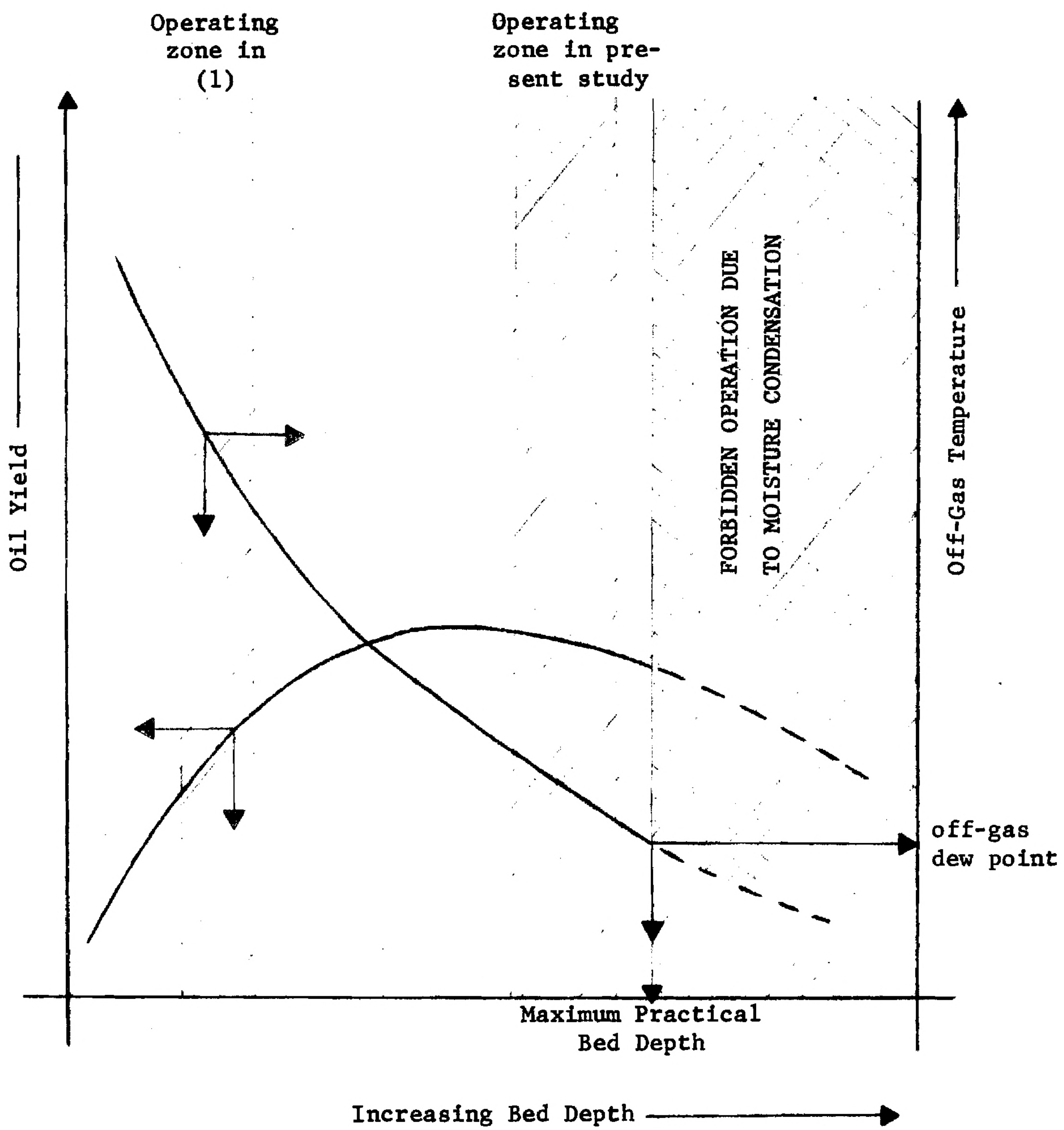

Figure 12

Oil Yield Variation with Increasing Bed Depth

Taken together, this all suggests that while the sum of the energy in the char and oil is basically dependent on the air/feed ratio, the distribution of the energy between the oil and the char is a function of both the bed depth and the air/feed. Thus a means to independently vary the relative amounts of oil and char in the pyrolysis products for a fixed air/feed 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/feed.* 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 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/feed), 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.+

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*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.

+Thus one of the important advantages of the AIRGITATOR system is its ability to continuously vary the bed depth, therefore providing the capability to vary the relative oil and char yields over a wide range.

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 13 is a crossplot of computed data from (1) and experimental data from the present study. The figure provides a convenient means for determining the required air/feed ratio for a given feed moisture percentage and further 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 (1). To illustrate the use of the figure, at a feed moisture percentage of 20 percent, the required energy for drying and processing is .444 kcal/gm (800 Btu/lb) dry feed. Correspondingly, at an air/feed value of 0.16 the available energy in the gas is .444 kcal/gm (800 Btu/lb) dry feed and that available in the char-oil is 3.611 kcal/gm (6,500 Btu/lb); thus establishing the relation between the moisture content and the air/feed. Finally for convenience the figure allows computation of the energy available in the char-oil mixture, as shown earlier in Figure 9.

Figure 14 presents a plot of the heating value of the non-condensible component of the off-gas in kcal/cubic meters as a function of air/feed. As before, and as in (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 (1) and thus again establishes the close correlation of the data from the two studies.

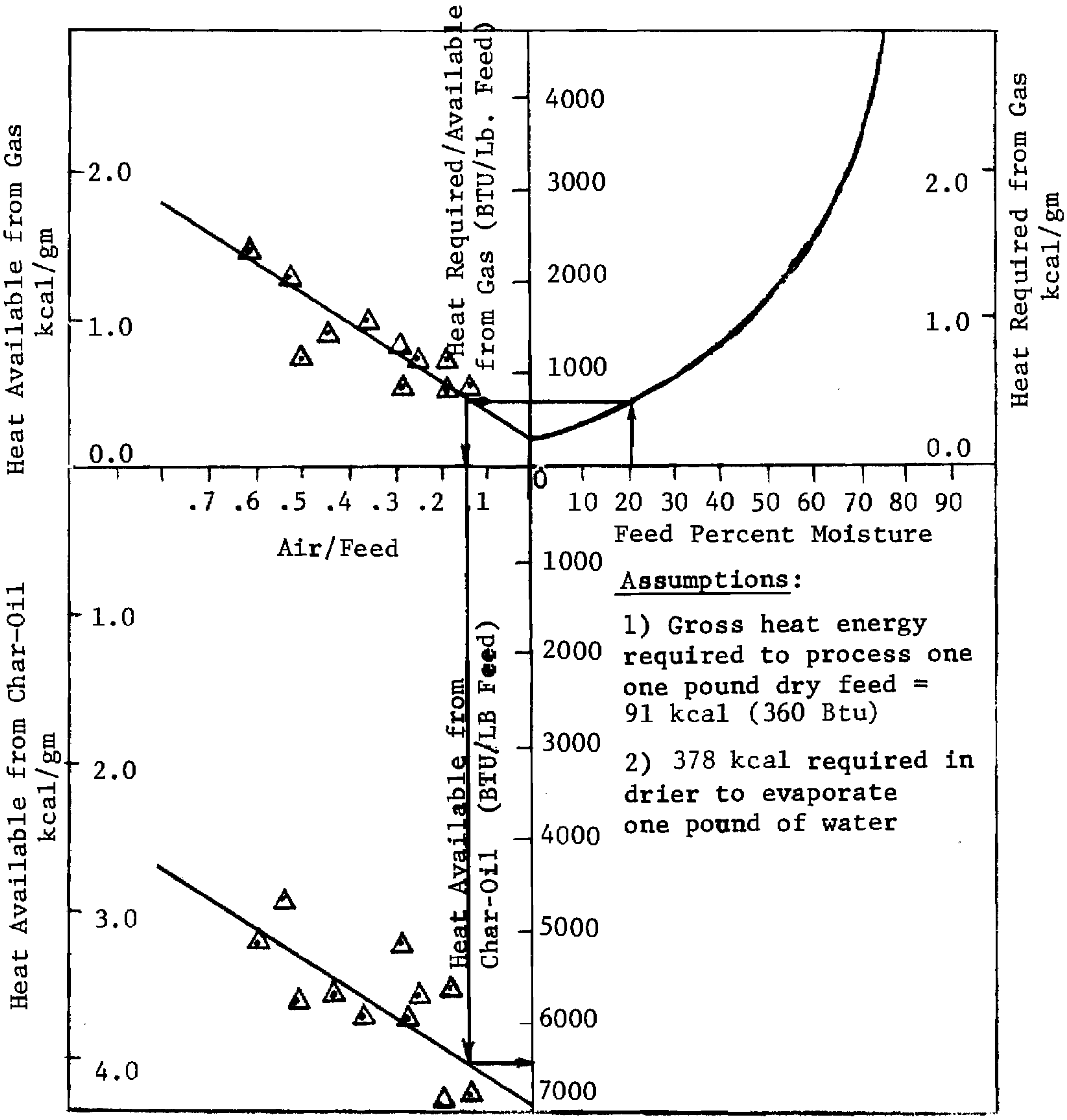

Figure 13

Effects of Feed Moisture on Available Energy from Char-Oil Mixture.

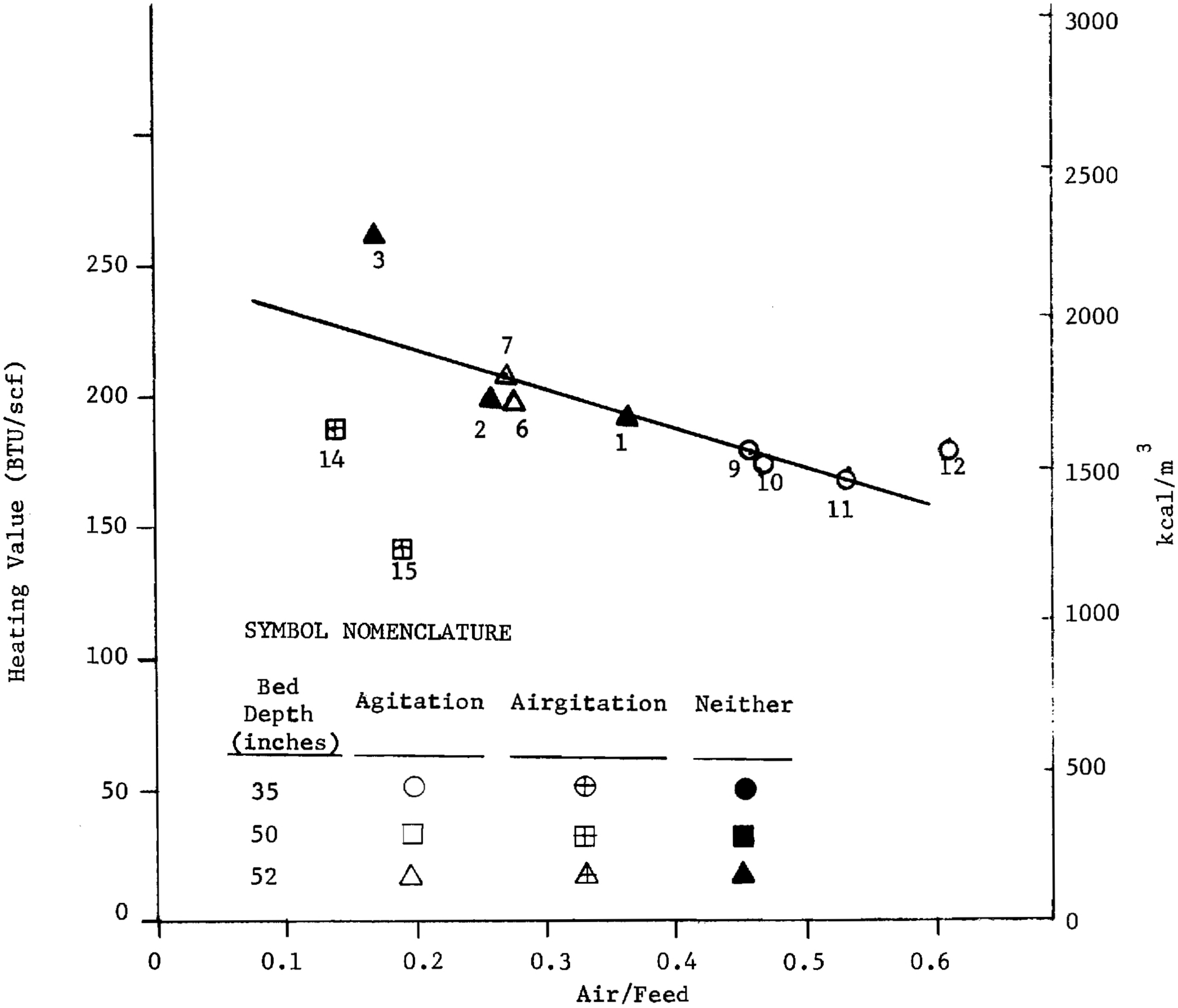

Figure 14

Heating Value of Non-Condensible Gas

SECTION V

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 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 so doing, the principal hindrance to flow through the converter is changed into a means for facilitating the flow. Such a system also possibly allows the processing of somewhat wetter feed than the present EES waste convertor permits. This section, then, presents a description of a "first generation" integrated mechanical agitation-process air supply system or "AIRGITATOR" and a discussion of the initial 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 possiblity of failure and the opportunity for leaks, by minimizing the number of welds. Thus an "L" shaped system was chosen.

The system is presented schematically in Figure 8 and the design is shown in Figure 15. The tubes are made of 4130 alloy steel and are typically .318 cm (1/8 inch) thick. The air delivery ports are .159 cm (1/16 inch) in diameter and located 1.26 cm (1/2 inches) apart. From the metal types and gages, it should be apparent that the system was designed to withstand a hugh torque in a relatively hostile environment. A photograph of the unit, fabricated in the EES shop, is presented in Figure 16.

A commercially available rotating coupling, which was compatible with the water and air flows required, was found; thus avoiding the necessity for designing and fabricating this component at the EES. This coupling, along with the final drive mechanism and the copper tube connections for the process air and cooling water are shown in Figure 17 which depicts the "AIRGITATOR" installed on top of the convertor. The installed system, as can be seen, is not complex, and involved a drive system, the coupling and the "L" shaped "AIRGITATOR".

In the initial design, the horizontal portion of the unit extended to within one inch of the inside walls of the convertor and the ends were cut off squarely. A later modification involved the removal of one inch from this horizontal portion and the beveling of the

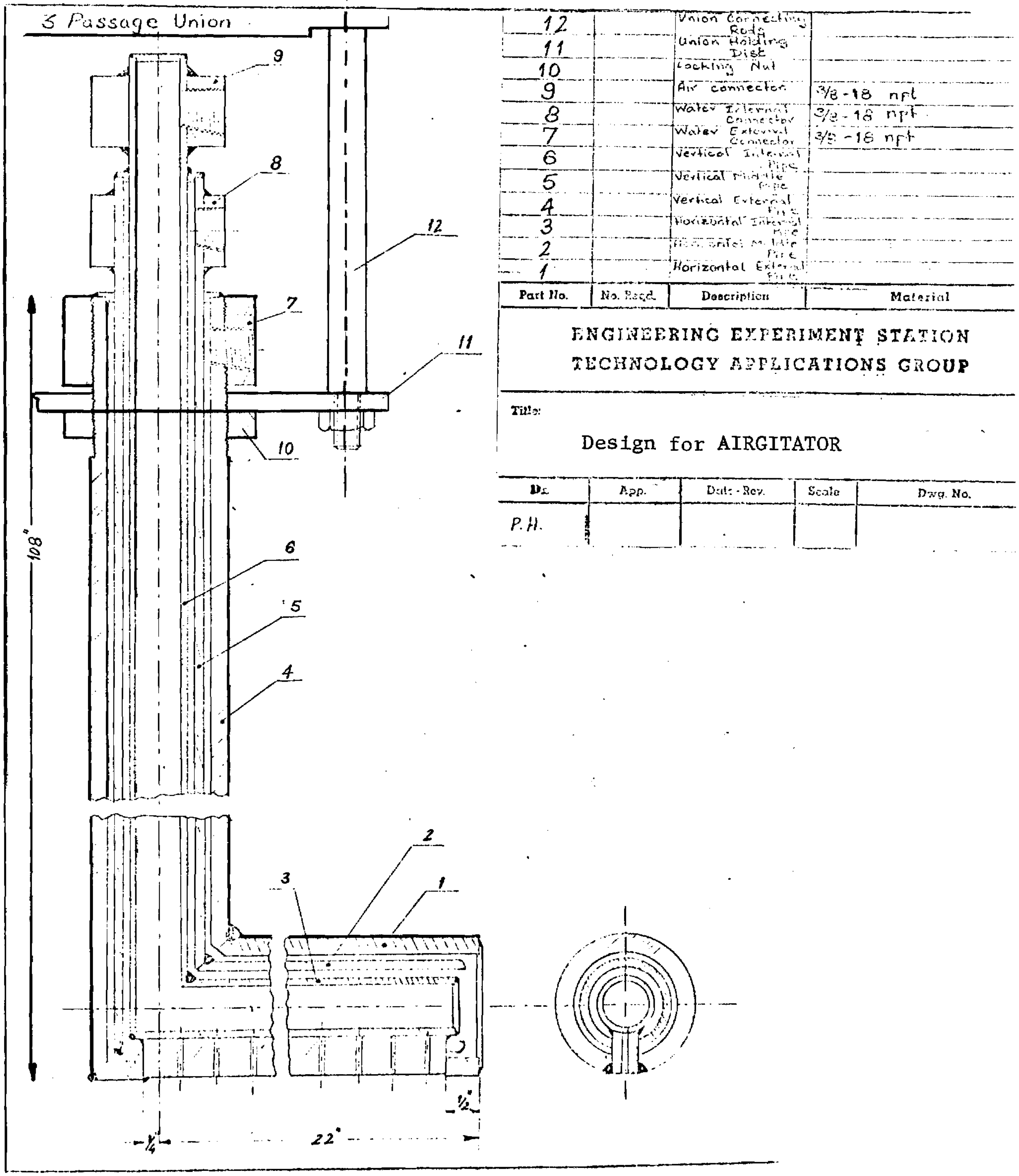

Figure 15

Integrated Mechanical Agitation - Process Air Supply System

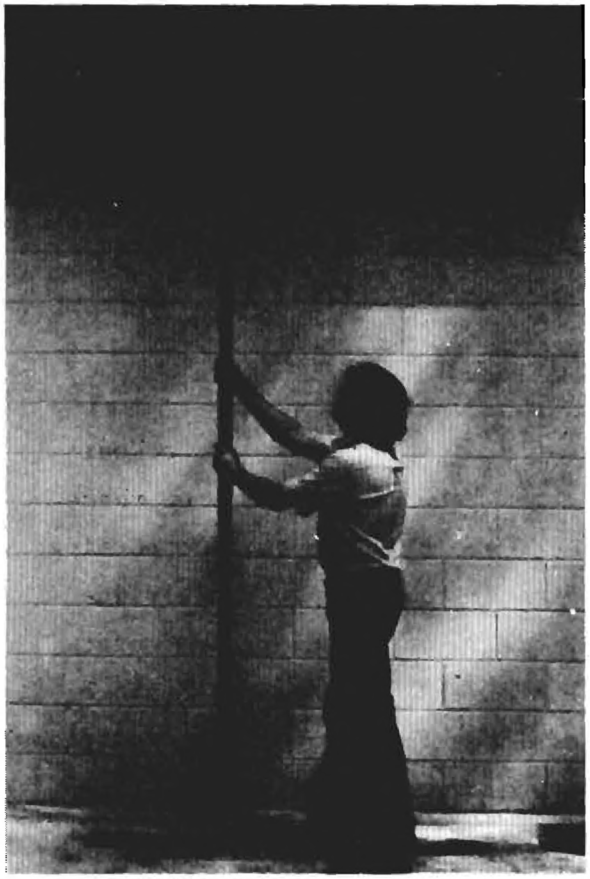

Figure 16
Overall View of AIRGITATOR

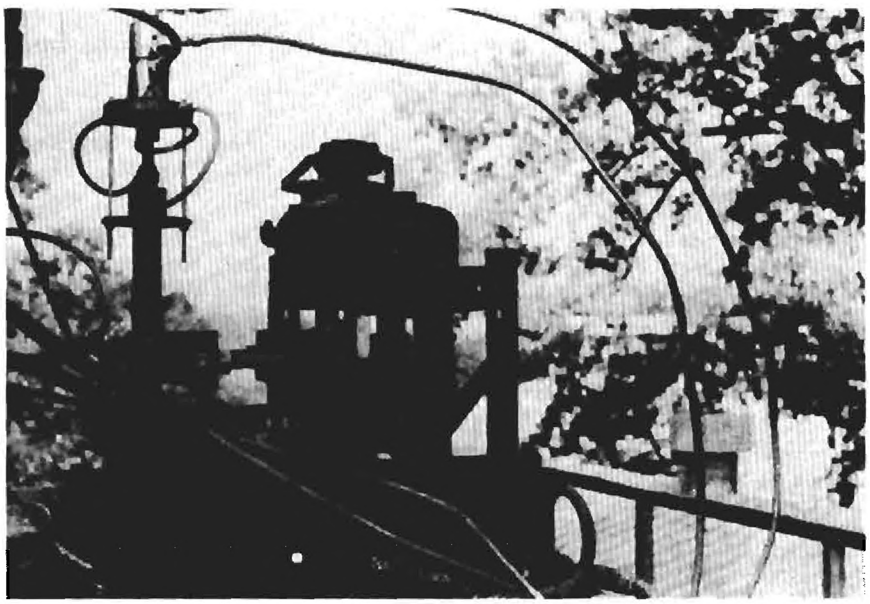

Figure 17
AIRGITATOR Installed on Pyrolytic Converter

end so that the end surface formed a sharp edge which cut through the char. These modifications were made to avoid binding of the 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.

SYSTEM TESTING

About midway through the main test program, the first checkout tests of the "AIRGITATOR" were conducted. The results of these first tests were almost disastrous; the main bearings supporting the unit failed after several hours of testing, apparently due to very large torques that occasionally were required to rotate the system. It was concluded that binding, as described above, had occurred and the indicated modifications were made. Additionally, the complete drive system was strengthened substantially.

The modified unit was then tested and no problems were encountered. Apparently the improvements made were sufficient to overcome the difficulty. One important feature in these 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 enabled a stable hot char zone to be established initially, but provided a cushion against "losing the char bed" in anomalous circumstances where the instantaneous feed rate exceeded the charring rate and threatened the loss of the hot char which sustains the bed operation.

Perhaps the most interesting feature of the latter tests were the relatively high off-gas temperatures achieved at very low air/feed ratios. The ease with which the system operated, the high quality

of the char and the clear ability of the system to operate at a much greater throughput than tested, taken together demonstrated that the potential of the "AIRGITATOR" is at least as great as has initially been forecast and is perhaps even greater. In addition, the ability of the system to vary the bed depth continuously provides an important capability with which to tailor the oil and char yields to meet a wide range of requirements.

SECTION VI

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SECTION VII

APPENDICES

A. Laboratory Procedure

B. Laboratory Test Results

C. Data Analysis Computer Program

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, used as feed material for the waste convertor, and chars produced by the convertor. The sample size received in the laboratory ranged from one to eight liters for the peanut hull feeds and from one to two liters for the char products. The samples were thoroughly mixed and divided by quartering or by a rifle 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 Model 4 Wiley 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--1. Percent Moisture in Peanut Hull 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 is ± 0.6 percent (absolute).

2. Percent Moisture and Percent Volatiles in Chars: These analyses were performed by ASTM Method D-271. The estimated error is ± 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 is ± 0.2 percent (absolute).

4. Heating Values: The heating values of the feeds and chars were determined in a Parr Plain (Isothermal Jacket) oxygen bomb calorimeter. Following the procedures described in pp. 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 ± one percent (relative) for pure, crystalline materials. Because of the heterogeneous nature of the samples, loss of volatiles form 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. In most cases however, the agreement was better than six percent (absolute) for carbon and oxygen in the feeds and chars. Agreement among replicate hydrogen or nitrogen determinations was better than one percent.

Oil Samples

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

Analytical Procedure--1. 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 $\pm$ five 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 that 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 convertor or from the upstream end of the condensers. The sample stream was passed through a series of water cooled condensers, a glass wool demister, an 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 Non-Condensible 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 using 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 ± five percent (relative).

APPENDIX B-LABORATORY DATA

Listed in the following pages are the results of the laboratory analysis described in Section IV for the feed, char, oil and off-gases from the test program. 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 Table 2, 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

TEST 1

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COM-POSITION[3]
WATER	Percent	4.4	8.3	11.9	N_2	44.37
ASH	Percent	3.4	10.9	-	CO	16.88
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	15.78
					H_2	16.17
					CH_4	4.60
CARBON	Percent	48.6	75.1	57.0	C_2H_6	0.52
HYDROGEN	Percent	6.0	2.6	7.6	C_2H_4	0.72
NITROGEN	Percent	1.7	2.5	3.5	C_3H_8	0.13
OXYGEN	Percent	43.7	8.9	31.9	C_3H_6	0.24
HEATING VALUE	kcal/gm	4.651	6.083	6.960		

1. The CHNO analysis and heating values are based on oil with the indicated mositure content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-2

LABORATORY ANALYSIS

TEST 2

	UNITS	FEED	CHAR [2]	OIL [1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION [3]
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
					CH_4	5.52
CARBON	Percent	47.0	82.9	55.5	C_2H_6	0.63
HYDROGEN	Percent	5.8	1.8	7.6	C_2H_4	0.90
NITROGEN	Percent	2.03	2.1	3.11	C_3H_8	0.14
OXYGEN	Percent	45.17	3.2	33.79	C_3H_6	0.27
HEATING VALUE	kcal/gm	4.397	7.111	5.299		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-3

LABORATORY ANALYSIS

TEST 3

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
WATER	Percent	5.0	4.6	21.1	N_2	33.8
ASH	Percent	1.2	6.5	-	CO	18.2
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	24.0
					H_2	12.5
					CH_4	9.5
CARBON	Percent	45.8	84.4	60.6	C_2H_6	0.6
HYDROGEN	Percent	5.4	1.7	7.7	C_2H_4	0.9
NITROGEN	Percent	0.1	1.1	1.3	C_3H_8	0.1
OXYGEN	Percent	48.8+.1	6.4	30.4	C_3H_6	0.3
HEATING VALUE	kcal/gm	4.569	7.345	5.728		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-4

LABORATORY ANALYSIS

TEST 6

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION[3]
WATER	Percent	4.6	2.7	17.9	N_2	41.1
ASH	Percent	2.3	6.5	-	CO	9.8
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	22.4
					H_2	18.7
					CH_4	6.7
CARBON	Percent	47.3	72.4	60.1	C_2H_6	0.6
HYDROGEN	Percent	5.7	1.7	8.6	C_2H_4	-
NITROGEN	Percent	1.2	2.9	2.4	C_3H_8	0.6
OXYGEN	Percent	45.8	16.5	28.9	C_3H_6	-
HEATING VALUE	kcal/gm	4.539	7.550	No Fire		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-5

LABORATORY ANALYSIS

TEST 7

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION[3]
WATER	Percent	4.6	0.6	16.1	N_2	41.9
ASH	Percent	2.3	9.8	-	CO	24.51
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	8.14
					H_2	15.07
					CH_4	8.91
CARBON	Percent	47.3	73.6	57.6	C_2H_6	0.65
HYDROGEN	Percent	5.7	1.8	8.6	C_2H_4	-
NITROGEN	Percent	1.2	2.7	6.5	C_3H_8	0.78
OXYGEN	Percent	45.8	12.1	27.3	C_3H_6	-
HEATING VALUE	kcal/gm	4.539	7.127	5.978		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-6

LABORATORY ANALYSIS

TEST 9

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PERCENT COMPOSITION[3]
WATER	Percent	22.3	0.6	20.3	N_2	45.32
ASH	Percent	4.6	9.8	-	CO	19.89
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	15.36
					H_2	6.14
					CH_4	5.67
CARBON	Percent	48.3	73.6	56.9	C_2H_6	0.66
HYDROGEN	Percent	5.9	1.8	8.7	C_2H_4	0.52
NITROGEN	Percent	1.2	2.7	1.1	C_3H_8	0.13
OXYGEN	Percent	44.6	12.1	33.3	C_3H_6	0.20
HEATING VALUE	kcal/gm	4.874	6.702	6.582		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-7

LABORATORY ANALYSIS

TEST 10

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
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
					CH_4	4.40
CARBON	Percent	48.3	74.8	53.6	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.5	9.1	C_2H_4	0.50
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	10.3	36.2	C_3H_6	0.18
HEATING VALUE	kcal/gm	4.873	6.636	6.258		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-8

LABORATORY ANALYSIS

TEST 11

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COM-POSITION[3]
WATER	Percent	22.3	3.2	28.6	N_2	46.98
ASH	Percent	4.6	17.0	-	CO	17.91
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	18.18
					H_2	11.13
					CH_4	4.63
CARBON	Percent	48.4	77.8	51.5	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.3	8.9	C_2H_4	0.53
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	3.1	38.5	C_3H_6	0.16
HEATING VALUE	kcal/gm	4.873	6.596	5.818		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-9

LABORATORY ANALYSIS

TEST 12

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COM-POSITION[3]
WATER	Percent	22.3	1.2	34.0	N_2	46.88
ASH	Percent	4.6	20.1	-	CO	21.86
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	16.36
					H_2	8.72
					CH_4	4.84
CARBON	Percent	48.3	77.3	47.0	C_2H_6	0.43
HYDROGEN	Percent	5.9	0.9	8.7	C_2H_4	0.63
NITROGEN	Percent	1.2	1.1	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	8.9	43.2	C_3H_6	0.19
HEATING VALUE	kcal/gm	4.773	6.027	6.117		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-10

LABORATORY ANALYSIS

TEST 14

	UNITS	FEED	CHAR [2]	OIL [1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION [3]
WATER	Percent	6.1	1.2	14.7	N_2	40.3
ASH	Percent	2.8	7.1	-	CO	23.2
ACID INSOLUBLE ASH	Percent	0.5	1.0	-	CO_2	19.3
VOLATILES		-	12.2	-	H_2	9.84
					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	42.7	11.5	30.8	C_3H_6	0.1
HEATING VALUE	kcal/gm	4.727	6.959	6.281		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-11

LABORATORY ANALYSIS

TEST 15

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION[3]
WATER	Percent	6.1	0.9	18.1	N_2	47.0
ASH	Percent	2.8	10.2	-	CO	11.1
ACID INSOLUBLE ASH	Percent	0.5	3.0	-	CO_2	26.1
VOLATILES		-	11.0	-	H_2	0.5
					CH_4	3.33
CARBON	Percent	50.6	78.7	56.8	C_2H_6	0.99
HYDROGEN	Percent	6.1	1.4	6.29	C_2H_4	-
NITROGEN	Percent	0.7	0.7	1.0	C_3H_8	0.20
OXYGEN	Percent	42.7	9.1	35.91	C_3H_6	0.13
HEATING VALUE	kcal/gm	4.727	6.911	5.817		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

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	.485	.191	.021	.303	2704
Char	.025	.751	.026	.089	10950
Feed	.017	.486	.061	.437	8372
Water	.770	0	0	.230	0

From the testing the char yield is 21.7 kg, per 100 kg feed; the measured amount of air per 100 kg feed is 36.4 kg and the amount of the moisture is 4.6 kg per 100 kg feed. The energy losses (L) are estimated at 13,608 kcal (54,000 Btu) for each 45.36 kg (100 lb) feed (or about 7 percent).

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

Then variations of plus and minus 10 percent of each of the coefficients in the eight equations are made and the resulting

*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.

values of each of the eight unknowns are determined. Using these results the measured versus the computed values of the oil composition can 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	Percent Measured	Percent Computed	Percent Dif.
C	.657	.837	+ 27.4
H	.071	.0344	- 51.5
O	.242	.185	- 23.6
N	.04	- .056	--

Not only is the difference between the values for C, H and O substantial, but the computed value for N is physically impossible. Clearly, significant inconsistencies between the measured and the computed results are 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 $\pm$ 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	Percent Measured	Percent Computed	Percent Dif.
C	.657	.654	+ .45
H	.071	.043	_ 39
0	.242	.268	+ 10.7
N	.04	.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 )= .0189
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
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NOMINAL W( 6 )= .025
+10% OF NOM W( 6 )= .0275
MG= 57.9196 MO= 25.3716 MW= 36.0088 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= .026886 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
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NOMINAL W( 13 )= .11
+10% OF NOM 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= .294888 WNO=-.166113

NOMINAL 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

NOMINAL W( 16 )= .017
+10% OF NOM 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

NOMINAL 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
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NOMINAL W( 20 )= 8372
+10% OF NOM W( 20 )= 9209.2
MG= 57.4638 MO= 32.087 MW= 29.7492 HVO= 12608.6
WCO= .664634 WHO= 4.87003E-2 WOO= .322447 WNO=-3.58318E-2
-10% OF NOM W( 20 )= 7534.8
MG= 58.6015 MO= 19.528 MW= 42.0704 HVO= 17032.9
WCO= 1.13326 WHO= 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= 24.631 MW= 30.796 HVO= 15086.2
WCO= .816189 WHO= 5.33032E-2 WOO= .303389 WNO=-.172881
-10% OF NOM W( 21 )= .693
MG= 52.1923 MO= 26.084 MW= 41.0237 HVO= 13423.7
WCO= .856255 WHO= 1.66061E-2 WOO= 7.31996E-2 WNO= .053939


NOMINAL 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


NOMINAL 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


NOMINAL W( 25 )= 0
+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
-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


NOMINAL 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=-5.20134E-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


NOMINAL W( 27 )= 13713
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+10% OF NCM W( 27 )= 15084.3
MG= 58.2455 MO= 22.8399 MW= 38.2146 HVO= 15087.8
WCO= .927253 WHO= 2.69284E-2 WOO= .112757 WNO=-6.69391E-2
-10% OF NCM 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= 35.4053 HVO= 14248.1
WCO= .827633 WHO= 3.68315E-2 WOO= .209677 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= 58.1698 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= 3.45419E-2 WOO= .186084 WNO=-5.60604E-2


NOMINAL W( 32 )= 54000
+10% OF NOM W( 32 )= 59400
MG= 58.0694 MO= 24.9234 MW= 36.3072 HVO= 14369.7
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);"MN=";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="PUN16"
12 FILE #17="RUN17",#18="RUN19"
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
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
```

B 446

DRAFT

DEVELOPMENT OF A PROTOTYPE SYSTEM FOR PYROLYSIS OF AGRICULTURAL WASTES INTO FUELS AND OTHER PRODUCTS

A REPORT TO
MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO

Under Grant R 803403-01-0

January 1976

By
ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia 30332

Principal Authors

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DRAFT

ABSTRACT

An experimental study of the performance of the one ton/hr pyrolytic convertor located at the Georgia Tech Engineering Experiment Station has been conducted. Peanut hulls were used as the feed in a series of thirteen tests. In addition, two tests were conducted using sawdust. The objects of the test program were to determine the effects of scale, feed material, mechanical agitation, air/feed and bed depth on the product yields of the EES pyrolytic convertor. Also investigated was the performance of an integrated mechanical agitation-air supply system (AIRGITATOR) designed to improve the throughput of the unit.

From the tests, and after comparison with earlier smaller scale work with sawdust, it appears that changing feed and scale, and the use of mechanical agitation have little influence on the product yields. Bed depth, while not affecting the total potentially available energy in the char and oil, substantially influences the relative amounts of these products. The air/feed ratio again appears to be the dominant influencing variable and data from the present study and earlier work are shown to correlate to a single curve.

The influence on system performance of the integrated mechanical agitation-air supply system, while not investigated comprehensively, appears to be very favorable. Using this system, off-gas temperatures were raised, while stable operation was maintained at very low values of air/feed.

This report is submitted in fulfillment of EES Project Number B-446 in an initial reporting period. The work was supported under Grant Number R 803403-01-0 of the Environmental Protection Agency. Work was completed in December 1975.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

Symbols	Definition	Units
h	Enthalpy	Btu/lbm
HV	Heating Value	Btu/lbm
L	Losses (see equation 2)	Btu
M	Mass	lbm
w	Weight Fraction	lbm/lbm

Subscripts	
a	Air
c	Carbon
ch	Char
f	Fuel
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

ACKNOWLEDGEMENTS

This effort was supported by the Municipal Environmental Research Laboratory of the Environmental Protection Agency under Grant R 803403-01-0. We wish to express our appreciation to Mr. Donald A. Oberacker of MERL for his many contributions and suggestions. And a note of thanks is offered to Ms. Beth Lanier for her invaluable assistance in the preparation of this document.

SECTION I

CONCLUSIONS

From the results of this work the following conclusions can be drawn:

- The effects of the air/feed ratio on product energy yields appears to be dominant; changing scale and feed material, and the effects of mechanical agitation are of minor importance compared with air/feed.
- The available energy in the char-oil mixture appears from the results of this and earlier work to be a single function of air/feed; all the data correlated to a common curve.
- While the total energy in the char-oil mixture is a function only of air/feed, the relative amounts of char and oil can be changed significantly by varying the bed depth.
- The processing of peanut hulls through the convertor presents no problems either with or without the use of mechanical agitation.
- The integrated mechanical agitation-air supply system or "AIRGITATOR", which was tested successfully, appears to offer many advantages in increased through-put, operating stability and off-gas temperature at very low values of air/feed. The ability of this system to allow continuous variation in the bed depth provides an additional, significant and attractive feature.
- The overall mass, energy, and chemical balances appear to be satisfactory; thus giving confidence to the results of the testing.

SECTION II

RECOMMENDATIONS

The results of the study further reinforce the attractiveness of the mobile pyrolytic convertor concept by providing additional operating data and basic understanding of the physical processes at work. However, while the design, fabrication and test of the complete mobile system can be initiated in the very near future, several technical studies should be made before this final phase begins. These include:

(1) an investigation of the operating and ignition characteristics and derating required of a modified gasoline engine operating on the low BTU pyrolysis gas.

(2) a study of the burning characteristics of the char-oil mixture in various combinations with coal.

(3) further development and test of the integrated mechanical agitation-air supply system (AIRGITATOR) evaluated in the current work.

When these studies have been completed, successfully, the design, fabrication and test of the full-scale mobile pyrolysis converter itself should be initiated. Upon successful operation of this component the complete mobile system should be designed and constructed.

SECTION III

INTRODUCTION

GENERAL

This report describes an experimental program designed to improve the technology required for the development of a mobile pyrolysis system for conversion of agricultural and forestry wastes at the site of their production into a clean and easily transportable fuel. The program involves a series of tests using peanut hulls, primarily, as the feed in the one ton/hr Georgia Tech Engineering Experiment Station (EES) pyrolytic convertor pilot plant and is a follow-on study to earlier work (1) using wood waste as the feed material in a smaller, 500 lb/hr (EES) pilot plant.

The rationale for the portable concept has been described previously (1, 2, 3, 4) and will not be repeated here. However, two additional elements, which make the concept even more attractive, have come to light, i.e.

(1) The application of the mobile pyrolysis concept to large barges* moving on the thousands of miles of inland and intercoastal waterways appears to have great promise. This would not only permit an increase in the scale of the mobile system but would also allow its application to the municipal waste of smaller communities which presently cannot individually justify or afford a large, economical waste conversion system, but which in groups could successfully operate such a system.

(2) The char-oil fuel produced by the mobile pyrolysis system was considered primarily in (1) 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

---

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

Engineering (6) General Motors (7) and at the ERDA, Pittsburgh Labs (8) that 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 minimum 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 as a boiler fuel.

These two considerations should have relatively little influence on the planned development program for the portable system, but strengthen significantly the justification for the portable concept with production of the char-oil fuel.

OBJECTIVES

The investigation, which was primarily experimental, had several objectives, i.e.

- To determine the effects of scale on pyrolytic convertor performance.
- To determine the effects of changing feed material on pyrolytic convertor performance.
- To determine the effects of mechanical agitation on pyrolytic convertor performance.
- To determine the performance of an integrated mechanical agitation-process air supply system.
- To determine the influence of air/feed and bed depth on product yields.

In the following sections a description of the study is presented.

SECTION IV

TESTING

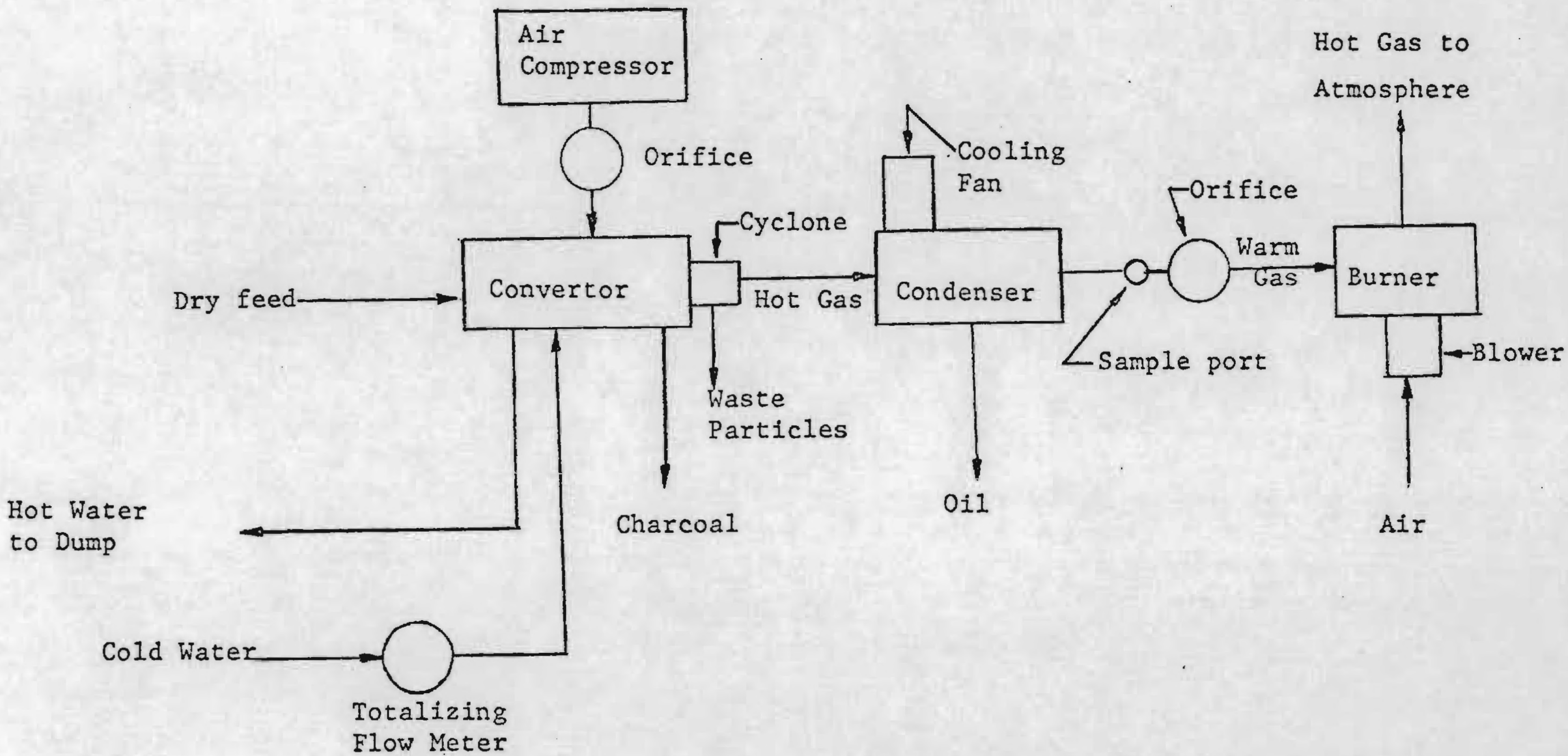
GENERAL

The experimental program was conducted in the new, one ton/hr EES pilot plant. Peanut hulls were used as the feed material in a series of 13 tests and sawdust was used in 2 tests, for a total of 15 tests in the complete study. All told, approximately 50 tons of hulls were used in the program. The tests involved investigation of the influences of scale, feed, air/feed, mechanical agitation and bed depth on product yields. In addition, the performance of an integrated mechanical agitation-process air system on product yields and process rates was studied. This section presents a description of the test facilities, the calibration and test procedure, the laboratory procedure, the data reduction methodology and the results of the 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 then 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 18 feet tall and is 6 feet on each side. The inside of the unit is cylindrical, with a diameter of 4 feet and a depth of 8 feet. The feed enters the convertor 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



EES Pyrolytic Unit Process Flow Diagram

Figure 1

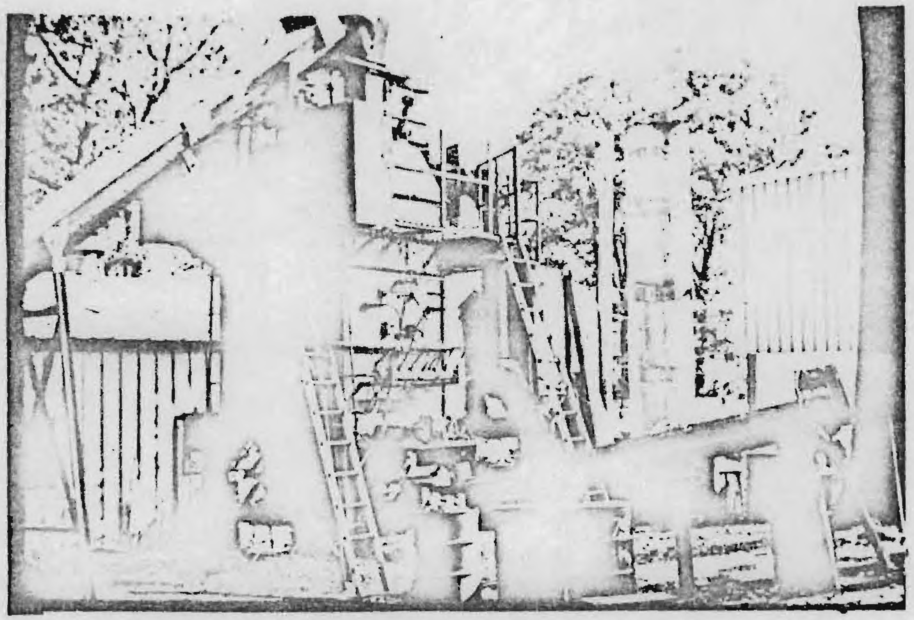


Figure 2

Overall View of Advanced EES Pyrolytic Converter

Figure 3

Close-Up View of EES Pyrolytic Converter

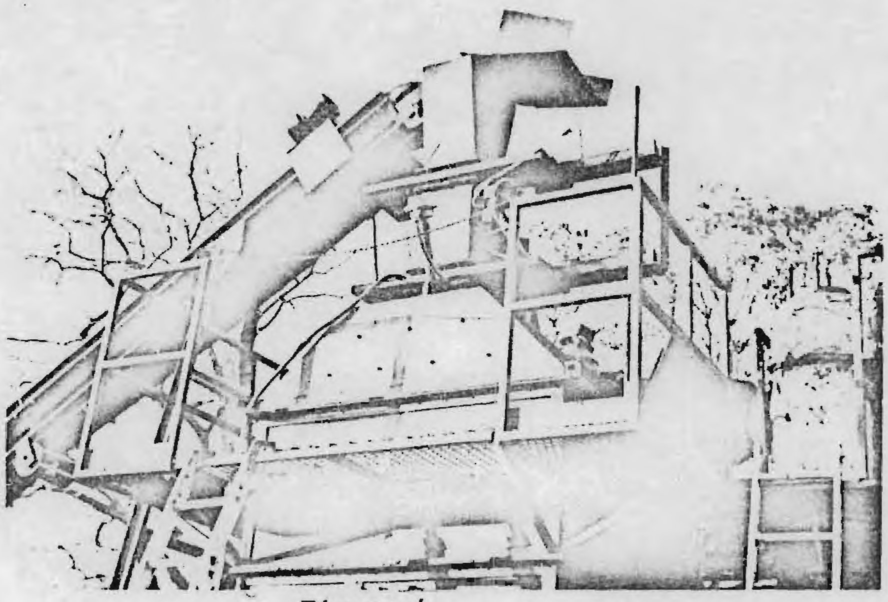


Figure 4

Close-Up View of Conveyer and Input System - EES Pyrolytic Convertor

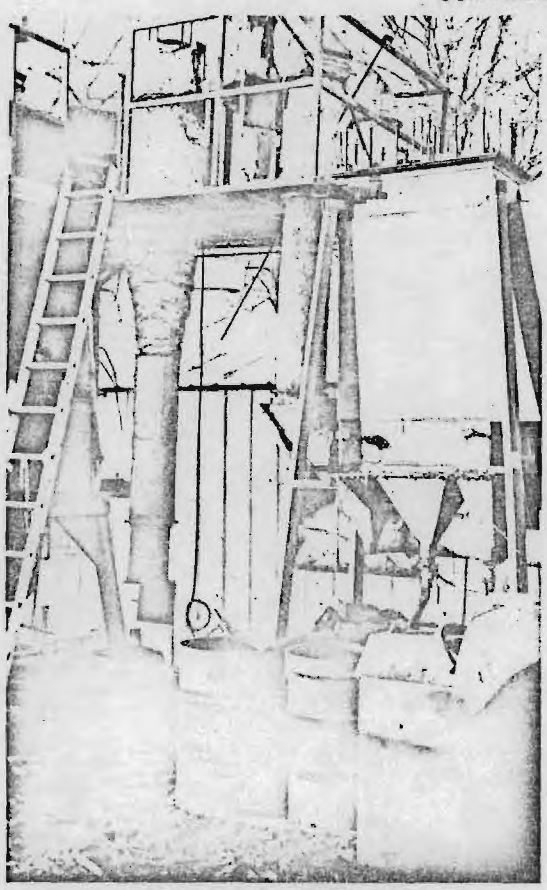


Figure 5

Close-Up view of Cyclone and Condenser System - EES Pyrolytic Convertor

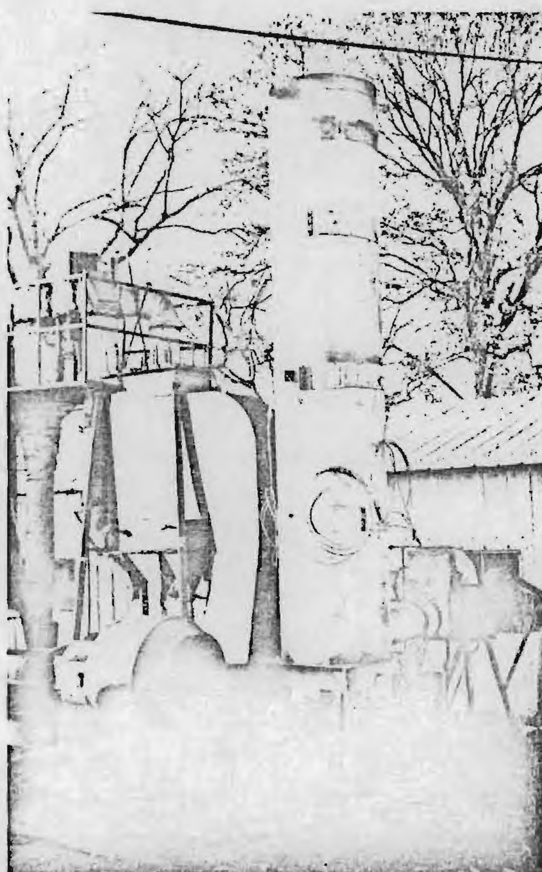


Figure 6

Close-Up View of Off-Gas Burner-EES Pyrolytic Convertor proximity and thereby produce sufficient heat for pyrolysis of the remaining feed material. The char at the bottom of the bed passes through two counter-rotating drums and into a screw conveyor that transports it to a valve assembly where it is emptied 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 non-condensible gases pass through the draft fan and into the burner which incinerates the mixture.

The instrumentation used in the study includes:

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

The system operates at a few inches of water below ambient; thus any leaks present generally result in the introduction of air into the system. However, within the cavity between the sliding plates of the gate valve, the displacement of the pyrolysis gas by the input feed does result in some lost gas when the gate valve operates. As the process rate of the unit increases, the gas production increases and the 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 10 inches of water. These doors provide a safe means of relieving overpressures for any system malfunction.

The process rate of the system is governed by the rotational speed of the char output drums. A level indicator senses the need for additional feed and activates the gate valve and conveyor system to provide the necessary input. Thus the gate valve cycles only upon demand, not continuously; hence the gases lost through this 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 the cooling air flow. In all but the last tests the condenser was operated at about 200°F, however, to determine the influence of condenser temperature an oil yields, the condenser temperature was dropped to 170-180°F in the last test. It has been observed that oil droplets are frequently carried in suspension through the off-gas system, past the draft fan and into burner. This results in some loss of oil; however, analytical techniques are 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 convertor 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 constructed by a high torque gear drive system. The maximum rotation speed of the agitator was about one RPM.

In the latter phase of the testing, an integrated mechanical agitation-process air system (AIRGITATOR) was also tested. A schematic view of this system is shown in Figure 8. The system is driven by the same gear drive as the simpler agitator and is described in more detail in Section V.

It might 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 in the stream which make conventional instrumentation techniques impractical. Instead, analytical techniques involving nitrogen, carbon, hydrogen and oxygen balances were used to compute the flows of the various constituents which make up the off-gas stream.

CALIBRATION AND TEST PROCEDURE

Prior to the testing many elements of the system instrumentation were carefully calibrated. The accuracy of some components such as the thermocouples, however, was not checked since the required 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. However, 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 sufficiently

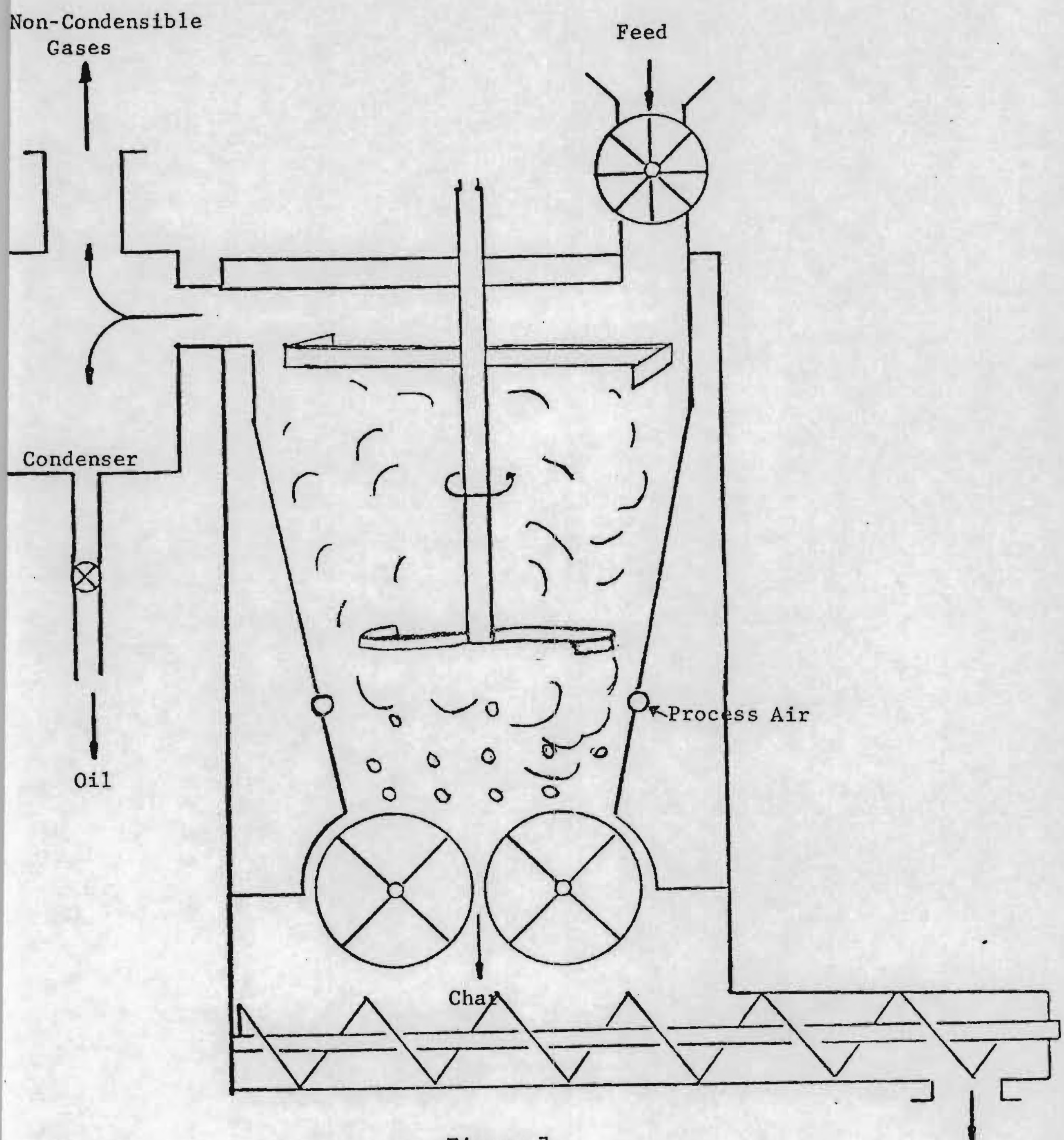


Figure 7

Schematic of EES Convertor with Rotating Agitator

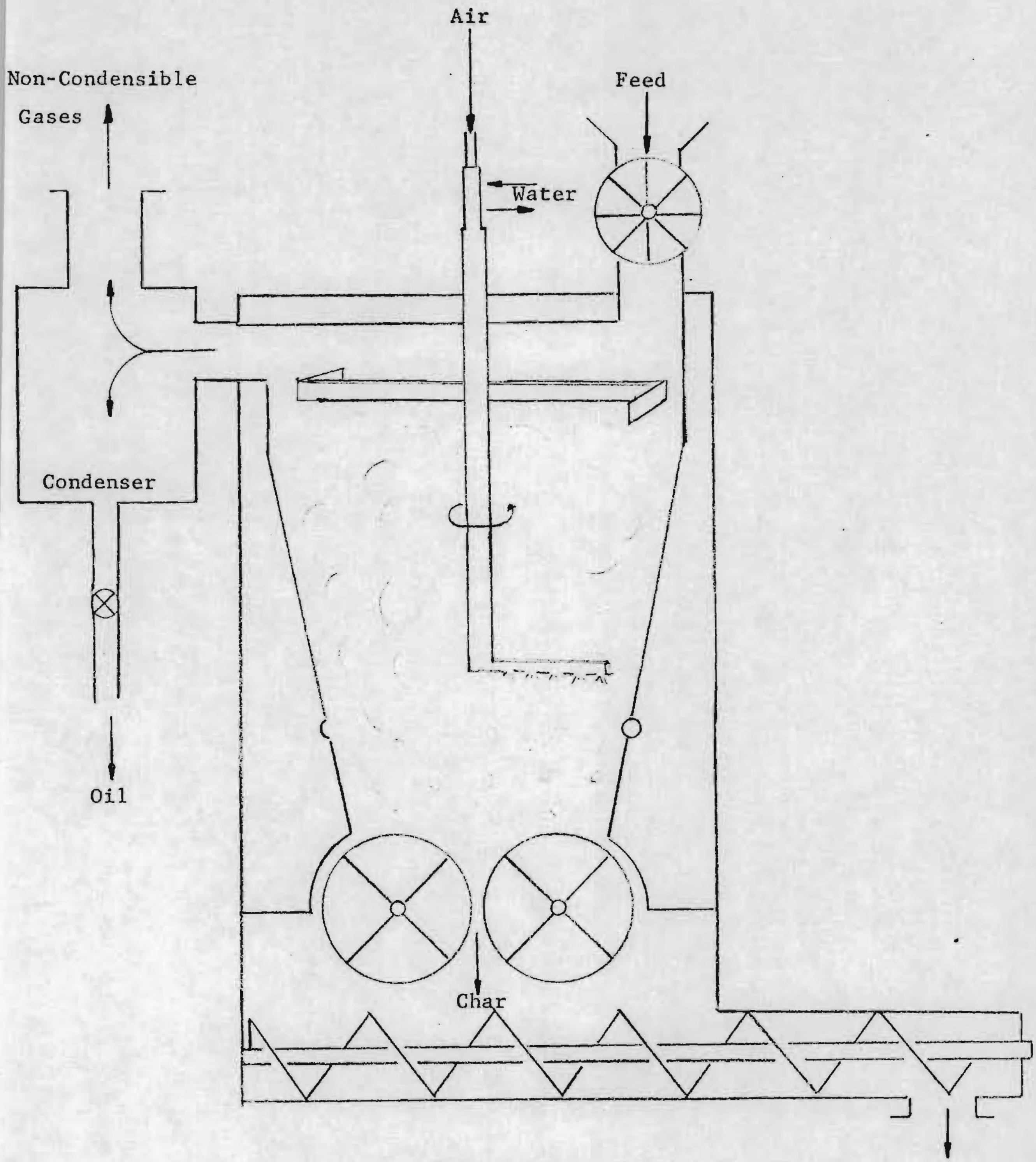


Figure 8

Schematic of EES Convertor with Integrated Mechanical Agitation - Air Supply System

elevated the process air was introduced slowly and the element 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 operating capacity chosen for the test. Likewise, the process air feed rate was adjusted to correspond to the desired ratio of air-to-feed for the test. The system was then allowed to come to a steady-state condition, which required 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 the ability to establish a given feed process rate and given air-to-feed ratio was limited to a tolerance of plus or minus about 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-gasses was taken. Every effort was made to insure that the unit remained 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 its completion all of the char and oil produced were collected and representative samples of each obtained. The char sample was obtained by use of a grain sampler. The oil was collected in a 55 gallon drum, mixed throughly and a sample of about one pint taken. All of the feed grab samples were mixed and cut using a rifle splitter to obtain a composite sample of several pounds.

LABORATORY PROCEDURE**

The laboratory played a vital role in the determination of the feed and products characteristics and in the subsequent analysis of the data. Thus the work was checked carefully and every precaution made to insure the accuracy of the results. However, despite these efforts there are occasional instances where inconsistencies did arise. While 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 and 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. While these variations are predominantly less than one percent, the overwhelming impression is of good repeatability. The presence, expecially in the CHNO analysis, of even small inconsistencies was found to have a significant effect on the test results. Thus, while these data by ordinary standards stand up well, 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

** This description, in a slightly modified form, has been published in (1) but is included here for completeness.

- 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
- percent C_3 components
- percent C_4 components

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

Solid Samples

Sample Preparation--The solid samples examined consisted of the dried peanut hulls, used as feed material for the waste convertor, and chars produced by the convertor. The sample size received in the laboratory ranged from one to eight liters for the peanut hull feeds and from one to two liters for the char products. The samples were thoroughly mixed and divided by quartering or by a rifle 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 Model 4 Wiley 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--1. Percent Moisture in Peanut Hull Feeds: Duplicate 1.000 gram samples were placed in aluminum dishes and dried for one hour at 105°F in a forced air oven. The dried samples were cooled in a desiccator and weighed. The estimated error is $\pm$ 0.6 percent (absolute).

2. Percent Moisture and Percent Volatiles in Chars: These analyses were performed by ASTM Method D-271. The estimated error is ± 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 is ± 0.2 percent (absolute).

4. Heating Values: The heating values of the feeds and chars were determined in a Parr Plain (Isothermal Jacket) oxygen bomb calorimeter. Following the procedures described in pp. 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 ± one percent (relative) for pure, crystalline materials. Because of the heterogeneous nature of the samples, loss of volatiles form 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. In most cases however, the agreement was better than six percent (absolute) for carbon and oxygen in the feeds and chars. Agreement among replicate hydrogen or nitrogen determinations was better than one percent.

Oil Samples

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

Analytical Procedure--1. 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 $\pm$ five 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 that 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 convertor or from the upstream end of the condensers. The sample stream was passed through a series of water cooled condensers, a glass wool demister, an 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 Non-Condensible 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 using 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 ± five percent (relative).

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 was 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 is 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 and oil 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 non-condensible 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 can be written. These equations have been solved on the Georgia Tech Control Data CYBER 70 computer and the calculated results compared with the remaining observed data to obtain a measure of the internal consistency of the entire set of results. 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 data into a generally consistent form. Since it must be recognized that all the data is subject to some uncertainty, it has been assumed that on the average the modified values (e.g. the original value plus the variation) are likely superior to those actually measured or computed and therefore these 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 is generally consistent with earlier results (1) and shows 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:

$$(HV_g + hg)\, M_g + (HV_o + ho)\, M_o + (HV_{ch} + h_{ch})\, M_{ch} + h_{wo}\, M_{wo} =$$
$$(HV_f + h_f)\, M_f + h_a\, M_a + h_{wi}\, M_{wi} - \text{[conduction and cooling water losses]}$$

By establishing ambient conditions as a reference, h_f and h_a can be set to zero. Now generally the sensible and latent heat terms involving h_g, h_o, h_{ch}, and h_{wi} and the heat losses are small in comparison to the other terms. Thus 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.

Conservation of Nitrogen:

$$w_{ng} Mg + w_{no} M_{o} + w_{nch} M_{ch} = w_{nf} M_{f} + w_{ha} Ma \quad (3)$$

Conservation of Carbon:

$$w_{cg} M_{g} + w_{co} Mo + w_{cch} M_{ch} = w_{cf} M_{f} \quad (4)$$

Conservation of Hydrogen:

$$w_{hg} M_{g} + w_{ho} M_{o} + w_{hch} M_{ch} + w_{hwo} M_{wo} = w_{hf} M_{f} + w_{hwi} M_{wi} \quad (5)$$

Conservation of Oxygen:

$$w_{og} M_{g} + w_{oo} M_{o} + w_{och} M_{ch} + w_{owo} H_{wo} = w_{of} M_{f} + w_{oa} M_{a} + w_{owi} M_{wi} \quad (6)$$

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

$$HV_{o} = 14{,}500\, w_{co} + 61000\, w_{ho} \quad (7)$$

The C, H, N, O analysis of the oil requires that:

$$w_{co} + w_{ho} + w_{no} + w_{oo} = 1 \quad (8)$$

Likewise the C, H, N, O analysis of the char and feed requires that:

$$w_{cch} + w_{hch} + w_{nch} + w_{och} = 1 - w_{xch} \quad (9)$$

$$w_{cf} + w_{hf} + w_{nf} + w_{of} = 1 - w_{xf} \quad (10)$$

Correspondingly, a computed C, H, N, O composition of the off-gas from the gas chromatographic results requires that:

$$w_{cg} + w_{hg} + w_{ng} + W_{og} = 1 \quad (11)$$

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

The procedure, therfore, 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_{och}, w_{ow}, w_{of}, and w_{oa}
are "known to within a certain precision; generally less than 10 percent.

Once values of the eight "unknowns' are determined, a sensitivity analysis by which the effect on the computed values of the "unknowns" of individual variations in each of the 26 "known" coefficients is conducted. Those coefficients, which have a major influence on the solution, are thereby identified. Since the final object is to obtain as internally consistent a set of data as possible, the next step is a least squares procedure by which

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

** The C, H, N, O composition of the oil and its heating value have been chosen as "unknowns" first, because there is no ash in the oil as there is for the feed and the char, and second, because it is believed there is greater uncertainity in the oil composition and heating value due to the presence of water, than for the gas (which could have just as easily been used.)

variations between the measured and computed values of w_{co}, w_{ho}, w_{no}, and w_{oo}, are minimized. This is accomplished by introduction of combinations of up to four of the major influencing coefficients and by allowing the values to vary simultaneously about their "known" value, usually within bounds of $\pm$ 10%. A least squares program then selects that combination of the major influencing coefficients while minimizes the sum of the squares of the difference between the computed and measured data. This generally results in a complete set of transformed data which is very nearly consistent internally and which represents an exact solution to the first eight equations.

In one case, Test 14, variations in the "known" coefficients of considerably more than 10% were required to bring the system of equations in a proper balance. This occurred both with the char and the feed carbon content which was adjusted significantly. However, since the modified data for this case (as seen in the next section) plots up well with all the other results, it is believed that whatever the cause of this anomaly, the applied correction is made apparently in the proper term and to the required extent.

Presented in Appendix B are listings of the computer programs for the sensitivity analysis (SENSAN) and the least squares procedure (ITERAT) developed from the analysis. Also presented are sample calculations for Test 1 (Run 4) to illustrate the output of these two programs.

TEST RESULTS

Overview of Test Conditions

The experimental program involved a series of 15 tests; 13 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 the first part of the study. Of the 15 reported tests, two were checkouts of the first generation integrated mechanical agitation-process air supply system or "AIRGITATOR", for which no quantitative data was recorded. Besides these two tests, two more were found to have defective off-gas compositions, apparently due to an air leak somewhere in the system. Thus while some data for these latter two tests were obtained, the primary basis for the results presented in this section is the 11 remaining tests.

Of the 11, ten were conducted using the hulls, and one with sawdust. There was one extended run of 12 hours using hulls (Test 7), but normally the runs lasted two to three hours, sometimes slightly more or less. In addition, two of the 11 were conducted using the "AIRGITATOR". In the 9 basic tests, the influence of mechanical agitation, changing feed material, changing bed depth and the air/feed ratio was studied. In the latter two tests, the performance of the "AIRGITATOR" was evaluated at a fixed bed depth.

Table 1 presents a summary of the test conditions, along with some of the observed data from the pilot plant tests. Study of the table shows that basic agitation was involved in eight of the 15 tests conducted, while three were completed without any form of agitation. Four tests were made with the "AIRGITATOR".

TABLE 1

TEST SUMMARY

Test Number	Feed	Feed Rate lb/hr	% Char Yield	% Oil & Aqueous Yield	Air/Feed	Off-Gas Temp. (°F)	Bed Depth	Agitation	Airgitation
1	Peanut Hulls	1260	21.7	3.9	.364	207	52	No	No
2	Peanut Hulls	859	23.9	8.5	.265	200	52	No	No
3	Pine Sawdust	1490	26.6	5.7	.172	235	52	No	No
4	Pine Sawdust	1022	24.9	7.0	.251	285	52	Yes	No
5	Peanut Hulls	1090	28.8	7.9	.227	188	52	Yes	No
6	Peanut Hulls	1060	32.1	7.2	.277	186	52	Yes	No
7	Peanut Hulls	1050	22.9	4.7	.270	190	52	Yes	No
8	CHECK OUT "AIRGITATOR"							No	Yes
9	Peanut Hulls	900	40.0	16.1	.458	174	35	Yes	No
10	Peanut Hulls	1105	24.9	4.53	.464	190	35	Yes	No
11	Peanut Hulls	1257	27.0	23.4	.539	188	35	Yes	No
12	Peanut Hulls	1038	28.4	17.8	.613	182	35	Yes	No
13	CHECK OUT MODIFIED "AIRGITATOR"							No	Yes
14	Peanut Hulls	1080	41.4	3.5	.140	345	50	No	Yes
15	Peanut Hulls	715	28.3	26.2	.190	440	50	No	Yes

TOTAL OPERATING TIME = 119.5 hours

TOTAL FEED PROCESSED = 95,510 pounds

Further, it is seen that testing was conducted at two bed depths, i.e. 50-52 inches and 35 inches. The air/feed varied from 0.14 to 0.613; a range within which most operations would be found. Study of the off-gas temperatures indicates they were generally in the range of 170 to 190^{o}F, except the two tests with sawdust, which ran somewhat hotter. While not reported, the condenser temperature was usually in the range of 200 to 210^{o}F, except in the last test where it was set at 175^{o}F to determine the influence of condenser temperature on oil recovered.

Additional study of the table shows that the dry feed rates varied from slightly over 700 lb/hr to nearly 1,500 lb/hr. One puzzling result is the wide variation in the recovered oil and aqueous phases from the condenser. Reference to Appendix A reveals that sometimes the water content is quite significant, and other times it is small. Apparently minor variations in the off-gas and condenser temperatures can produce significant changes in the oil moisture content. Because a very substantial part of the oil yield exists, it is believed, in the form of more volatile hydrocarbons, the recovered yields (on a dry basis), with the exception of Test 15, are generally much smaller than the computed yields, as discussed in the following section.

In the course of the testing, almost 100,000 pounds of feed were consumed and the unit was operated for a total of 119.5 hours.

Analysis of the Data

Besides the data shown in Table 1, the laboratory analysis of the feed, char, oil and non-condensible off-gas are presented in Appendix A. The data from these tables was transformed in the manner described in the previous section to produce a generally

Table 2

Summary of Transformed Data

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
(Gas)												
N_2	lb/lb	.485	.530 (-8%)	.382 (-8%)	.442	.434	.517 (-8%)	.574	.478	.510 (-8%)	.396	.351
C	lb/lb	.191	.199	.258 (-2%)	.194	.201	.199	.163	.189	.199	.216	.218
H_2	lb/lb	.021	.021	.027	.028	.028	.017	.019	.017	.016	.018	.011
O_2	lb/lb	.303	.289	.364	.336	.338	.306	.244	.314	.314	.369	.422
HV	BTU/lb	2700	2680	3540	2750	2750	2400	2370	2310	2530 (-8%)	2380	1540
(Char)												
N_2	lb/lb	.025	.021	.011	.029	.027	.027	.008	.008	.011	.011	.007
C	lb/lb	.721 (4%)	.829	.844	.724	.795 (-8%)	.677 (8%)	.808 (-8%)	.809 (-4%)	.773	.393 (-50%)	.818 (-4%)
H_2	lb/lb	.026	.018	.017	.017	.016 (5.5%)	.018	.015	.013	.009	.018	.014
O_2	lb/lb	.089	.032	.064	.165	.121	.121	.103	.031	.089	.115	.091
HV	BTU/lb	11000	12800	13200	12200 (10%)	12600 (2%)	12100	11900	12300	11500	12500	12400
(Feed)												
N_2	lb/lb	.017	.021	.001	.012	.012	.012	.012	.012	.012	.007	.007
C	lb/lb	.457 (6%)	.462 (2%)	.450 (2%)	.445 (6%)	.473	.444 (8%)	.464 (4%)	.444 (8%)	.483	.304 (40%)	.466 (8%)
H_2	lb/lb	.061	.058	.054	.057	.057	.059	.059	.059	.059	.061	.061

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
O_2	lb/lb	.437	.452	.488	.457	.458	.446	.446	.446	.446	.427	.427
HV	BTU/lb	8370	7920	7730 (6%)	8170	8330 (-2%)	8600 (2%)	8250 (6%)	7900 (10%)	8600 (2%)	8510	8510
WNO	lb/lb-oil	.041	.047	.016	.029	.078	.014	.015	.015	.017	.012	.012
HVO	BTU/lb-oil	12100	12100	97600	12000	11700	14100	11600	15500	15800	15800	16300
WT CHAR	lb/100 lb dry feed	21.7	23.9	26.6	32.1	22.9	40.0	24.9	27.0	28.4	41.4	28.3
WGT FEED	100 lb dry	100	100	100	100	100	100	100	100	100	100	100
WGT AIR	lb/100 lb dry feed	36.4	26.5	17.2	27.7	27	45.8	46.4	53.9	61.3	14.0	19.0
WGT MOIS-TURE	lb/100 lb dry feed	4.6	4.5	5.3	4.8	4.8	28.7	28.7	28.7	28.7	6.5	6.5
ENERGY LOSSES	BTU/100 lb dry feed	54000	54000	54000	54000	54000	54000	54000	54000	54000	27000	54000
WEIGHT FRACTIONS OF ELEMENTS IN OIL												
C	lb/lb	.657	.831	.758	.732	.687	.737	.725	.722	.712	.703	.694

	Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
Measured	H_2	lb/lb	.071	.059	.067	.080	.081	.080	.084	.080	.075	.077	.077
	O_2	lb/lb	.242	.064	.145	.158	.155	.168	.176	.182	.197	.208	.217
	N_2	lb/lb	.040	.047	.016	.029	.078	.014	.015	.015	.017	.012	.012
Computed	C	lb/lb	.650	.813	.670	.723	.723	.582	.743	.691	.679	.660	.676
	H_2	lb/lb	.043	.004	.001	.021	.024	.093	.013	.090	.097	.102	.106
	O_2	lb/lb	.269	.144	.306	.210	.175	.270	.215	.212	.181	.152	.107
	N_2	lb/lb	.034	.039	.024	.046	.078	.056	.028	.008	.043	.087	.111
	MASSES												
	Gas	lb/100 lb	57.7	39.5	33.3	44.2	47.8	68.2	63.4	88.6	94.0	27.5	42.4
	Oil	lb/100 lb	29.1	22.8	20.7	27.9	14.0	6.49	21.4	8.45	11.3	12.4	20.9
	Moisture	lb/100 lb	32.5	44.9	42.0	36.7	36.1	59.8	65.4	58.5	56.4	39.2	33.9

consistent set of results which is believed to be, on the average, more accurate than the original raw data. This transformed data is presented in Table 2 and is the basis for all further discussion of the testing. Shown also in the table, in parentheses, are the amounts the transformed data was changed from the original. Inspection reveals that only a minor part of the data has been modified and the changes are generally small.

While many of the modifications appear to be random, there is a rough pattern to some of the changes. For example, there appear to be relatively frequent reductions of the order of 8 percent on 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 where the carbon content of the feed and the heating value of the feed must be increased about 6 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, are the considerable variations present in the computed oil heating values and also in the measured values tabulated in Appendix A. 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, which 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 13,335 Btu/lb. Regarding the laboratory reported heating values which are for the indicated moisture contents, again an average of the dry heating values is probably a more accurate value (in passing it should be noted that the uncertainity in the moisture percentage can be significant and thus the corrected heating value is also uncertain). However, upon adjusting the indicated numbers to a dry basis and after computing an average value, the result obtained is 14,230 Btu/lb which is 6.3% greater than the average of the computed results. It is believed that the justification for working with these average values is adequate, and that these two values are sufficiently in agreement to satisfy the accuracy requirements of the study.

Using the results presented in Table 2, several informative graphs can be drawn. This is done in the next six figures which correlate closely with corresponding figures in (1).

Graphical Data Presentations

Perhaps the most important results of the entire program are those plotted in Figure 9 which presents the percent available energy of the char and oil (related to the feed) as a function of the air/feed ratio. The figure shows that for all the tests, at various bed depth, with and without agitation and with both sawdust and peanut hulls, the data correlates to a single line. This line is identical to that reported in (1) using sawdust in a unit 1/2 the geometric scale 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 10 for which the best fit straight line is again identical to both that in Figure 9 and that from (1).

This suggests therefore, that to an acceptable engineering precision the available energy fraction of the feed in the char-oil mix is independent of unit scale, feed material, bed depth and the presence of mechanical agitation; and is a linear function only of the air/feed ratio.

Figure 11 presents an energy breakdown of the pyrolysis products as a function of the air/feed ratio. Examination of the figure reveals the relative consistency of the data and, as in Figure 9, suggests that the dominant influencing variable is the air/feed ratio. Comparison of similar results from (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 with the results from (1). And finally the combined energy in the char-oil agrees very well with the results from (1).

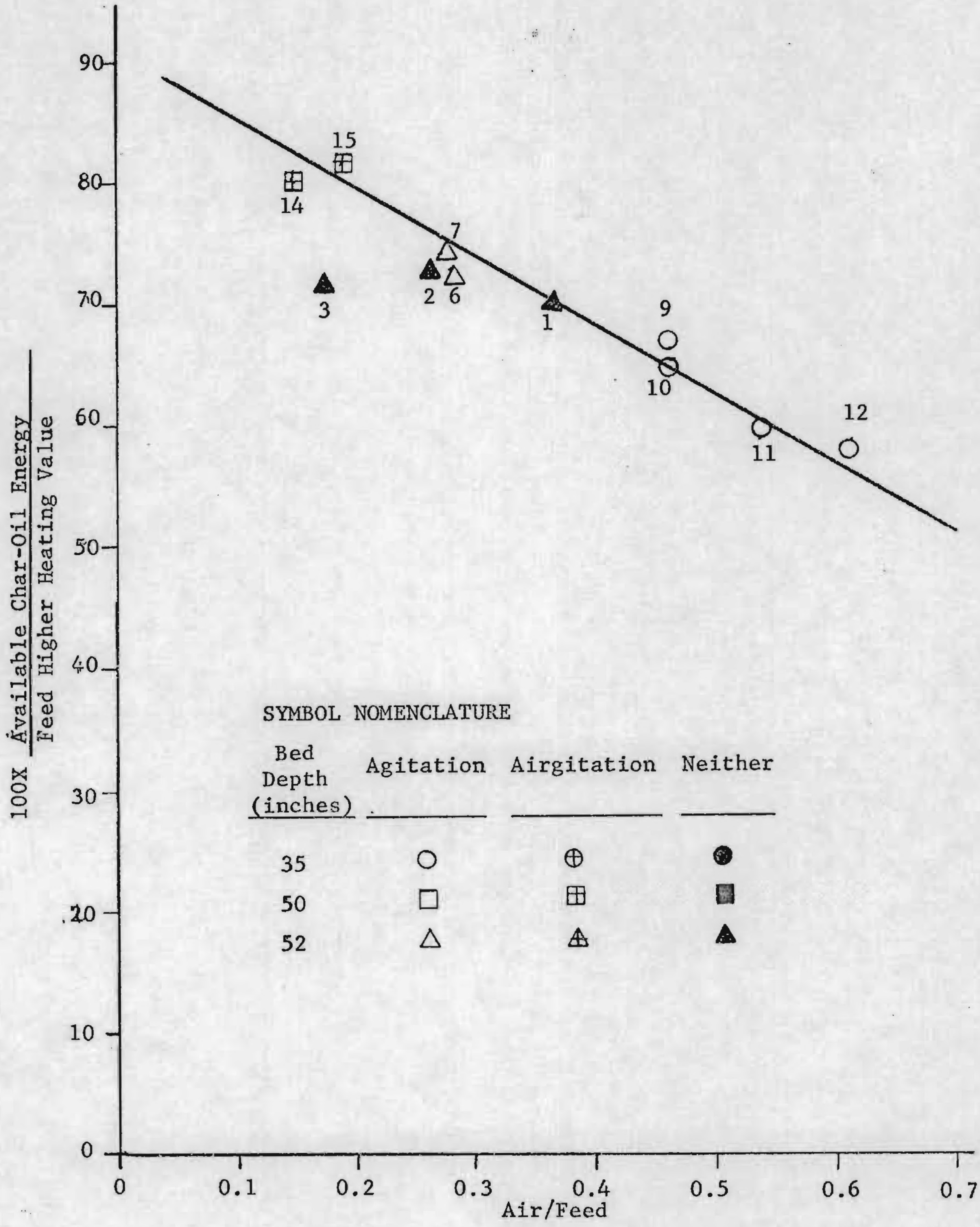

Figure 9

Percent Available Energy in Char-Oil Mixture

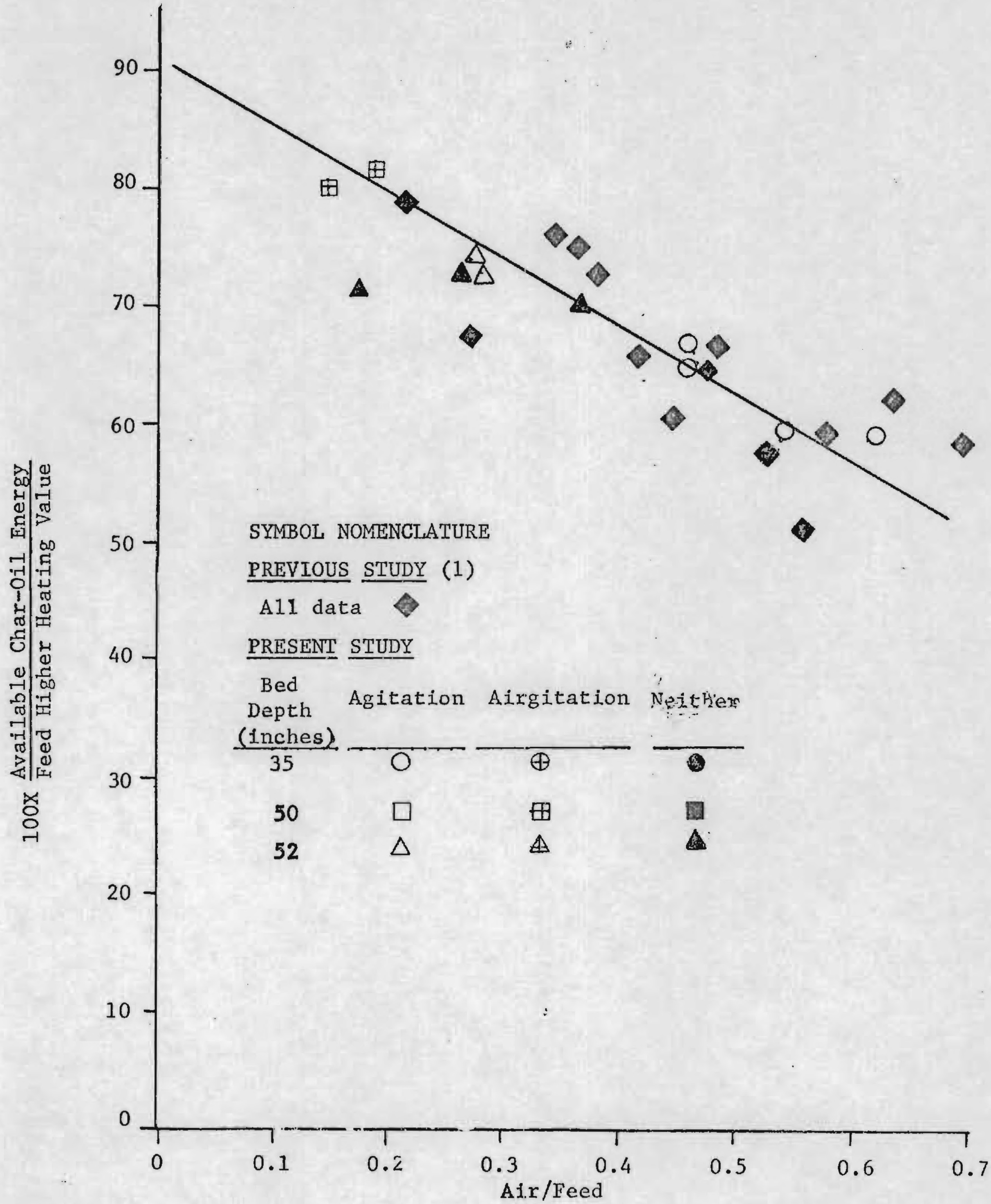

Figure 10

Percent Available Energy in Char-Oil Mixture- Composite of all Data

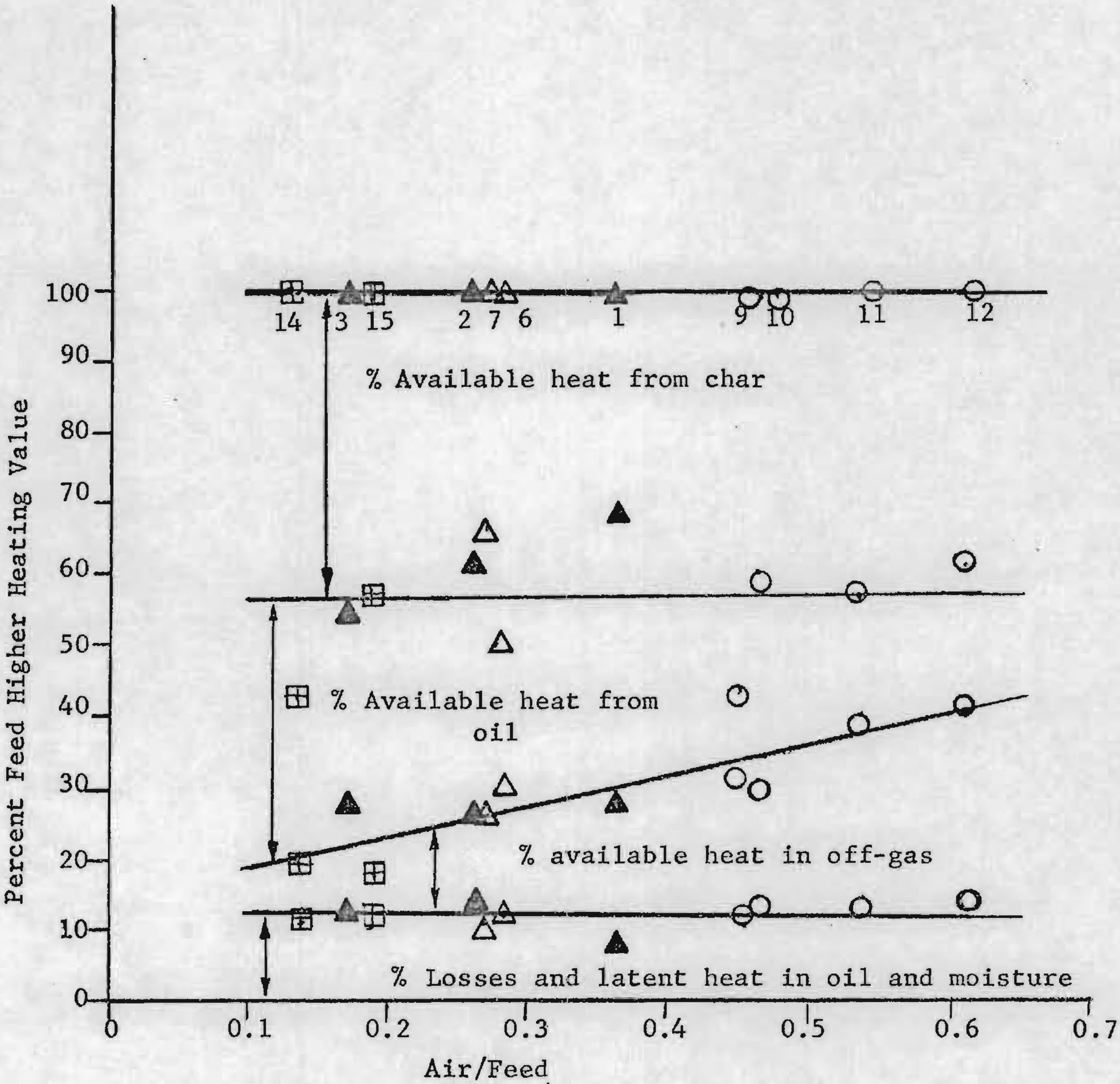

Figure 11

Energy Breakdown of Pyrolysis Products

However, there is a significant difference in the way in which the separate energies in the oil and char vary from those presented in (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/feed ratio:

In (1), the char yields linearly decreased with increasing air/feed while in the present study the char yields remain practically constant and independent of air/feed, whereas the oil yields decrease with increasing air/feed. However, in (1) the pyrolysis off-gas temperatures were always in the range of 300-350°F while in the present study the off-gas temperatures using peanut hulls[+] and with the exception of Test 14 and 15[++], were in the range of 170-200°F. 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 taught that when pyrolytic oils are heated, a significant degree 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 part of the original oil evaporated, while a considerable portion was converted into solid carbon. The result was the almost constant char yields and a diminishing oil yield with increasing air/feed.

+ The off-gas temperatures with the sawdust were somewhat higher, but still low in comparison with the tests in (1) using sawdust.

++ Test 14 and 15 were conducted using the integrated mechanical agitation-air supply system and for reasons presently not completely understood produced relatively high off-gas temperatures at very low air/feed ratios.

The reason why the off-gas temperatures in the present study were generally so low compared with the results from (1) is because the bed depth was generally near the maximum. The results from (1), at a smaller scale, had suggested that for maximum oil yields a larger bed depth was desirable and therefore, in the present study the larger 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 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. Under these conditions a breakdown of the oily products occurs to produce more gaseous constituents. For increasing bed depth, the oil yields increase 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 12 which also shows the surmised operating zones for the present study and that for (1).

Taken together, this all suggests that while the sum of the energy in the char and oil is basically dependent only on the air/feed ratio, the distribution of the energy between the oil and the char is a function of both the bed depth and the air/feed. Thus a means to independently vary the relative amounts of oil and char

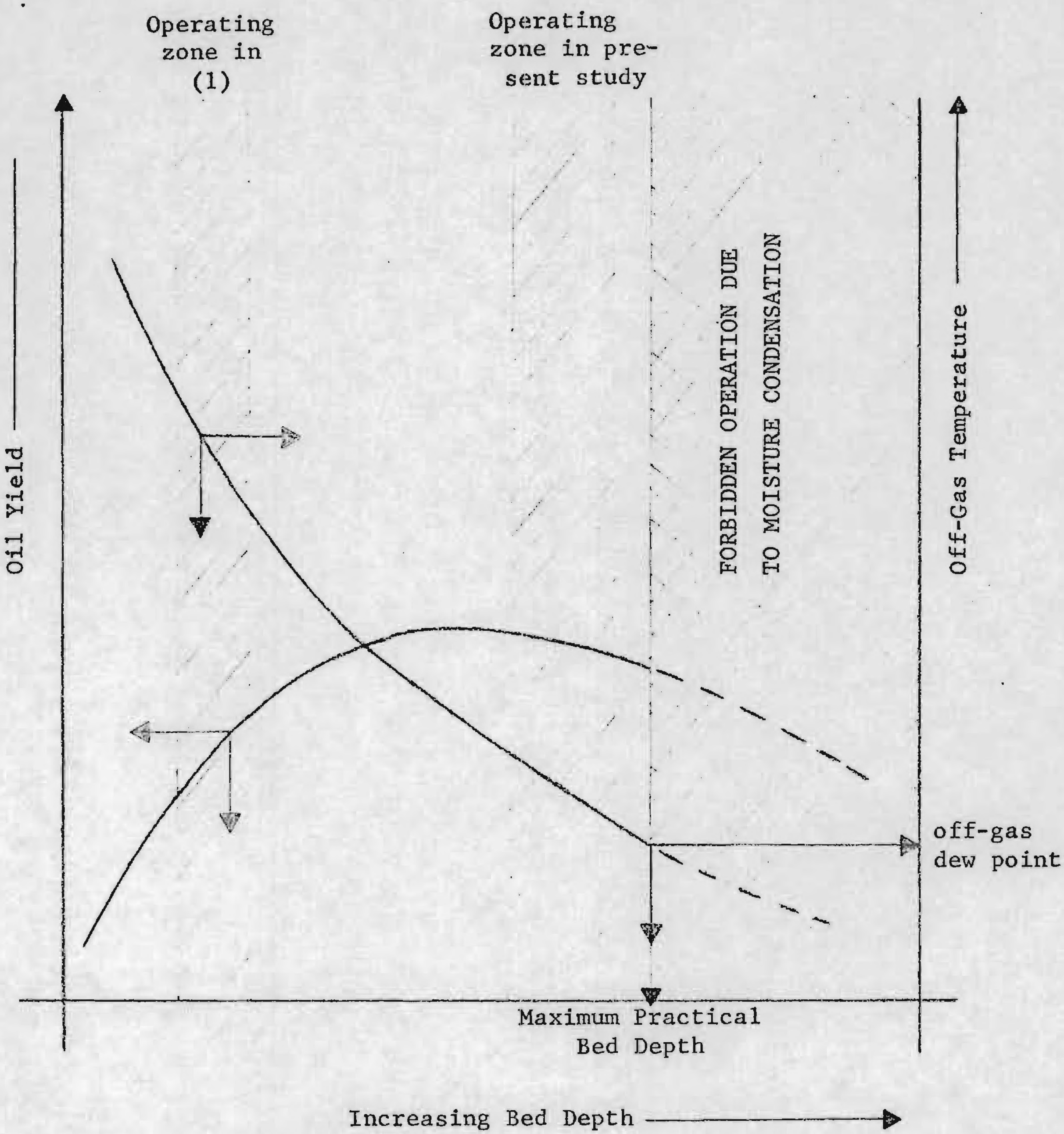

Figure 12

Oil Yield Variation with Increasing Bed Depth

in the pyrolysis products for a fixed air/feed exists. Conveniently, the off-gas yields appear to be relatively independent of the bed depth and only a function of air/feed.*** 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 noted that when the 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 theoretically available energy in the char-oil mixture is constant (at a given air/feed), 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.

*** This indicates that 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.

Thus 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 13 is a crossplot of computed data from (1) and experimental data from the present study. The figure provides a convenient means for determining the required air/feed ratio for a given feed moisture percentage and further 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 (1). To illustrate the use of the figure, at a feed moisture percentage of 20 percent, the required energy for drying and processing is 800 Btu/lb dry feed. Correspondingly, at an air/feed value of .16 the available energy in the char-oil is 6,500 Btu/lb; thus establishing the relation between the moisture content and the air/feed. Finally for convenience the figure allows computation of the energy available in the char-oil mixture, as shown earlier in Figure 9.

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‡ Thus one of the important advantages of the AIRGITATOR system is its ability to continuously vary the bed depth, therefore providing the capability to vary the relative oil and char yields over a wide range.

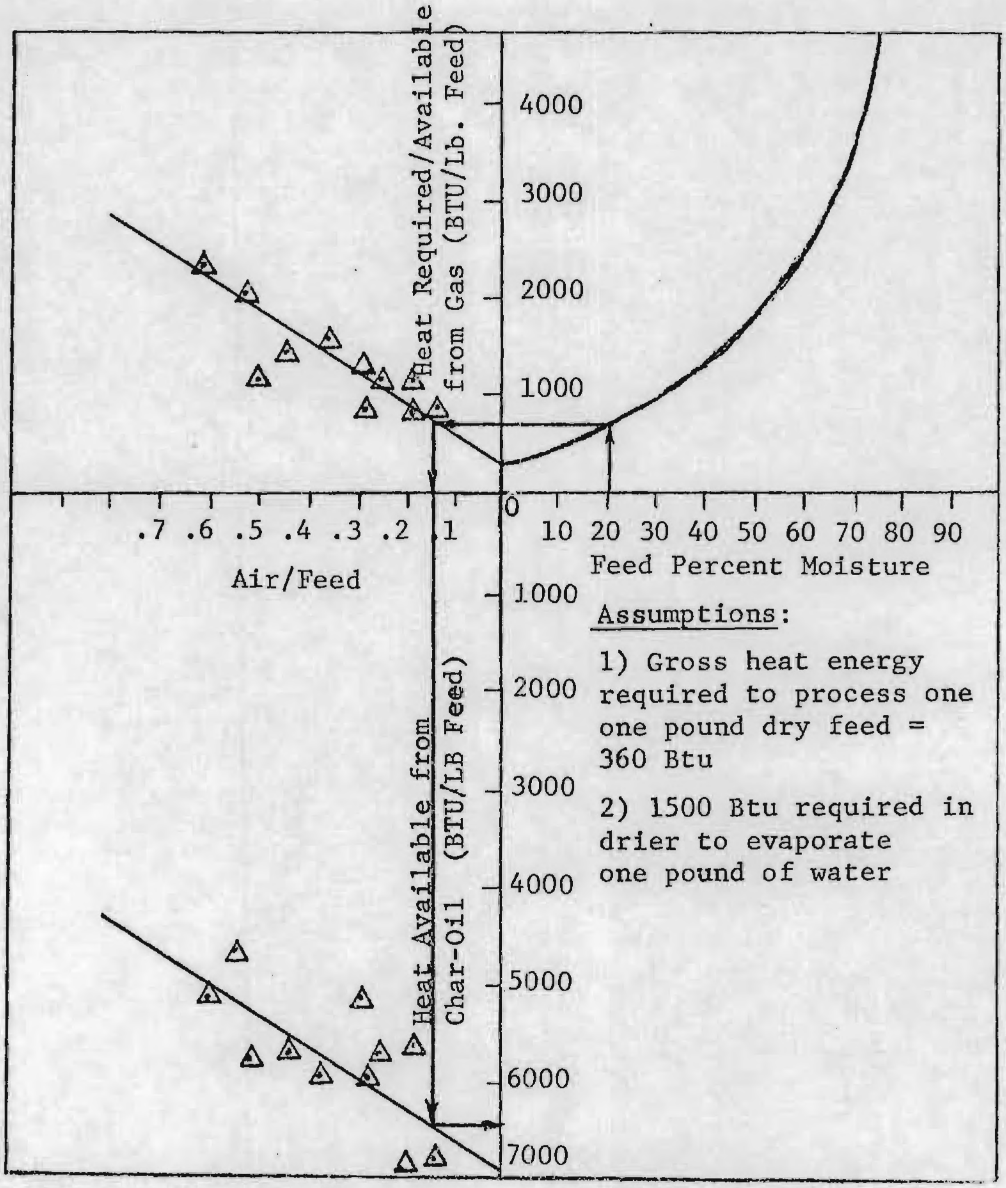

Figure 13

Effects of Feed Moisture on Available Energy from Char-Oil Mixture.

Figure 14 presents a plot of the heating value of the non-condensible component of the off-gas in Btu/standard cubic feet as a function of air/feed. As before, and as in (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 (1) and thus again establishes the close correlation of the data from the two studies.

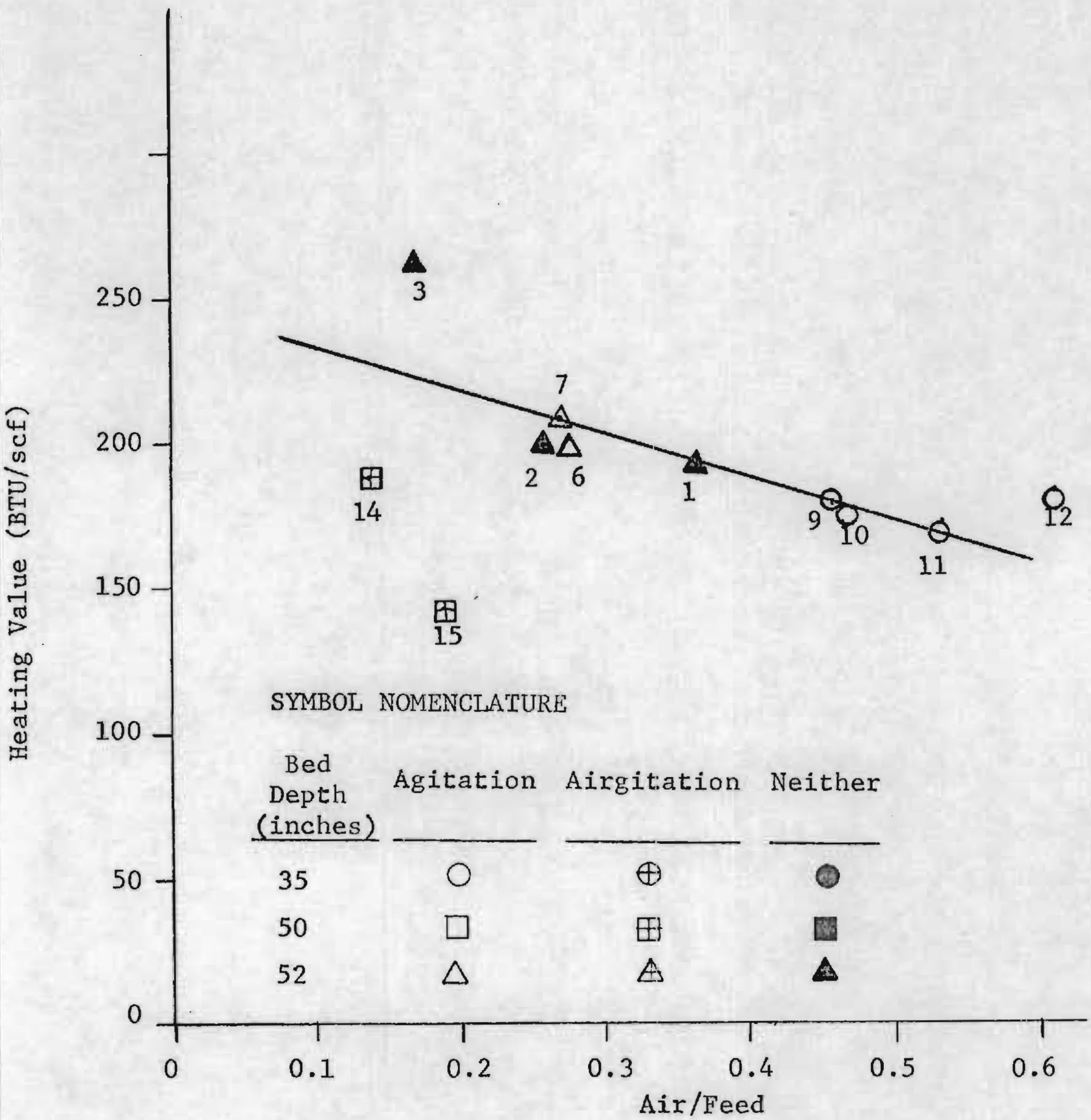

Figure 14

Heating Value of Non-Condensible Gas

SECTION V

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 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 so doing, the principal hindrance to flow through the converter is changed into a means for facilitating the flow. Such a system also possibly allows the processing of somewhat wetter feed than the present EES waste converter permits. This section, then, presents a description of a "first generation" integrated mechanical agitation-process air supply system or "AIRGITATOR" and a discussion of the initial 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 possiblity of failure and the opportunity for leaks, by minimizing the number of welds. Thus an "L" shaped system was chosen.

The system is presented schematically in Figure 8 and the design is shown in Figure 15. The tubes are made of 4130 stainless steel and are typically 1/8 inch thick. The air delivery parts are 1/16 inch in diameter and located 1/2 inches apart. From the metal types and gages, it should be apparent that the system was designed to withstand a huge torque in a relatively hostile environment. A photograph of the unit, fabricated in the EES shop, is presented in Figure 16.

A commercially available rotating coupling, which was compatible with the water and air flows required, was found; thus avoiding the necessity for designing and fabricating this component at the EES. This coupling, along with the final drive mechanism and the copper tube connections for the process air and cooling water are shown in Figure 17 which depicts the "AIRGITATOR" installed on top of the convertor. The installed system, as can be seen, is not complex, and involved a drive system, the coupling and the "L" shaped "AIRGITATOR".

In the initial design, the horizontal portion of the unit extended to within one inch of the inside walls of the convertor and the ends were cut off squarely. A later modification involved the removal of one inch from this horizontal portion and the beveling of the

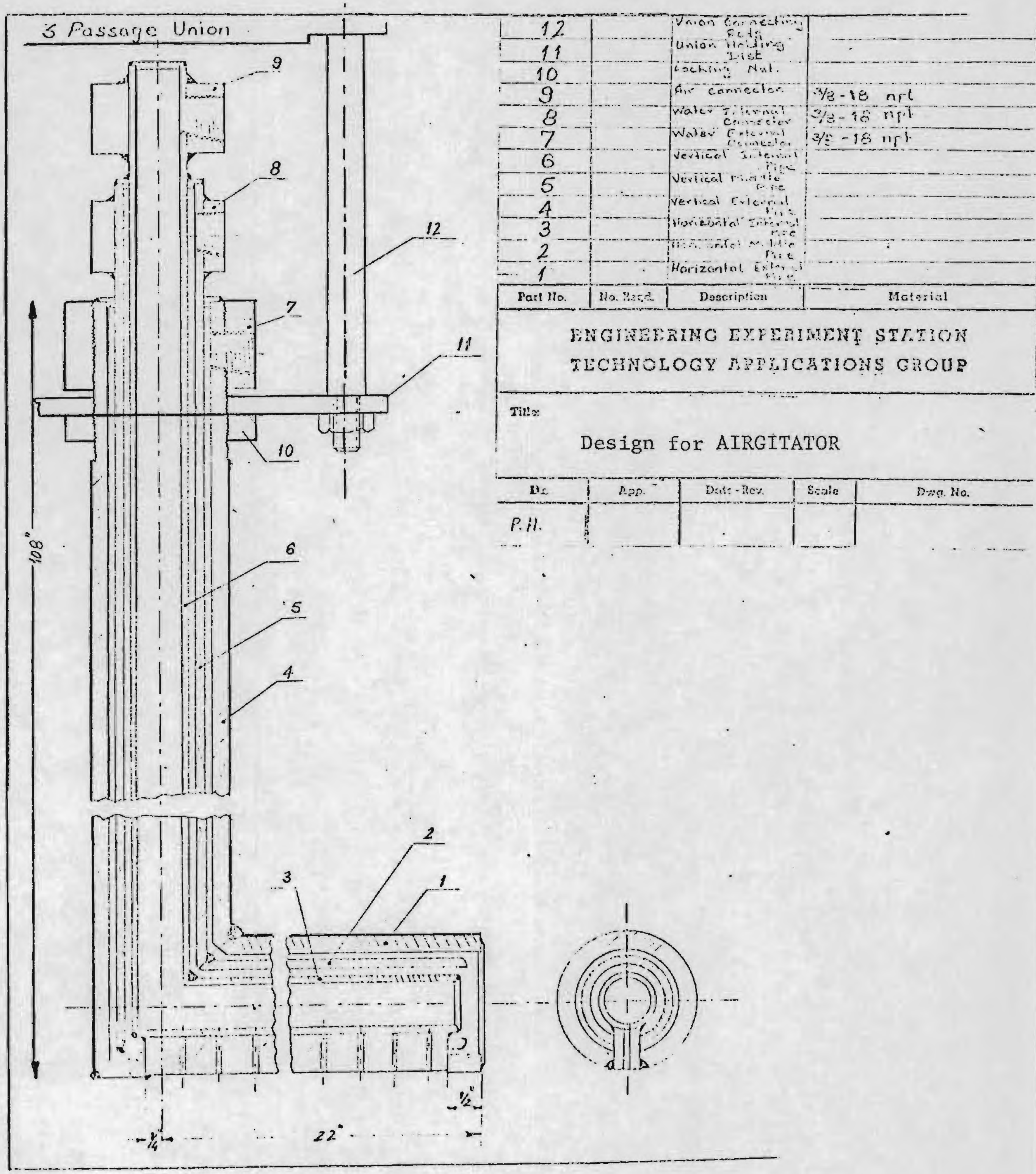

Figure 15

Integrated Mechanical Agitation - Process Air Supply System

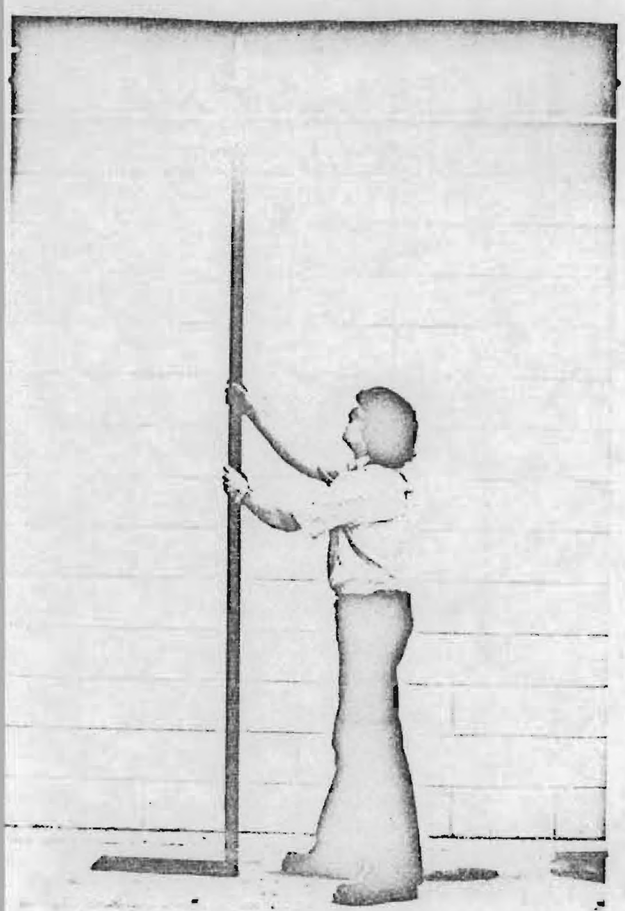

Figure 16

Overall View of AIRGITATOR

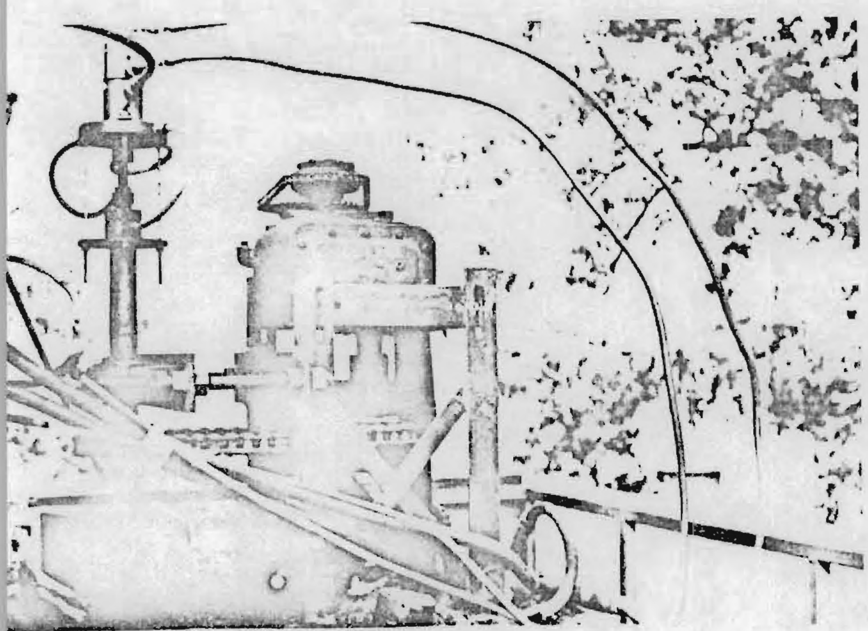

Figure 17

AIRGITATOR Installed on Pyrolytic Convertor end so that the end surface formed a sharp edge which cut through the char. These modifications were made to avoid binding of the feed between the walls and the end of the unit, in situations where due to irregularities in the inner surface, the end appraoched the wall too closely.

SYSTEM TESTING

About midway through the main test program, the first checkout tests of the "AIRGITATOR" were conducted. The results of these first tests were almost disastrous; the main bearings supporting the unit failed after several hours of testing, apparently due to very large torques that occasionally were required to rotate the system. It was concluded that binding, as described above, had occurred and the indicated modifications were made. Additionally, the complete drive system was strengthened substantially.

The modified unit was then tested and no problems were encountered. Apparently the improvements made were sufficient to overcome the difficulty. One important feature in these 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 enabled a stable hot char zone to be established initially, but provided a cushion against "losing the char bed" in anomalous circumstances where the instantaneous feed rate exceeded the charring rate and threatened the loss of the hot char which sustains the bed operation.

Perhaps the most interesting feature of the latter tests were the relatively high off-gas temperatures achieved at very low air/feed ratios. The ease with which the system operated, the high quality

of the char and the clear ability of the system to operate at a much greater throughput than tested, taken together demonstrated that the potential of the "AIRGITATOR" is at least as great as has initially been forecast and is perhaps even greater. In addition, the ability of the system to vary the bed depth continuously provides an important capability with which to tailor the oil and char yields to meet a wide range of requirements.

SECTION VI

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SECTION VII

APPENDICES

A. Laboratory Test Results

B. Data Analysis Computer Program

APPENDIX A-LABORATORY DATA

Listed in the following pages are the results of the laboratory analysis described in Section IV for the feed, char, oil and off-gases from the test program. 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 Table 2, have been corrected for this moisture. The CHNO analysis and heating values for the feed and char are on a dry basis.

TABLE A-1

LABORATORY ANALYSIS

TEST 1

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION
WATER	Percent	4.4	8.3	11.9	N_2	44.37
ASH	Percent	3.4	10.9	-	CO	16.88
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	15.78
					H_2	16.17
					CH_4	4.60
CARBON	Percent	48.6	75.1	57.0	C_2H_6	0.52
HYDROGEN	Percent	6.0	2.6	7.6	C_2H_4	0.72
NITROGEN	Percent	1.7	2.5	3.5	C_3H_8	0.13
OXYGEN	Percent	43.7	8.9	31.9	C_3H_6	0.24
HEATING VALUE	Btu/ lb	8372	10950	12528		

1. The CHNO analysis and heating values are based on oil with the indicated mositure content.

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

TABLE A-2

LABORATORY ANALYSIS

TEST 2

	UNITS	FEED	CHAR [2]	OIL [1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: 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
					CH_4	5.52
CARBON	Percent	47.0	82.9	55.5	C_2H_6	0.63
HYDROGEN	Percent	5.8	1.8	7.6	C_2H_4	0.90
NITROGEN	Percent	2.03	2.1	3.11	C_3H_8	0.14
OXYGEN	Percent	45.17	3.2	33.79	C_3H_6	0.27
HEATING VALUE	Btu/lb	7915	12800	9539		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

TABLE A-3

LABORATORY ANALYSIS

TEST 3

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COM-POSITION
WATER	Percent	5.0	4.6	21.1	N_2	33.8
ASH	Percent	1.2	6.5	-	CO	18.2
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	24.0
					H_2	12.5
					CH_4	9.5
CARBON	Percent	45.8	84.4	60.6	C_2H_6	0.6
HYDROGEN	Percent	5.4	1.7	7.7	C_2H_4	0.9
NITROGEN	Percent	0.1	1.1	1.3	C_3H_8	0.1
OXYGEN	Percent	48.8+.1	6.4	30.4	C_3H_6	0.3
HEATING VALUE	Btu/lb	8225	13221	10311		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

TABLE A-4

LABORATORY ANALYSIS

TEST 6

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION
WATER	Percent	4.6	2.7	17.9	N_2	41.1
ASH	Percent	2.3	6.5	–	CO	9.8
ACID INSOLUBLE ASH	Percent	–	–	–	CO_2	22.4
					H_2	18.7
					CH_4	6.7
CARBON	Percent	47.3	72.4	60.1	C_2H_6	0.6
HYDROGEN	Percent	5.7	1.7	8.6	C_2H_4	–
NITROGEN	Percent	1.2	2.9	2.4	C_3H_8	0.6
OXYGEN	Percent	45.8	16.5	28.9	C_3H_6	–
HEATING VALUE	Btu/lb	8170.67	13590	No Fire		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

TABLE A-5

LABORATORY ANALYSIS

TEST 7

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COM-POSITION
WATER	Percent	4.6	0.6	16.1	N_2	41.9
ASH	Percent	2.3	9.8	-	CO	24.51
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	8.14
					H_2	15.07
					CH_4	8.91
CARBON	Percent	47.3	73.6	57.6	C_2H_6	0.65
HYDROGEN	Percent	5.7	1.8	8.6	C_2H_4	-
NITROGEN	Percent	1.2	2.7	6.5	C_3H_8	0.78
OXYGEN	Percent	45.8	12.1	27.3	C_3H_6	-
HEATING VALUE	Btu/lb	8170.67	12828	10761		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

TABLE A-6

LABORATORY ANALYSIS

TEST 9

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION
WATER	Percent	22.3	0.6	20.3	N_2	45.32
ASH	Percent	4.6	9.8	-	CO	19.89
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	15.36
					H_2	6.14
					CH_4	5.67
CARBON	Percent	48.3	73.6	56.9	C_2H_6	0.66
HYDROGEN	Percent	5.9	1.8	8.7	C_2H_4	0.52
NITROGEN	Percent	1.2	2.7	1.1	C_3H_8	0.13
OXYGEN	Percent	44.6	12.1	33.3	C_3H_6	0.20
HEATING VALUE	Btu/lb	8773	12063	11848		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

TABLE A-7

LABORATORY ANALYSIS

TEST 10

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION
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
					CH_4	4.40
CARBON	Percent	48.3	74.8	53.6	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.5	9.1	C_2H_4	0.50
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	10.3	36.2	C_3H_6	0.18
HEATING VALUE	Btu/lb.	8773	11945	11264		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

TABLE A-8

LABORATORY ANALYSIS

TEST 11

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION
WATER	Percent	22.3	3.2	28.6	N_2	46.98
ASH	Percent	4.6	17.0	–	CO	17.91
ACID INSOLUBLE ASH	Percent	1.4	–	–	CO_2	18.18
					H_2	11.13
					CH_4	4.63
CARBON	Percent	48.4	77.8	51.5	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.3	8.9	C_2H_4	0.53
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	3.1	38.5	C_3H_6	0.16
HEATING VALUE	Btu/lb	8773	11872	10473		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

TABLE A-9

LABORATORY ANALYSIS

TEST 12

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PERCENT COMPOSITION
WATER	Percent	22.3	1.2	34.0	N_2	46.88
ASH	Percent	4.6	20.1	-	CO	21.86
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	16.36
					H_2	8.72
					CH_4	4.84
CARBON	Percent	48.3	77.3	47.0	C_2H_6	0.43
HYDROGEN	Percent	5.9	0.9	8.7	C_2H_4	0.63
NITROGEN	Percent	1.2	1.1	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	8.9	43.2	C_3H_6	0.19
HEATING VALUE	Btu/lb	8773	10848	11010		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

TABLE A-10

LABORATORY ANALYSIS

TEST 14

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PERCENT COMPOSITION
WATER	Percent	6.1	1.2	14.7	N_2	40.3
ASH	Percent	2.8	7.1	-	CO	23.2
ACID INSOLUBLE ASH	Percent	0.5	1.0	-	CO_2	19.3
VOLATILES		-	12.2	-	H_2	9.84
					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	42.7	11.5	30.8	C_3H_6	0.1
HEATING VALUE	Btu/ lb	8508	12527	11305		

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1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

TABLE A-11

LABORATORY ANALYSIS

TEST 15

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION
WATER	Percent	6.1	0.9	18.1	N_2	47.0
ASH	Percent	2.8	10.2	-	CO	11.1
ACID INSOLUBLE ASH	Percent	0.5	3.0	-	CO_2	26.1
VOLATILES		-	11.0	-	H_2	0.5
					CH_4	3.33
CARBON	Percent	50.6	78.7	56.8	C_2H_6	0.99
HYDROGEN	Percent	6.1	1.4	6.29	C_2H_4	-
NITROGEN	Percent	0.7	0.7	1.0	C_3H_8	0.20
OXYGEN	Percent	42.7	9.1	35.91	C_3H_6	0.13
HEATING VALUE	Btu/lb	8508	12439	10471		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

APPENDIX B-LISTING OF DATA REDUCTION COMPUTER PROGRAM

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

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= 15189.4
WCO= .813636 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= .793034 WHO= .034429 WOO= .184937 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= .184937 WNO=-5.14157E-2
-10% OF NOM W(3)= .0189
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 14526.9
WCO= .836796 WHO= .039235 WOO= .184937 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= 36.0088 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
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```
NOMINAL W( 13 )= .11
+10% OF NOM W( 13 )= .121
MG= 58.0327 MO= 25.3575 MW= 35.9098 HVO= 13405.2
WCO= .836796 WHO= 2.08469E-2 WOO= .184997 WNO=-4.26336E-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= .294888 WNO=-.166113

NOMINAL 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

NOMINAL W( 16 )= .017
+10% OF NOM 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

NOMINAL 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
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NOMINAL W( 20 )= 9372
+10% OF NOM W( 20 )= 9209.2
MG= 57.4638 MO= 32.097 MW= 29.7492 HVO= 12608.6
WCO= .664634 WHO= 4.97003E-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 WHO= 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= 24.631 MW= 30.796 HVO= 15086.2
WCO= .816189 WHO= 5.33032E-2 WOO= .303399 WNO=-.172891
-10% OF NOM W( 21 )= .693
MG= 52.1923 MO= 26.084 MW= 41.0237 HVO= 13423.7
WCO= .856255 WHO= 1.66061E-2 WOO= 7.31996E-2 WNO= .053939

NOMINAL 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

NOMINAL 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

NOMINAL W( 25 )= 0
+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
-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

NOMINAL 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

NOMINAL W( 27 )= 13713
```

```
+10% OF NOM W( 27 )= 15084.3
MG= 58.2459 MO= 22.8399 MW= 38.2146 HVO= 15087.8
WCO= .927253 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= 35.4053 HVO= 14248.1
WCO= .827633 WHO= 3.68315E-2 WOO= .208677 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= 3.23278E-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= 58.1698 MO= 13.5884 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= 3.45410E-2 WOO= .186084 WNO=-5.60604E-2


NOMINAL W( 32 )= 54000
+10% OF NOM W( 32 )= 59400
MG= 58.0694 MO= 24.9234 MW= 36.3072 HVO= 14369.7
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	.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
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),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
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
```

B-446
(Corrections)

October 1976

DEVELOPMENT OF A PROTOTYPE SYSTEM FOR PYROLYSIS OF AGRICULTURAL WASTES INTO FUELS AND OTHER PRODUCTS

by

J. W. Tatom and A. R. Colcord

Engineering Experiment Station
Georgia Institute of Technology
Atlanta, Georgia 30332

Grant No. R 803430-01-0
Program Element No. EHE-624

EPA Project Officer: W. W. Liberick, Jr.

Industrial Environmental Research Laboratory
Office of Energy, Minerals and Industry
Cincinnati, Ohio 45268

Prepared for

U. S. ENVIRONMENTAL PROTECTION AGENCY
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ABSTRACT

An experimental study of the performance of the one tonne/hr pyrolytic convertor located at the Georgia Tech Engineering Experiment Station has been conducted. Peanut hulls were used as the feed in a series of thirteen tests. In addition, two tests were conducted using sawdust. The objects of the test program were to determine the effects of scale, feed material, mechanical agitation, air/feed and bed depth on the product yields of the EES pyrolytic convertor. Also investigated was the performance of an integrated mechanical agitation-air supply system (AIRGITATOR) designed to improve the throughput of the unit.

From the tests, and after comparison with earlier smaller scale work with sawdust, it appears that changing feed and scale, and the use of mechanical agitation have little influence on the product yields. Bed depth, while not affecting the total potentially available energy in the char and oil, substantially influences the relative amounts of these products. The air/feed ratio again appears to be the dominant influencing variable and data from the present study and earlier work are shown to correlate to a single curve.

The influence on system performance of the integrated mechanical agitation-air supply system, while not investigated comprehensively, appears to be very favorable. Using this system, off-gas temperatures were raised, while stable operation was maintained at very low values of air/feed.

This report is submitted in fulfillment of EES Project Number B-446 in an initial reporting period. The work was supported under Grant Number R 803430-01-0 of the Environmental Protection Agency. Work was completed in December 1975.

CONTENTS

FIGURES

TABLES

NOMENCLATURE

Symbols	Definition	Units
h	Enthalpy	kcal/gm
HV	Heating Value	kcal/gm
L	Losses (see equation 2)	kcal
M	Mass	gm
w	Weight Fraction	gm/gm

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

ACKNOWLEDGEMENTS

This effort was supported by the Industrial Environmental Research Laboratory of the Environmental Protection Agency under Grant R 803430-01-0. We wish to express our appreciation to Mr. Donald A. Oberacker of MERL for his many contributions and suggestions. And a note of thanks is offered to Ms. Beth Lanier for her invaluable assistance in the preparation of this document.

SECTION I

CONCLUSIONS

From the results of this work the following conclusions can be drawn:

- The effects of the air/feed ratio on product energy yields appears to be dominant; changing scale and feed material, and the effects of mechanical agitation are of minor importance compared with air/feed.
- The available energy in the char-oil mixture appears from the results of this and earlier work to be a single function of air/feed; all the data correlated to a common curve.
- While the total energy in the char-oil mixture is a function only of air/feed, the relative amounts of char and oil can be changed significantly by varying the bed depth.
- The processing of peanut hulls through the convertor presents no problems either with or without the use of mechanical agitation.
- The integrated mechanical agitation-air supply system or "AIRGITATOR", which was tested successfully, appears to offer many advantages in increased through-put, operating stability and off-gas temperature at very low values of air/feed. The ability of this system to allow continuous variation in the bed depth provides an additional, significant and attractive feature.
- The overall mass, energy, and chemical balances appear to be satisfactory; thus giving confidence to the results of the testing.

SECTION II

RECOMMENDATIONS

The results of the study further reinforce the attractiveness of the mobile pyrolytic convertor concept by providing additional operating data and basic understanding of the physical processes at work. However, while the design, fabrication and test of the complete mobile system can be initiated in the very near future, several technical studies should be made before this final phase begins. These include:

(1) an investigation of the operating and ignition characteristics and derating required of a modified gasoline engine operating on the low heating value gas.

(2) a study of the burning characteristics of the char-oil mixture in various combinations with coal and petroleum oil.

(3) further development and test of the integrated mechanical agitation-air supply system (AIRGITATOR) evaluated in the current work.

When these studies have been completed, successfully, the design, fabrication and test of the full-scale mobile pyrolysis converter itself should be initiated. Upon successful operation of this component the complete mobile system should be designed and constructed.

SECTION III

INTRODUCTION

GENERAL

This report describes an experimental program designed to improve the technology required for the development of a mobile pyrolysis system for conversion of agricultural and forestry wastes at the site of their production into a clean and easily transportable fuel. The program involves a series of tests using peanut hulls, primarily, as the feed in the one tonne/hr Georgia Tech Engineering Experiment Station (EES) pyrolytic convertor pilot plant and is 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 lb/hr) EES pilot plant.

RATIONALE FOR MOBILE PYROLYSIS CONCEPT

Agricultural wastes, while representing a huge potential source of energy for the U. S., have certain adverse characteristics which have limited their use as fuels in the past and which must be dealt with in any successful energy conversion system. These characteristics include the facts that:

- Agricultural waste (organic matter) is typically quite wet, containing 30 to 70 percent water and therefore relatively low in heating value per pound.
- Since these materials would be scattered all over the countryside, the transportation costs per kcal to large thermal conversion plants would be very high.
- Because of the water content of these raw materials, the use of existing thermal conversion equipment is doubtful, at least at its rated capacity. Most likely new or modified facilities would 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 there is a serious conversion penalty using these as-received, wet materials.)

- 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, not continuously. Thus a steady supply of fuel from these wastes is not available and also it is impractical to tie-up capital 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. While initially the waste producer may be spending two to five dollars per tonne of raw wastes for disposal, he may hesitate or refuse in a long term contract to give away, or perhaps pay a disposal charge for his wastes. And clearly, once a facility for waste utilization has been constructed, the waste producer, upon termination of the original contract, has the waste utilizer in an uncomfortable economic position.

One solution to these problems is to utilize a mobile pyrolysis system that could be transported to the site of the 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 weight reduction and the associated transportation costs thereby affected would be very substantial. A further benefit to be derived is that since the system is portable it would provide greater leverage for 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 forestry 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.

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 the pyrolysis occurs 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 pounds) of a powered char-oil fuel, similar to coal, with a heating value of 6.00 to 9.00 kcal/gm (11,000-13,000 Btu/lb.) Thus, depending upon the feed moisture content, the energy available for use at the central thermal conversion plant could be 75 to 80 percent of that theoretically available from the original dry waste; and, using a boiler conversion efficiency of 80 to 85 percent, the overall steam-side efficiency of the process could be 65 to 70 percent. Hence the percent of useable energy could be as large and perhaps larger than 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. It could be blended with cheaper high sulfur coal to produce an additional economic advantage.

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

(1) The application of the mobile pyrolysis concept to large barges* moving on the thousands of miles of inland and intercoastal waterways appears to have great promise. This would not only permit an increase in the scale of the mobile system but would also allow its application to the municipal waste of smaller communities which presently cannot individually justify or afford a large, economical waste conversion system, but which in groups could successfully operate such a system.

(2) The char-oil fuel produced by the mobile pyrolysis system was considered primarily in (1) 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 the ERDA, Pittsburgh Labs (8) that 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 minimum 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 as a boiler fuel.

These two considerations should have relatively little influence on the planned development program for the portable system, but strengthen significantly the justification for the portable concept with production of the char-oil fuel.

OBJECTIVES

The investigation, which was primarily experimental, had several objectives, i.e.

---

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

- To determine the effects of scale on pyrolytic convertor performance.
- To determine the effects of changing feed material on pyrolytic convertor performance.
- To determine the effects of mechanical agitation on pyrolytic convertor performance.
- To determine the performance of an integrated mechanical agitation-process air supply system.
- To determine the influence of air/feed and bed depth on product yields.

In the following sections a description of the study is presented.

SECTION IV

TESTING

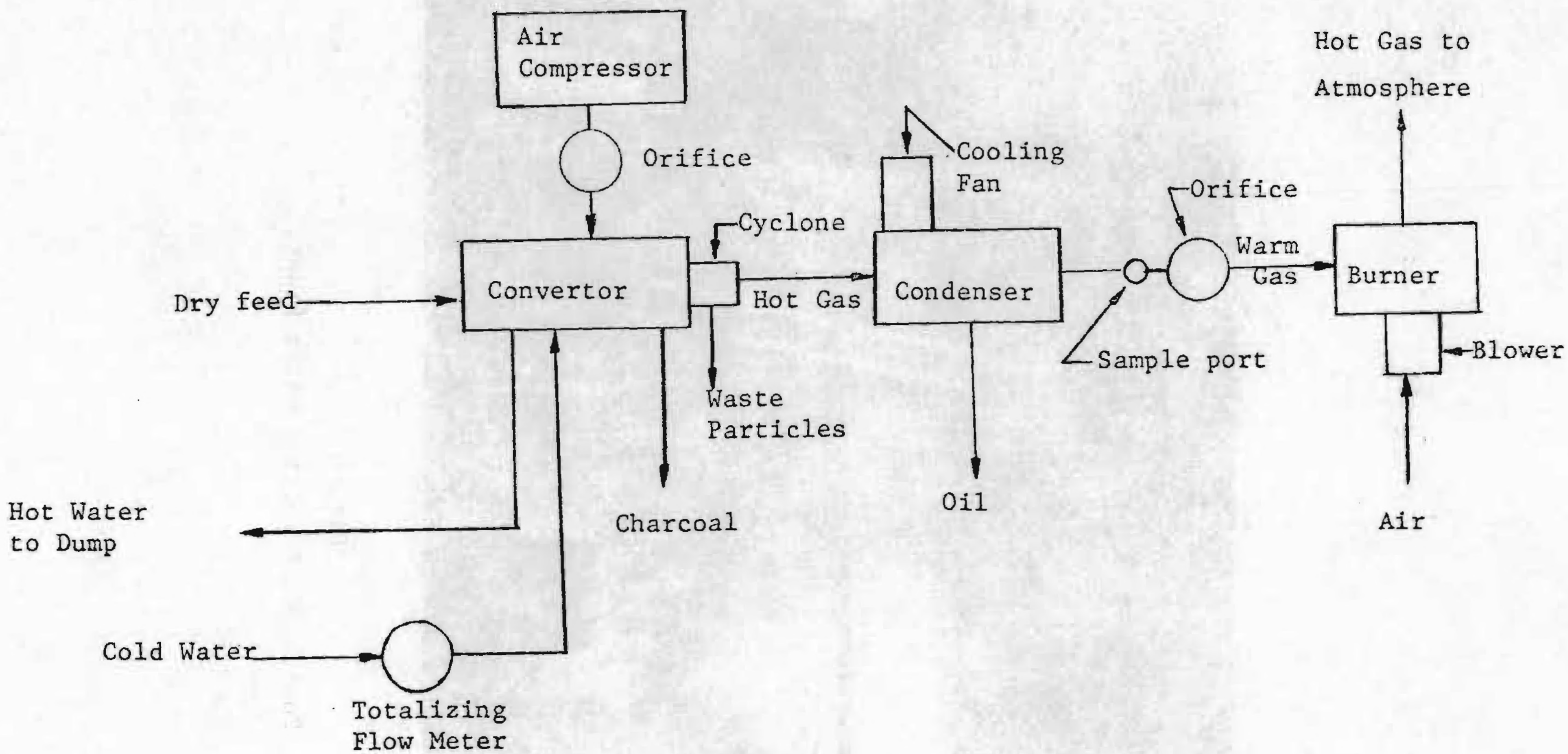
GENERAL

The 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 13 tests and sawdust was used in 2 tests, for a total of 15 tests in the complete study. All told, approximately 45.5 metric tons (50 tons) of hulls were used in the program. The tests involved investigation of the influences of scale, feed, air/feed, mechanical agitation and bed depth on product yields. In addition, the performance of an integrated mechanical agitation-process air system on product yields and process rates was studied. This section presents a description of the test facilities, the calibration and test procedure, the laboratory procedure, the data reduction methodology and the results of the 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 then 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 is 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 convertor 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



EES Pyrolytic Unit Process Flow Diagram

Figure 1

Figure 2
Fourth EES Pyrolytic Pilot Plant.

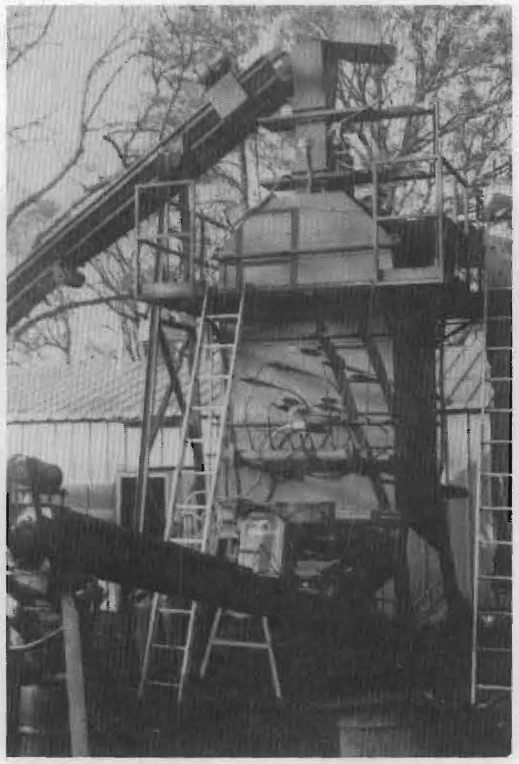


Figure 3

Close-Up View of EES Pyrolytic Converter

Figure 4

Close-Up View of Conveyer and Input System - EES Pyrolytic Converter

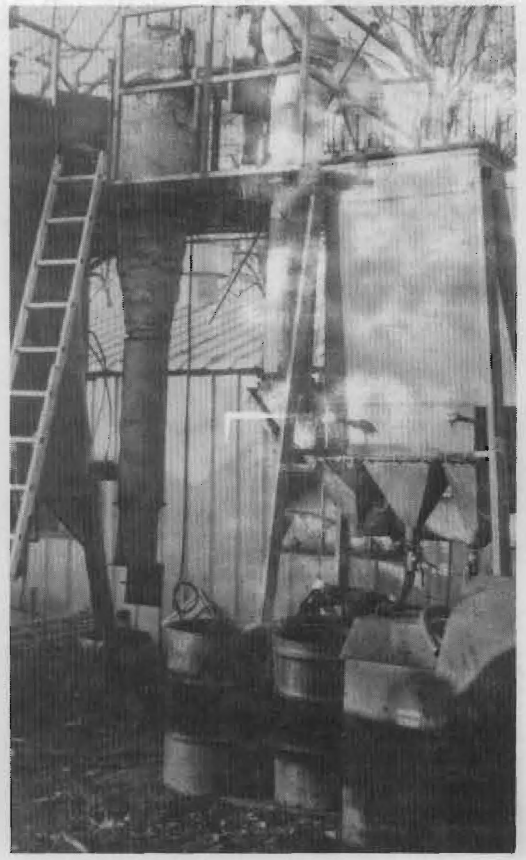


Figure 5

Close-Up view of Cyclone and Condenser System - EES Pyrolytic Converter

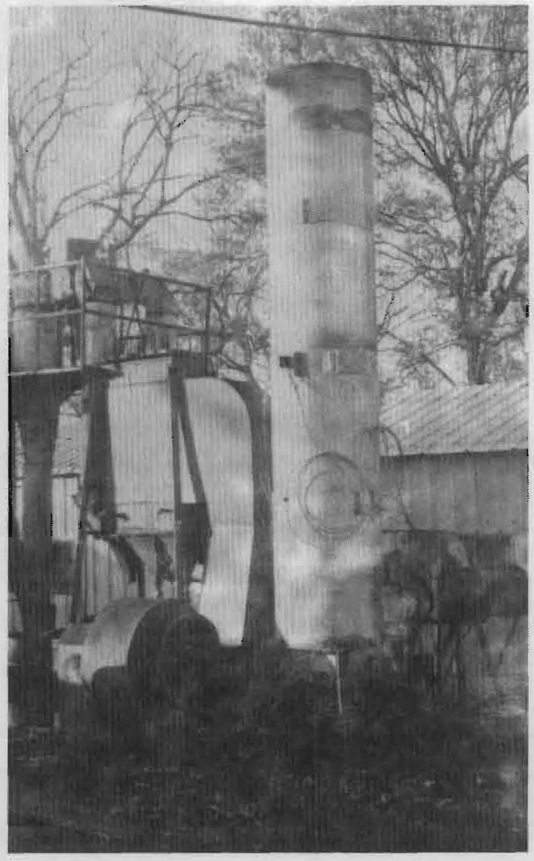


Figure 6

Close-Up View of Off-Gas Burner-EES Pyrolytic Converter 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 non-condensible 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/feed ratio.

The instrumentation used in the study includes:

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

The system operates at a few centimeters of water below ambient; thus any leaks present generally result in the introduction of air into the system. However, within the cavity between the sliding plates of the gate valve, the displacement of the pyrolysis gas by the input feed does result in some lost gas when the gate valve operates. As the process rate of the unit increases, the gas production increases and the 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 for 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 gate valve cycles only upon demand, not continuously; hence the gases lost through this 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 the cooling air flow. In all but the last tests the condenser was operated at about 93°C (200°F), however, to determine the influence of condenser temperature an oil yields, the condenser temperature was dropped to 77-82°C (170-180°F) in the last test. It has been observed that oil droplets are frequently carried in suspension through the off-gas system, past the draft fan and into burner. This results in some loss of oil; however, analytical techniques are 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 convertor 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 RPM.

In the latter phase of the testing, an integrated mechanical agitation-process air system (AIRGITATOR) was also tested. A schematic view of this system is shown in Figure 8. The system is driven by the same gear drive as the simpler agitator and is described in more detail in Section V.

It might 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 in the stream which make conventional instrumentation techniques impractical. Instead, analytical techniques involving nitrogen, carbon, hydrogen and oxygen balances were used to compute the flows of the various constituents which make up the off-gas stream.

CALIBRATION AND TEST PROCEDURE

Prior to the testing many elements of the system instrumentation were carefully calibrated. The accuracy of some components such as the thermocouples, however, was not checked since the required 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. However, 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 sufficiently

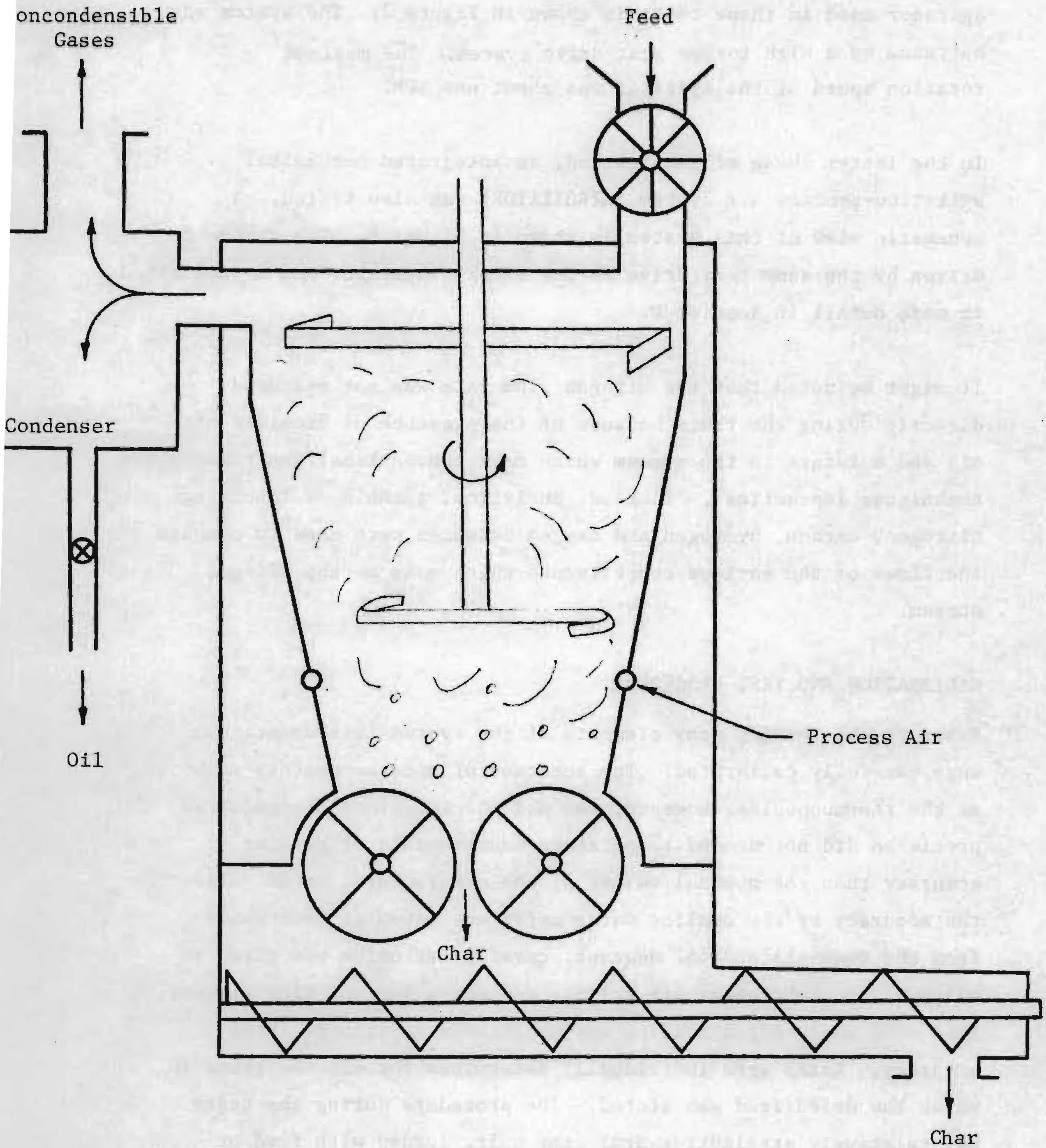


Figure 7

Schematic of EES Convertor with Rotating Agitator

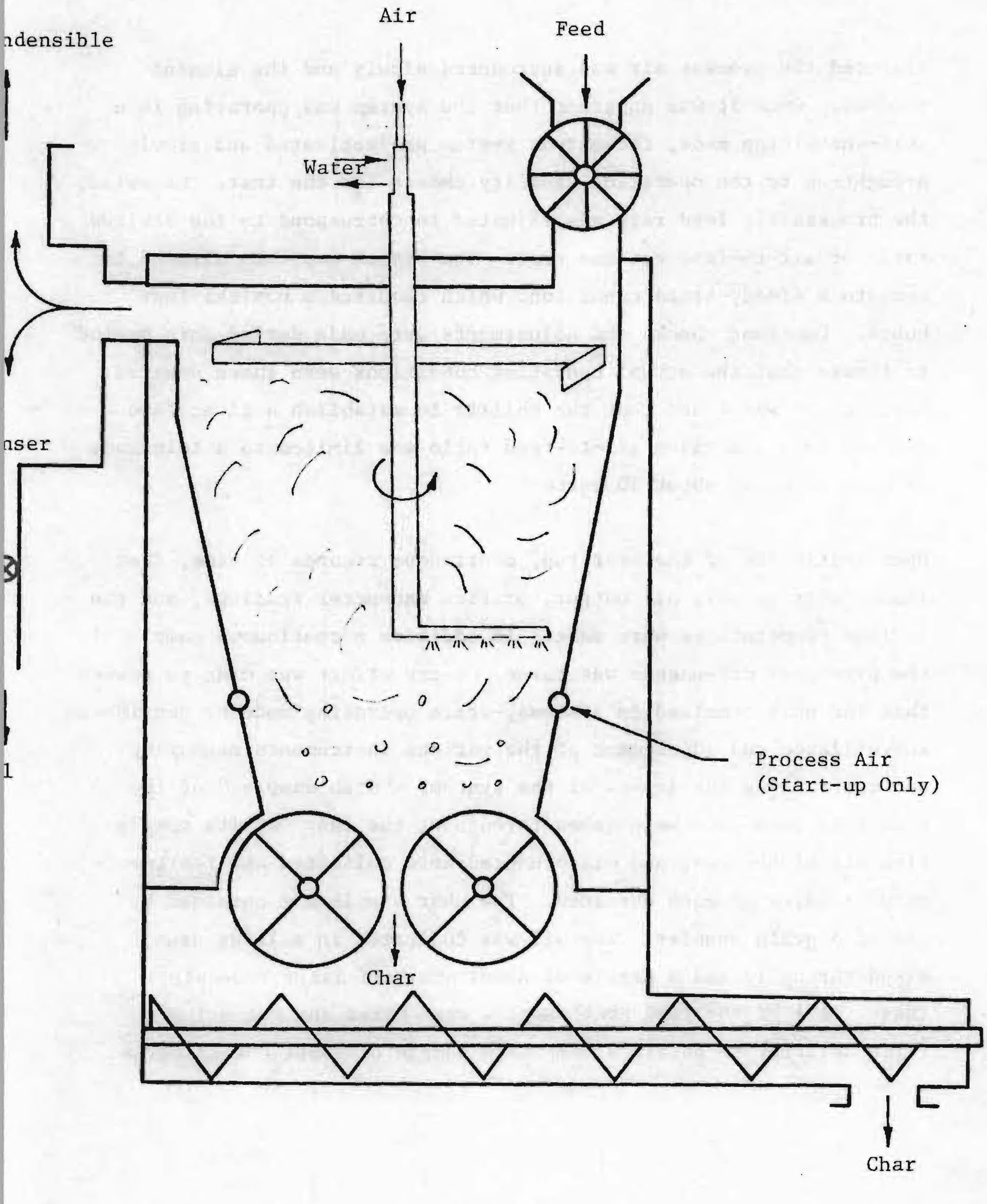


Figure 8

Schematic of EES Convertor with Integrated Mechanical Agitation - Air Supply System

elevated the process air was introduced slowly and the element 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 operating capacity chosen for the test. Likewise, the process air feed rate was adjusted to correspond to the desired ratio of air-to-feed for the test. The system was then allowed to come to a steady-state condition, which required 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 the ability to establish a given feed process rate and given air-to-feed ratio was limited to a tolerance of plus or minus about 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-gasses was taken. Every effort was made to insure that the unit remained 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 its completion all of the char and oil produced were collected and representative samples of each obtained. The char sample was obtained by use of a grain sampler. The oil was collected in a large drum, mixed throughly and a sample of about one-half liter (one pint) taken. All of the feed grab samples were mixed and cut using a rifle splitter to obtain a composite sample of about one kilogram.

LABORATORY TESTING

The laboratory played a vital role in the determination of the feed and products characteristics and in the subsequent analysis of the data. Thus the work was checked carefully and every precaution made to insure the accuracy of the results. However, despite these efforts there are occasional instances where inconsistencies did arise. While 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 and 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. While these variations are predominantly less than one percent, the overwhelming impression is of good repeatability. The presence, expecially in the CHNO analysis, of even small inconsistencies was found to have a significant effect on the test results. Thus, while these data by ordinary standards stand up well, 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
- percent C_3 components
- percent C_4 components

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 itself 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 was 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 is 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 and 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 non-condensible 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 can be written. These equations have been solved on the computer and the calculated results 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 data into a generally consistent form. Since it must be recognized that all the data is 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 is generally consistent with earlier results (1) and shows 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:

$$(HV_g + h_g) M_g + (HV_o + h_o) M_o + (HV_{ch} + h_{ch}) M_{ch} + h_{wo} M_{wo} =$$
$$(HV_f + h_f) M_f + h_a M_a + h_{wi} M_{wi} - \text{[conduction and cooling water losses]}$$

*A table of Nomenclature is presented on page vi.

By establishing ambient conditions as a reference, h_f and h_a can be set to zero. Now generally the sensible and latent heat terms involving h_g, h_o, h_{ch}, and h_{wi} and the heat losses are small in comparison to the other terms. Thus 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.

Conservation of Nitrogen:

$$w_{ng} Mg + w_{no} M_o + w_{nch} M_{ch} = w_{nf} M_f + w_{ha} Ma \qquad (3)$$

Conservation of Carbon:

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

Conservation of Hydrogen:

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

Conservation of Oxygen:

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

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

$$HV_o = 14,500\ w_{co} + 61000\ w_{ho} \qquad (7)$$

The C, H, N, O analysis of the oil requires that:

$$w_{co} + w_{ho} + w_{no} + w_{oo} = 1 \qquad (8)$$

Likewise the C, H, N, O analysis of the char and feed requires that:

$$w_{cch} + w_{hch} + w_{nch} + w_{och} = 1 - w_{xch} \quad (9)$$

$$w_{cf} + w_{hf} + w_{nf} + w_{of} = 1 - w_{xf} \quad (10)$$

Correspondingly, a computed C, H, N, O composition of the off-gas from the gas chromatographic results requires that:

$$w_{cg} + w_{hg} + w_{ng} + W_{og} = 1 \quad (11)$$

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

The procedure, therfore, 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_{och}, 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).

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

**The C, H, N, O composition of the oil and its heating value have been chosen as "unknowns" because it is believed there is greater uncertainty in the measured oil composition and heating value than for the feed, char or gas (which could have just as easily been used) due to the presence of water.

Once values of the eight "unknowns' are determined, a sensitivity analysis by which the effect on the computed values of the "unknowns" of individual variations in each of the 26 "known" coefficients is conducted. Those coefficients, which have a major influence on the solution, are thereby identified. Since the final object is to obtain as internally consistent a set of data as possible, the next step is a least squares procedure by which variations between the measured and computed values of w_{co}, w_{ho}, w_{no}, and w_{oo}, are minimized. This is accomplished by introduction of combinations of up to four of the major influencing coefficients and by allowing the values to vary simultaneously about their "known" value, usually within bounds of $\pm$ 10%. A least squares program then selects that combination of the major influencing coefficients while minimizes the sum of the squares of the difference between the computed and measured data. This generally results in a complete set of transformed data which is very nearly consistent internally and which represents an exact solution to the first eight equations.

In one case, Test 14, variations in the "known" coefficients of considerably more than 10% were required to bring the system of equations in a proper balance. This occurred both with the char and the feed carbon content which was adjusted significantly. However, since the modified data for this case (as seen in the next section) plots up well with all the other results, it is believed that whatever the cause of this anomaly, the applied correction is made apparently in the proper term and to the required extent.

Presented in Appendix C are listings of the computer programs for the sensitivity analysis (SENSAN) and the least squares procedure (ITERAT) developed from the analysis. Also presented are sample calculations for Test 1 (Run 4) to illustrate the output of these two programs.

TEST RESULTS

Overview of Test Conditions

The experimental program involved a series of 15 tests; 13 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 the first part of the study. Of the 15 reported tests, two were checkouts of the first generation integrated mechanical agitation-process air supply system or "AIRGITATOR", for which no quantitative data was recorded. Besides these two tests, two more were found to have defective off-gas compositions, apparently due to an air leak somewhere in the system. Thus while some data for these latter two tests were obtained, the primary basis for the results presented in this section is the 11 remaining tests.

Of the 11, ten were conducted using the hulls, and one with sawdust. There was one extended run of 12 hours using hulls (Test 7), but normally the runs lasted two to three hours, sometimes slightly more or less. In addition, two of the 11 were conducted using the "AIRGITATOR". In the 9 basic tests, the influence of mechanical agitation, changing feed material, changing bed depth and the air/feed ratio was studied. In the last two tests, the performance of the "AIRGITATOR" was evaluated at a fixed bed depth.

Table 1 presents a summary of the test conditions, along with some of the observed data from the pilot plant tests. Study of the table shows that basic agitation was involved in eight of the 15 tests conducted, while three were completed without any form of agitation. Four tests were made with the "AIRGITATOR".

TABLE I

TEST SUMMARY

Test Number[1]		Feed Rate kg/hr	Char Yield kg/kg dry feed	Oil & Aqueous Yield kg/kg dry feed	Off-Gas Yield kg/kg dry feed[2]	Air/Feed	Off-Gas Temp.[3] (°C)	Average Maximum Measured Bed Temperatures (°C)[4]	Bed (cm) Depth	Agitation	Airgitation
1	Peanut Hulls	572	.217	.039	1.108	.364	96	649	132	No	No
2	Peanut Hulls	390	.239	.085	.941	.265	93	732	132	No	No
3	Pine Sawdust	676	.266	.057	.849	.172	113	760	132	No	No
4	Pine Sawdust	464	.249	.070	.932	.251	140	732	132	Yes	No
5	Peanut Hulls	494	.288	.079	.86	.227	86	649	132	Yes	No
6	Peanut Hulls	481	.321	.072	.884	.277	85	716	132	Yes	No
7	Peanut Hulls	476	.229	.047	.994	.270	88	704	132	Yes	No
8						CHECK OUT "AIRGITATOR"				No	Yes
9	Peanut Hulls	408	.400	.161	.897	.458	78	960	89	Yes	No
10	Peanut Hulls	501	.249	.0453	1.17	.464	88	560	89	Yes	No
11	Peanut Hulls	570	.270	.234	1.035	.539	87	682	89	Yes	No
12	Peanut Hulls	471	.284	.178	1.151	.613	83	787	89	Yes	No
13						CHECK OUT MODIFIED "AIRGITATOR"				No	Yes
14	Peanut Hulls	490	.414	.035	.691	.140	174	471	127	No	Yes
15	Peanut Hulls	324	.283	.262	.645	.190	226	471	127	No	Yes

TOTAL FEED PROCESSED = 43,400 kg

TOTAL OPERATING TIME = 119.5 hours

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

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

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

[4] The indicated temperatures correspond to the average maximum measured by the thermocouples in the lower bed of the convertor. 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. Study of the data does indicate a general trend of increasing temperature with increasing air/feed; however, there is considerable scatter.

Further, it is seen that testing was conducted at two bed depths, i.e. 127-132 cm (50-52 inches) and 89 cm (35 inches). The air/feed varied from 0.14 to 0.613; a range within which most operations would be found. Study of the off-gas temperatures indicates they were generally in the range of 77 to 88°C, except the two tests with sawdust which ran somewhat hotter. While not reported, the condenser thermostat temperature was usually set in the range of 93 to 99°C except in the last test where it was set at 99°C to determine the influence of condenser temperature on oil recovered.

Additional study of the table shows that the dry feed rates varied from slightly over 300 kg/hr (700 lb/hr) to nearly 700 kg/hr (1,5000 lb/hr). One puzzling result is the wide variation in the recovered oil and aqueous phases from the condenser. Reference to Appendix reveals that sometimes the water content is quite significant, and other times it is small. Apparently minor variations in the off-gas and condenser temperatures can produce significant changes in the oil yield exists, it is believed, in the form of more volatile hydrocarbons, the recovered yields (on a dry basis), with the exception of Test 15, are generally much smaller than the computed yields, as discussed in the following section.

In the course of the testing, almost 42,000 kgm (100,000 pounds) of feed were consumed and the unit was operated for a total of 119.5 hours.

Analysis of the Data

Besides the data shown in Table 1, the laboratory analysis of the feed, char, oil and non-condensible off-gas are presented in Appendix A. The data from these tables was 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. This transformed data is presented in Table 2 and is the basis for all further discussion of the testing. Shown also in the table, in parentheses, are the amounts the transformed data was changed from the original. Inspection reveals that only a minor part of the data has been modified and the changes are generally small.

While many of the modifications appear to be random, there is a rough pattern to some of the changes. For example, there appear to be relatively frequent reductions of the order of 8 percent on 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 where the carbon content of the feed and the heating value of the feed must be increased about 6 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, are 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, which 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 7.408 kcal/gm (13,335 Btu/lb). Regarding the laboratory reported

Table 2

Summary of Transformed Data

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
(Gas)												
N_2	gm/gm	.485	.530 (-8%)	.382 (-8%)	.442	.434	.517 (-8%)	.574	.478	.510 (-8%)	.396	.351
C	gm/gm	.191	.199	.258 (-2%)	.194	.201	.199	.163	.189	.199	.216	.218
H_2	gm/gm	.021	.021	.027	.028	.028	.017	.019	.017	.016	.018	.011
O_2	gm/gm	.303	.289	.364	.336	.338	.306	.244	.314	.314	.369	.422
HV	kcal/gm	1.5	1.488	1.966	1.528	1.528	1.333	1.317	1.283	1.406 (-8%)	1.322	.856
(Char)												
N_2	gm/gm	.025	.021	.011	.029	.027	.027	.008	.008	.011	.011	.007
C	gm/gm	.721 (4%)	.829	.844	.724	.795 (-8%)	.677 (8%)	.808 (-8%)	.809 (-4%)	.773	.393 (-50%)	.818 (-4%)
H_2	gm/gm	.026	.018	.017	.017	.016 (5.5%)	.018	.015	.013	.009	.018	.014
O_2	gm/gm	.089	.032	.064	.165	.121	.121	.103	.031	.089	.115	.091
HV	*kcal/gm	6.111	7.111	7.333	6.778 (10%)	7.000 (2%)	6.722	6.611	6.833	6.389	6.944	6.889
(Feed)												
N_2	gm/gm	.017	.021	.001	.012	.012	.012	.012	.012	.012	.007	.007
C	gm/gm	.457 (6%)	.462 (2%)	.450 (2%)	.445 (6%)	.473	.444 (8%)	.464 (4%)	.444 (8%)	.483	.304 (40%)	.466 (8%)
H_2	gm/gm	.061	.058	.054	.057	.057	.059	.059	.059	.059	.061	.061
O_2	gm/gm	.437	.452	.488	.457	.458	.446	.446	.446	.446	.427	.427
HV	kcal/gm	4.650	4.400	4.294 (6%)	4.539	4.628 (-2%)	4.778 (2%)	4.583 (6%)	4.389 (10%)	4.778 (2%)	4.728	4.728

*Not ash free; on dry basis

Data		Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
WEIGHT FRACTIONS OF ELEMENTS IN OIL													
Measured	N_2	gm/gm	.040	.047	.016	.029	.078	.014	.015	.015	.017	.012	.012
	C	gm/gm	.657	.831	.758	.732	.687	.737	.725	.722	.712	.703	.694
	H_2	gm/gm	.071	.059	.067	.080	.081	.080	.084	.080	.075	.077	.077
	O_2	gm/gm	.242	.064	.145	.158	.155	.168	.176	.182	.197	.208	.217
Computed	N_2	gm/gm	.034	.039	.024	.046	.078	.056	.028	.008	.043	.087	.111
	C	gm/gm	.650	.813	.670	.723	.723	.582	.743	.691	.679	.660	.676
	H_2	gm/gm	.043	.004	.001	.021	.024	.093	.013	.090	.097	.102	.106
	O_2	gm/gm	.269	.144	.306	.210	.175	.270	.215	.212	.181	.152	.107
HV		kcal/gm	6.722	6.722	5.422	6.667	6.500	7.833	6.444	8.611	8.778	8.778	9.056

Table 2 - Continued

Data	Units	Test 1	Test 2	Test 3	Test 6	Test 7	Test 9	Test 10	Test 11	Test 12	Test 14	Test 15
MASSES												
CHAR	gm/100 gm dry Feed	21.7	23.9	26.6	32.1	22.9	40.0	24.9	27.0	28.4	41.4	28.3
FEED	100 gm dry	100	100	100	100	100	100	100	100	100	100	100
AIR	gm/100 gm dry Feed	36.4	26.5	17.2	27.7	27	45.8	46.4	53.9	61.3	14.0	19.0
MOISTURE(IN)	gm/100 gm dry Feed	4.6	4.5	5.3	4.8	4.8	28.7	28.7	28.7	28.7	6.5	6.5
OFF-GAS	gm/100 gm dry Feed	57.7	39.5	33.3	44.2	47.8	68.2	63.4	88.6	94.0	27.5	42.4
OIL	gm/100 gm dry Feed	29.1	22.8	20.7	27.9	14.0	6.49	21.4	8.45	11.3	12.4	20.9
MOISTURE(OUT)	gm/100 gm dry Feed	32.5	44.9	42.0	36.7	36.1	59.8	65.4	58.5	56.4	39.2	33.9
ENERGY LOSSES	kcal/100 gm dry Feed	30	30	30	30	30	30	30	30	30	15	30

heating values which are for the indicated moisture contents, again an average of the dry heating values is probably a more accurate value (in passing it should be noted that the uncertainity in the moisture percentage can be significant and thus the corrected heating value is also uncertain). However, upon adjusting the indicated numbers to a dry basis and after computing an average value, the result obtained is 7.906 kcal/gm which is 6.7% greater than the average of the computed results. It is believed that the justification for working with these average values is adequate, and that these two values are sufficiently in agreement to satisfy the accuracy requirements of the study.

Using the results presented in Table 2, several informative graphs can be drawn. This is done in the next six figures which correlate closely with corresponding figure in (1).

Graphical Data Presentations

Perhaps the most important results of the entire program are those plotted in Figure 9 which presents the percent available energy of the char and oil (related to the feed) as a function of the air/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 correlates to a single line. This line is identical to that reported in (1) using sawdust in a unit 1/2 the geometric scale 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 10 for which the best fit straight line is again identical to both that in Figure 9 and that from (1).

This suggests therefore, that to an acceptable engineering precision the available energy fraction of the feed in the char-oil mix is independent of unit scale, feed material, bed depth and the presence of mechanical agitation; and is a linear function only of the air/feed ratio.

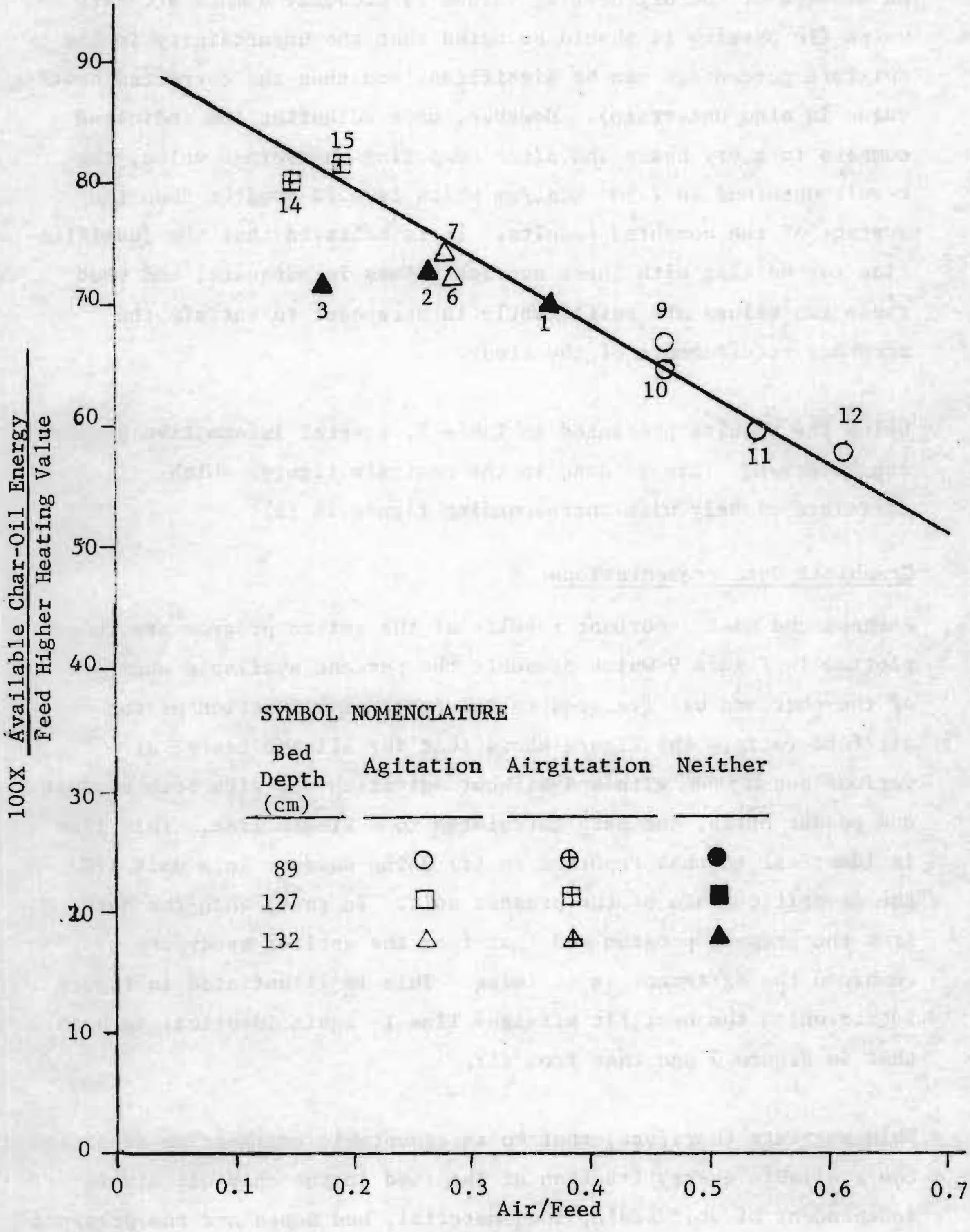

Figure 9

Percent Available Energy in Char-Oil Mixture

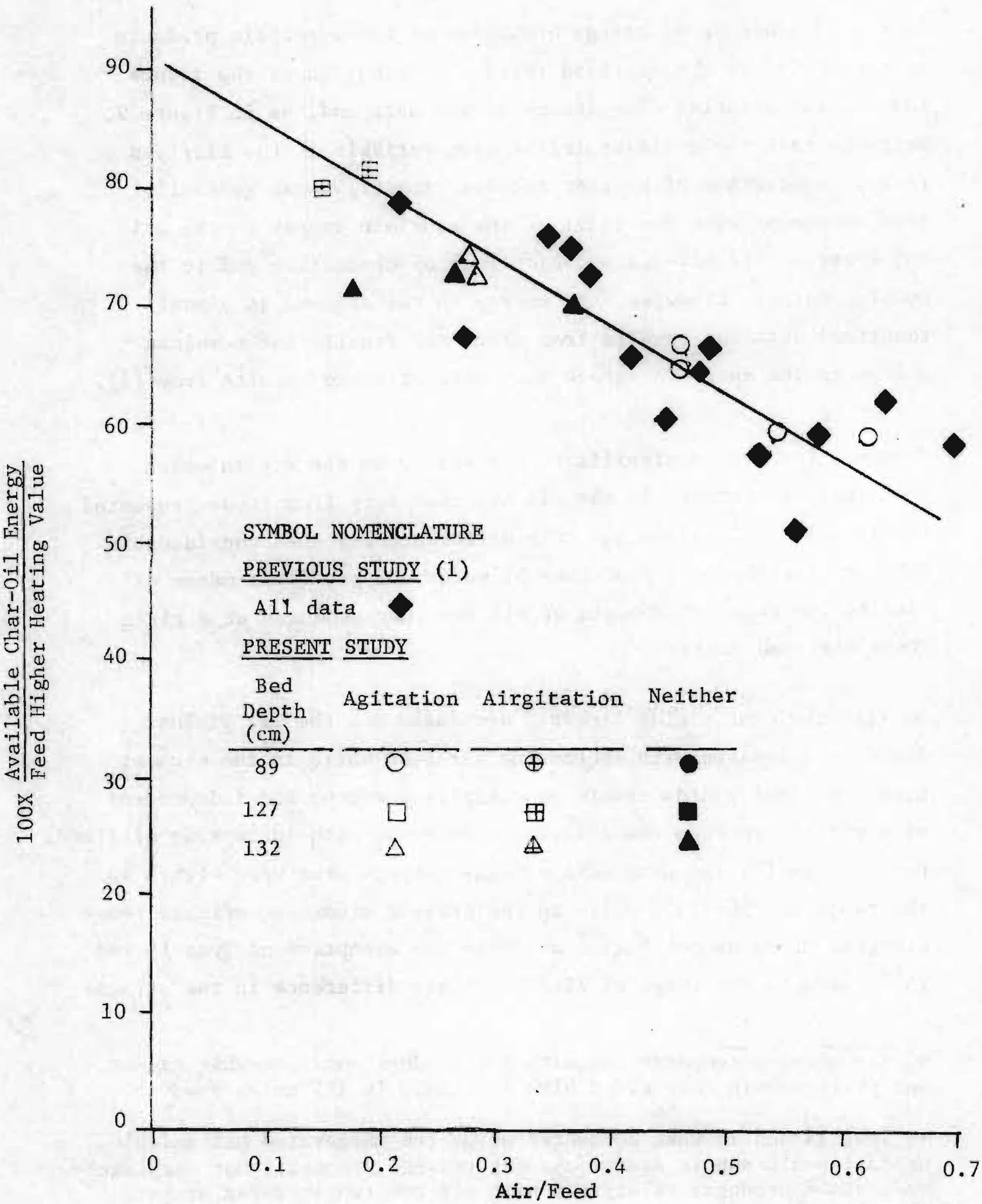

Figure 10

Percent Available Energy in Char-Oil Mixture- Composite of all Data

Figure 11 presents an energy breakdown of the pyrolysis products as a function of the air/feed ratio. Examination of the figure reveals the relative consistency of the data and, as in Figure 9, suggests that the dominant influencing variable is the air/feed ratio. Comparison of similar results from (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 with the results from (1). And finally the combined energy in the char-oil agrees very well with the results from (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 (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/feed ratio:

In (1), the char yields linearly decreased and the oil yields linearly increased with increasing air/feed while in the present study the char yields remain practically constant and independent of air/feed, whereas the oil yields decrease with increasing air/feed. However, in (1) the pyrolysis off-gas temperatures were always in the range of 150-175°C while in the present study the off-gas temperatures using peanut hulls[+] and with the exception of Test 14 and 15[++], were in the range of 75-95°C. This difference in the off-gas

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\+ The off-gas temperatures with the sawdust were somewhat higher, but still low in comparison with the tests in (1) using sawdust.

++ Test 14 and 15 were conducted using the integrated mechanical agitation-air supply system and for reasons presently not completely understood produced relatively high off-gas temperatures at very low air/feed ratios.

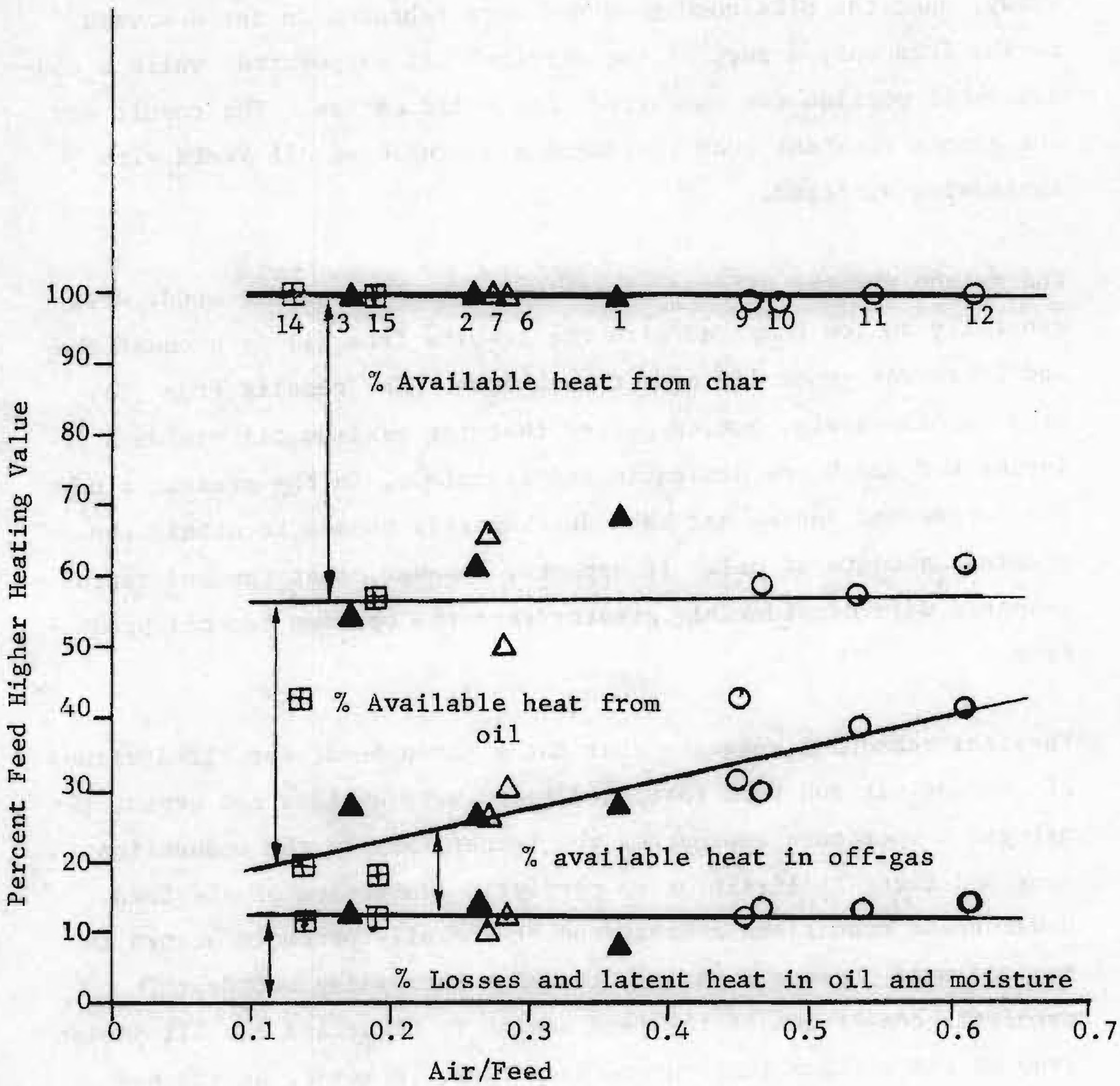

Figure 11

Energy Breakdown of Pyrolysis Products

temperature is very significant because in the latter case the higher boiling point oils are condensing in the bed. Laboratory experience has taught that when pyrolytic oils are heated, a significant degree 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 part of the original oil evaporated, while a considerable portion was converted into solid carbon. The result was the almost constant char yield and a diminishing oil yield with increasing air/feed.

The reason why the off-gas temperatures in the present study were generally so low compared with the results from (1) is because the bed depth was generally near the maximum. The results from (1), at a smaller scale, had suggested that for maximum oil yields a larger bed depth was desirable and therefore, in the present study the larger 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 a breakdown of the oily products occurs to produce 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 become unstable. All this behavior is illustrated graphically in Figure 12 which also shows the surmised operating zones for the present study and that for (1).

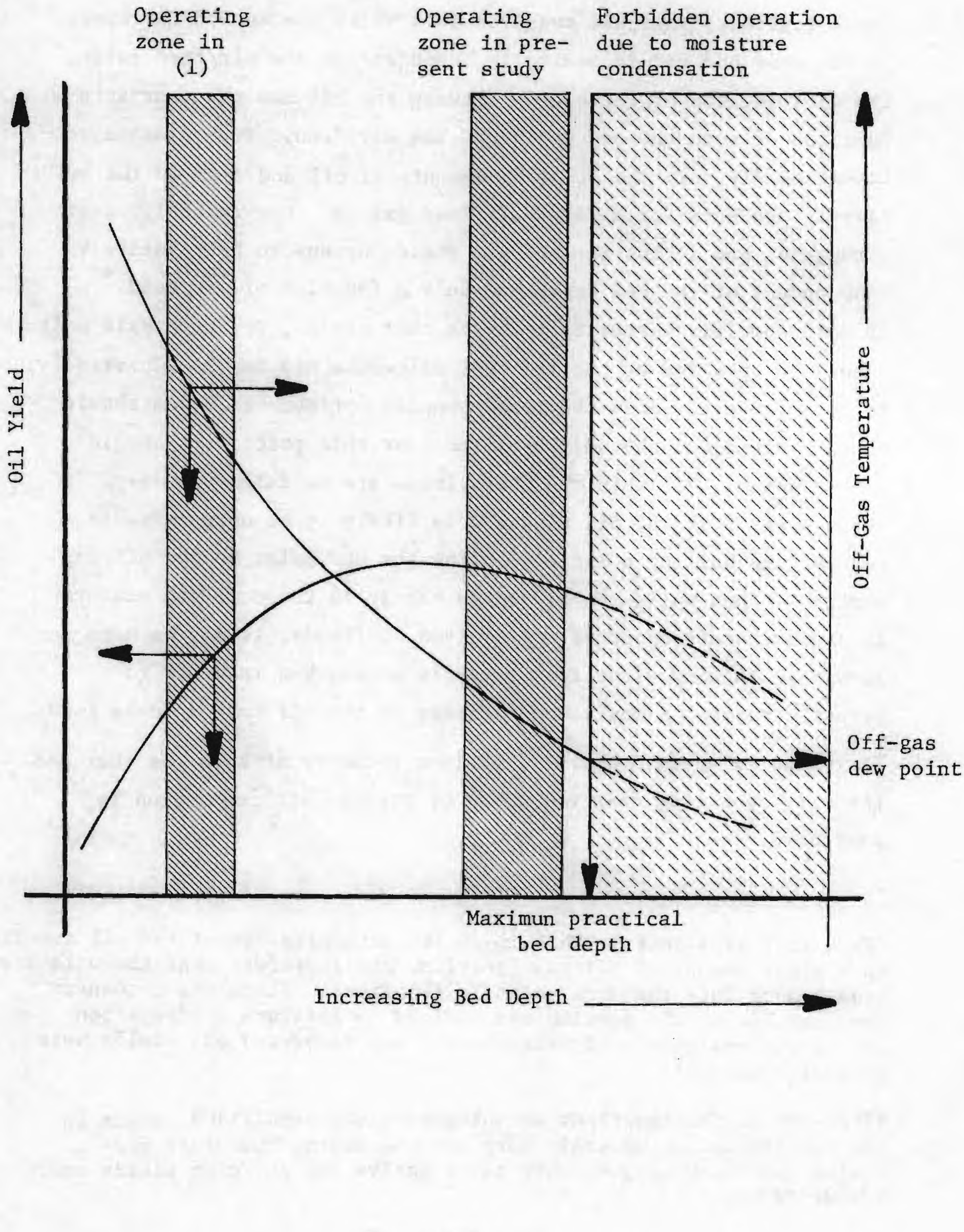

Figure 12

Oil Yield Variation with Increasing Bed Depth

Taken together, this all suggests that while the sum of the energy in the char and oil is basically dependent on the air/feed ratio, the distribution of the energy between the oil and the char is a function of both the bed depth and the air/feed. Thus a means to independently vary the relative amounts of oil and char in the pyrolysis products for a fixed air/feed 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/feed.* 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 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/feed), 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.+

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*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.

+Thus one of the important advantages of the AIRGITATOR system is its ability to continuously vary the bed depth, therefore providing the capability to vary the relative oil and char yields over a wide range.

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 13 is a crossplot of computed data from (1) and experimental data from the present study. The figure provides a convenient means for determining the required air/feed ratio for a given feed moisture percentage and further 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 (1). To illustrate the use of the figure, at a feed moisture percentage of 20 percent, the required energy for drying and processing is .444 kcal/gm (800 Btu/lb) dry feed. Correspondingly, at an air/feed value of 0.16 the available energy in the gas is .444 kcal/gm (800 Btu/lb) dry feed and that available in the char-oil is 3.611 kcal/gm (6,500 Btu/lb); thus establishing the relation between the moisture content and the air/feed. Finally for convenience the figure allows computation of the energy available in the char-oil mixture, as shown earlier in Figure 9.

Figure 14 presents a plot of the heating value of the noncondensible component of the off-gas in kcal/cubic meters as a function of air/feed. As before, and as in (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 (1) and thus again establishes the close correlation of the data from the two studies.

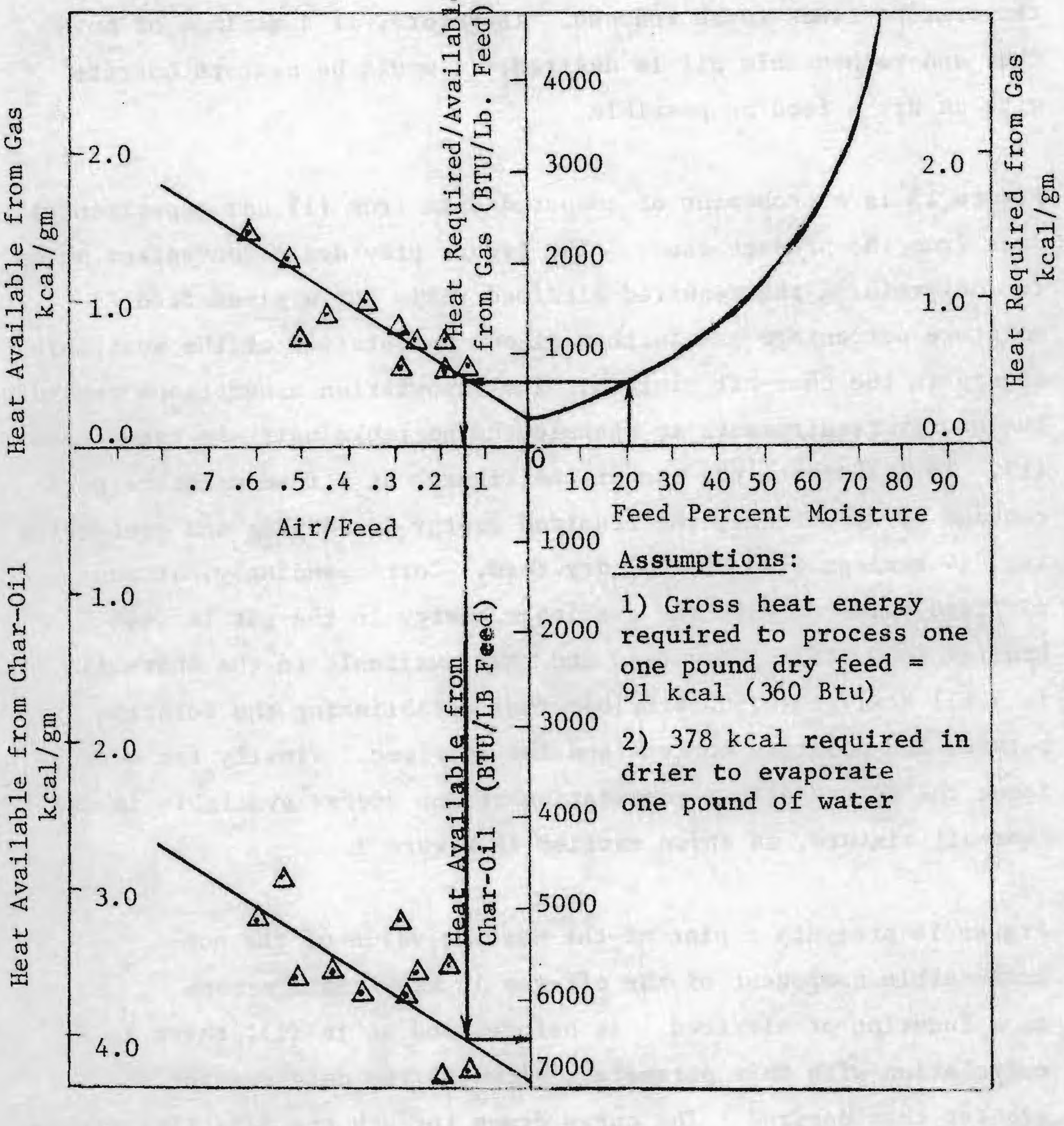


Figure 13

Effects of Feed Moisture on Available

Energy from Char-Oil Mixture.

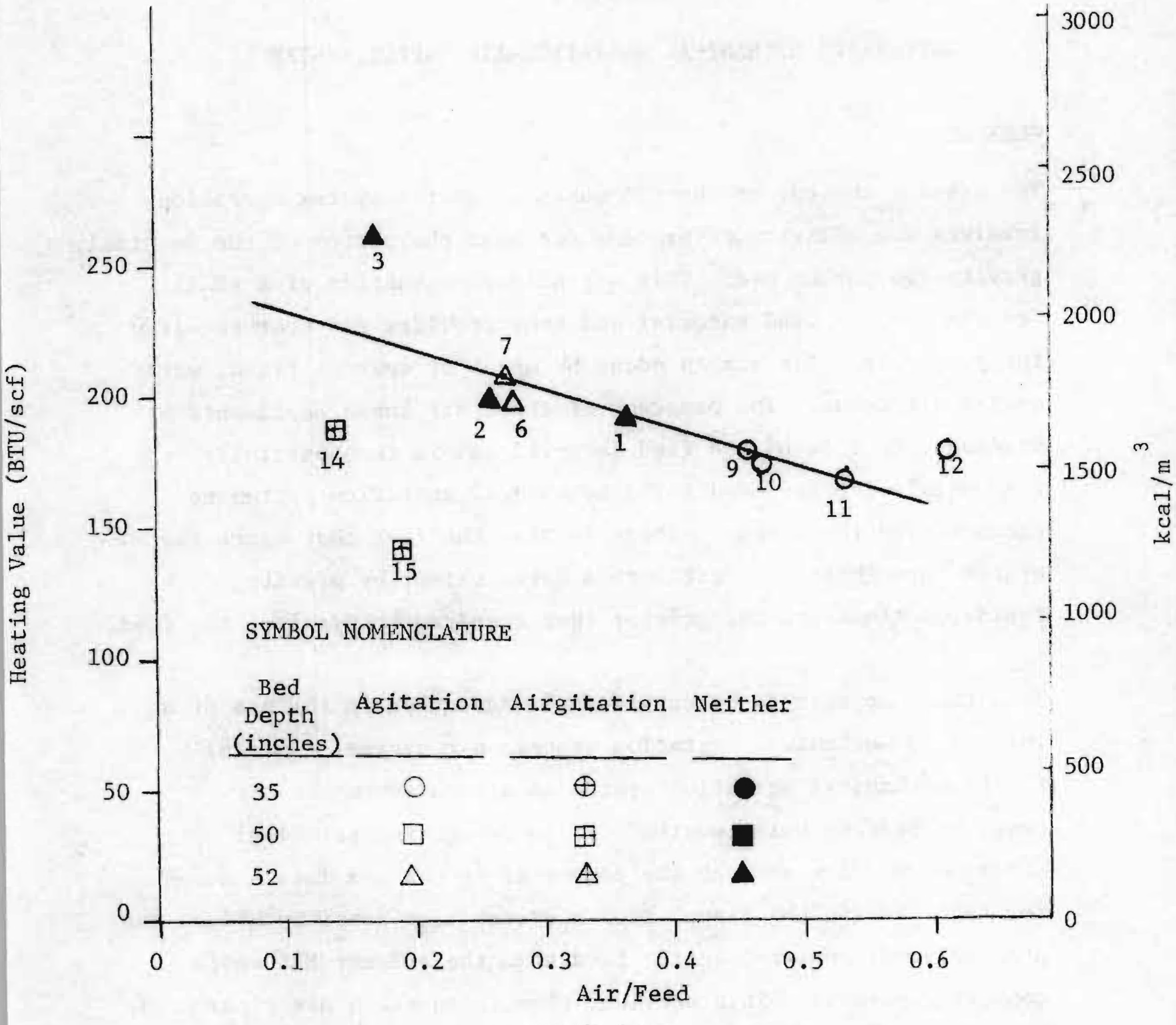


Figure 14

Heating Value of Non-Condensible Gas

SECTION V

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 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 so doing, the principal hindrance to flow through the converter is changed into a means for facilitating the flow. Such a system also possibly allows the processing of somewhat wetter feed than the present EES waste convertor permits. This section, then, presents a description of a "first generation" integrated mechanical agitation-process air supply system or "AIRGITATOR" and a discussion of the initial tests conducted with it.

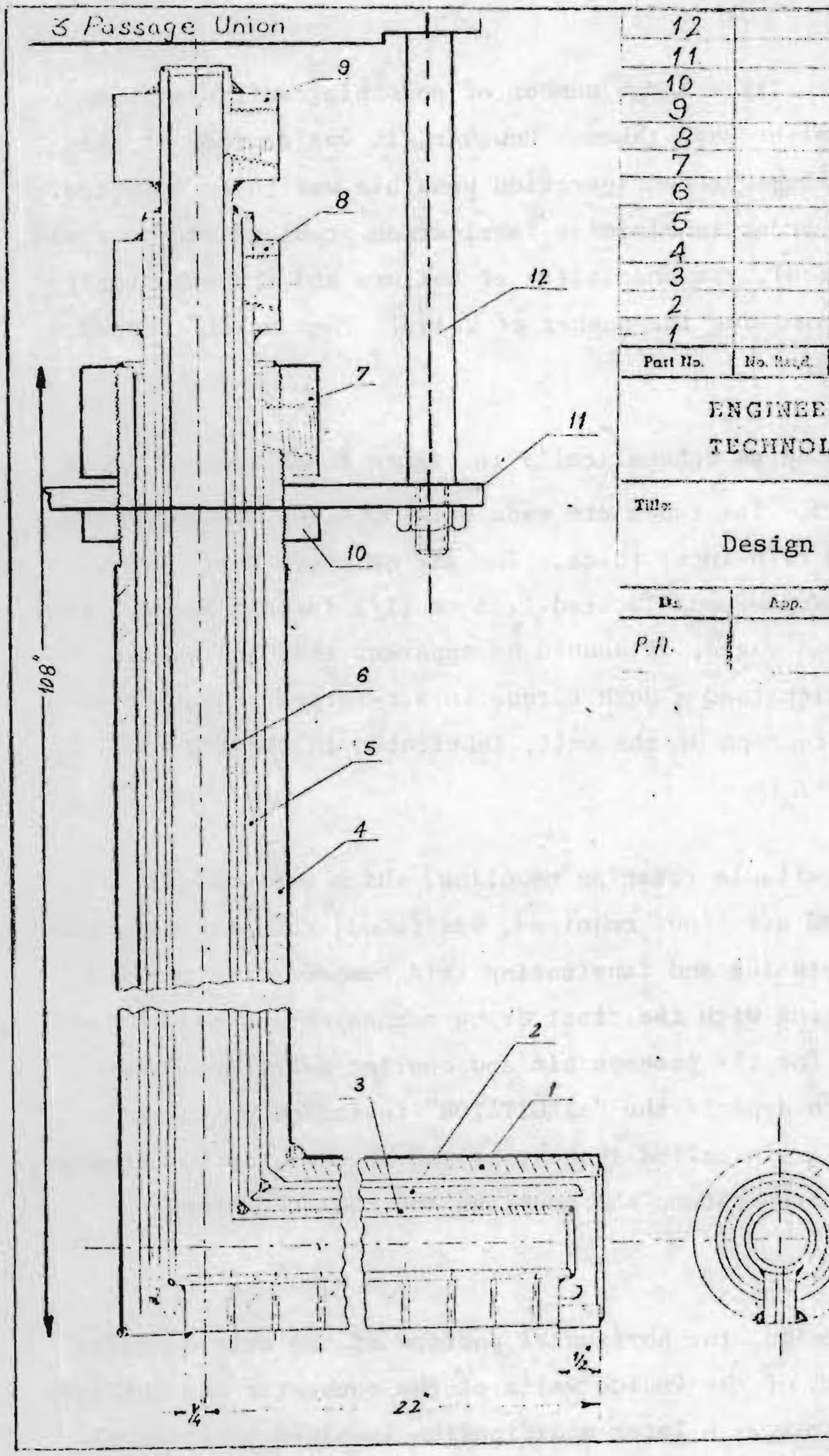
SYSTEM DESIGN

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 possiblity of failure and the opportunity for leaks, by minimizing the number of welds. Thus an "L" shaped system was chosen.

The system is presented schematically in Figure 8 and the design is shown in Figure 15. The tubes are made of 4130 alloy steel and are typically .318 cm (1/8 inch) thick. The air delivery ports are .159 cm (1/16 inch) in diameter and located 1.26 cm (1/2 inches) apart. From the metal types and gages, it should be apparent that the system was designed to withstand a hugh torque in a relatively hostile environment. A photograph of the unit, fabricated in the EES shop, is presented in Figure 16.

A commercially available rotating coupling, which was compatible with the water and air flows required, was found; thus avoiding the necessity for designing and fabricating this component at the EES. This coupling, along with the final drive mechanism and the copper tube connections for the process air and cooling water are shown in Figure 17 which depicts the "AIRGITATOR" installed on top of the convertor. The installed system, as can be seen, is not complex, and involved a drive system, the coupling and the "L" shaped "AIRGITATOR".

In the initial design, the horizontal portion of the unit extended to within one inch of the inside walls of the convertor and the ends were cut off squarely. A later modification involved the removal of one inch from this horizontal portion and the beveling of the



Part No.	No. Reqd.	Description	Material
12		Union Connecting Rods	
11		Union Holding Disk	
10		Locking Nut	
9		Air Connector	3/8-18 npt
8		Water Internal Connector	3/8-18 npt
7		Water External Connector	3/8-18 npt
6		Vertical Internal Pipe	
5		Vertical Middle Pipe	
4		Vertical External Pipe	
3		Horizontal Internal Pipe	
2		Horizontal Middle Pipe	
1		Horizontal External Pipe	

ENGINEERING EXPERIMENT STATION
TECHNOLOGY APPLICATIONS GROUP

Title: Design for AIRGITATOR

Dr.	App.	Date-Rev.	Scale	Dwg. No.
P.H.				

Figure 15

Integrated Mechanical Agitation - Process Air Supply System

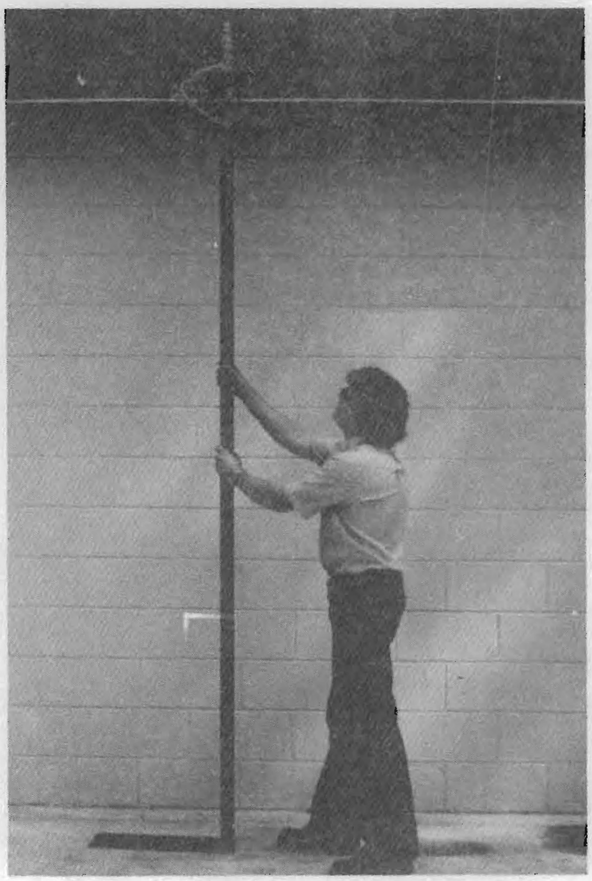


Figure 16
Overall View of AIRGITATOR

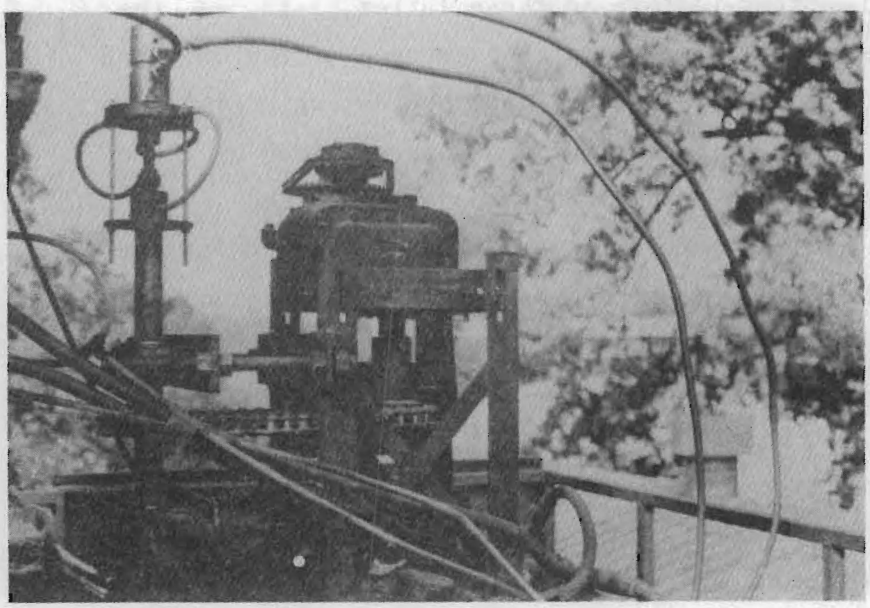


Figure 17
AIRGITATOR Installed on
Pyrolytic Converter

end so that the end surface formed a sharp edge which cut through the char. These modifications were made to avoid binding of the 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.

SYSTEM TESTING

About midway through the main test program, the first checkout tests of the "AIRGITATOR" were conducted. The results of these first tests were almost disastrous; the main bearings supporting the unit failed after several hours of testing, apparently due to very large torques that occasionally were required to rotate the system. It was concluded that binding, as described above, had occurred and the indicated modifications were made. Additionally, the complete drive system was strengthened substantially.

The modified unit was then tested and no problems were encountered. Apparently the improvements made were sufficient to overcome the difficulty. One important feature in these 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 enabled a stable hot char zone to be established initially, but provided a cushion against "losing the char bed" in anomalous circumstances where the instantaneous feed rate exceeded the charring rate and threatened the loss of the hot char which sustains the bed operation.

Perhaps the most interesting feature of the latter tests were the relatively high off-gas temperatures achieved at very low air/feed ratios. The ease with which the system operated, the high quality

of the char and the clear ability of the system to operate at a much greater throughput than tested, taken together demonstrated that the potential of the "AIRGITATOR" is at least as great as has initially been forecast and is perhaps even greater. In addition, the ability of the system to vary the bed depth continuously provides an important capability with which to tailor the oil and char yields to meet a wide range of requirements.

SECTION VI

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SECTION VII

APPENDICES

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, used as feed material for the waste convertor, and chars produced by the convertor. The sample size received in the laboratory ranged from one to eight liters for the peanut hull feeds and from one to two liters for the char products. The samples were thoroughly mixed and divided by quartering or by a rifle 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 Model 4 Wiley 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--1. Percent Moisture in Peanut Hull 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 is ± 0.6 percent (absolute).

2. Percent Moisture and Percent Volatiles in Chars: These analyses were performed by ASTM Method D-271. The estimated error is $\pm$ 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 is $\pm$ 0.2 percent (absolute).

4. Heating Values: The heating values of the feeds and chars were determined in a Parr Plain (Isothermal Jacket) oxygen bomb calorimeter. Following the procedures described in pp. 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 $\pm$ one percent (relative) for pure, crystalline materials. Because of the heterogeneous nature of the samples, loss of volatiles form 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. In most cases however, the agreement was better than six percent (absolute) for carbon and oxygen in the feeds and chars. Agreement among replicate hydrogen or nitrogen determinations was better than one percent.

Oil Samples

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

Analytical Procedure--1. 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 $\pm$ five 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 that 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 convertor or from the upstream end of the condensers. The sample stream was passed through a series of water cooled condensers, a glass wool demister, an 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 Non-Condensible 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 using 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 ± five percent (relative).

APPENDIX B-LABORATORY DATA

Listed in the following pages are the results of the laboratory analysis described in Section IV for the feed, char, oil and off-gases from the test program. 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 Table 2, 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

TEST 1

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-[3] CENT COM-POSITION
WATER	Percent	4.4	8.3	11.9	N_2	44.37
ASH	Percent	3.4	10.9	-	CO	16.88
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	15.78
					H_2	16.17
					CH_4	4.60
CARBON	Percent	48.6	75.1	57.0	C_2H_6	0.52
HYDROGEN	Percent	6.0	2.6	7.6	C_2H_4	0.72
NITROGEN	Percent	1.7	2.5	3.5	C_3H_8	0.13
OXYGEN	Percent	43.7	8.9	31.9	C_3H_6	0.24
HEATING VALUE	kcal/gm	4.651	6.083	6.960		

1. The CHNO analysis and heating values are based on oil with the indicated mositure content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-2

LABORATORY ANALYSIS

TEST 2

	UNITS	FEED	CHAR[2]	OIL[1]	OFF-GAS: NON-CONDENSIBLE COMPONENTS	OFF-GAS: PER-CENT COMPOSITION[3]
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
					CH_4	5.52
CARBON	Percent	47.0	82.9	55.5	C_2H_6	0.63
HYDROGEN	Percent	5.8	1.8	7.6	C_2H_4	0.90
NITROGEN	Percent	2.03	2.1	3.11	C_3H_8	0.14
OXYGEN	Percent	45.17	3.2	33.79	C_3H_6	0.27
HEATING VALUE	kcal/gm	4.397	7.111	5.299		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-3

LABORATORY ANALYSIS

TEST 3

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION[3]
WATER	Percent	5.0	4.6	21.1	N_2	33.8
ASH	Percent	1.2	6.5	-	CO	18.2
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	24.0
					H_2	12.5
					CH_4	9.5
CARBON	Percent	45.8	84.4	60.6	C_2H_6	0.6
HYDROGEN	Percent	5.4	1.7	7.7	C_2H_4	0.9
NITROGEN	Percent	0.1	1.1	1.3	C_3H_8	0.1
OXYGEN	Percent	48.8+.1	6.4	30.4	C_3H_6	0.3
HEATING VALUE	kcal/gm	4.569	7.345	5.728		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-4

LABORATORY ANALYSIS

TEST 6

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
WATER	Percent	4.6	2.7	17.9	N_2	41.1
ASH	Percent	2.3	6.5	-	CO	9.8
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	22.4
					H_2	18.7
					CH_4	6.7
CARBON	Percent	47.3	72.4	60.1	C_2H_6	0.6
HYDROGEN	Percent	5.7	1.7	8.6	C_2H_4	-
NITROGEN	Percent	1.2	2.9	2.4	C_3H_8	0.6
OXYGEN	Percent	45.8	16.5	28.9	C_3H_6	-
HEATING VALUE	kcal/gm	4.539	7.550	No Fire		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-5

LABORATORY ANALYSIS

TEST 7

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
WATER	Percent	4.6	0.6	16.1	N_2	41.9
ASH	Percent	2.3	9.8	-	CO	24.51
ACID INSOLUBLE ASH	Percent	-	-	-	CO_2	8.14
					H_2	15.07
					CH_4	8.91
CARBON	Percent	47.3	73.6	57.6	C_2H_6	0.65
HYDROGEN	Percent	5.7	1.8	8.6	C_2H_4	-
NITROGEN	Percent	1.2	2.7	6.5	C_3H_8	0.78
OXYGEN	Percent	45.8	12.1	27.3	C_3H_6	-
HEATING VALUE	kcal/gm	4.539	7.127	5.978		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-6

LABORATORY ANALYSIS

TEST 9

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COMPOSITION[3]
WATER	Percent	22.3	0.6	20.3	N_2	45.32
ASH	Percent	4.6	9.8	-	CO	19.89
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	15.36
					H_2	6.14
					CH_4	5.67
CARBON	Percent	48.3	73.6	56.9	C_2H_6	0.66
HYDROGEN	Percent	5.9	1.8	8.7	C_2H_4	0.52
NITROGEN	Percent	1.2	2.7	1.1	C_3H_8	0.13
OXYGEN	Percent	44.6	12.1	33.3	C_3H_6	0.20
HEATING VALUE	kcal/gm	4.874	6.702	6.582		

1. The CHNO analysis and heating value are based on oil with the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-7

LABORATORY ANALYSIS

TEST 10

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
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
					CH_4	4.40
CARBON	Percent	48.3	74.8	53.6	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.5	9.1	C_2H_4	0.50
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	10.3	36.2	C_3H_6	0.18
HEATING VALUE	kcal/gm	4.873	6.636	6.258		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-8

LABORATORY ANALYSIS

TEST 11

					OFF - GAS	
	UNITS	FEED	CHAR[2]	OIL[1]	NON-CONDENSIBLE COMPONENTS	PER-CENT COMPOSITION[3]
WATER	Percent	22.3	3.2	28.6	N_2	46.98
ASH	Percent	4.6	17.0	-	CO	17.91
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	18.18
					H_2	11.13
					CH_4	4.63
CARBON	Percent	48.4	77.8	51.5	C_2H_6	0.41
HYDROGEN	Percent	5.9	1.3	8.9	C_2H_4	0.53
NITROGEN	Percent	1.2	0.8	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	3.1	38.5	C_3H_6	0.16
HEATING VALUE	kcal/gm	4.873	6.596	5.818		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-9

LABORATORY ANALYSIS

TEST 12

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION[3]
WATER	Percent	22.3	1.2	34.0	N_2	46.88
ASH	Percent	4.6	20.1	-	CO	21.86
ACID INSOLUBLE ASH	Percent	1.4	-	-	CO_2	16.36
					H_2	8.72
					CH_4	4.84
CARBON	Percent	48.3	77.3	47.0	C_2H_6	0.43
HYDROGEN	Percent	5.9	0.9	8.7	C_2H_4	0.63
NITROGEN	Percent	1.2	1.1	1.1	C_3H_8	0.09
OXYGEN	Percent	44.6	8.9	43.2	C_3H_6	0.19
HEATING VALUE	kcal/gm	4.773	6.027	6.117		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-10

LABORATORY ANALYSIS

TEST 14

	UNITS	FEED	CHAR [2]	OIL [1]	OFF - GAS: NON-CONDENSIBLE COMPONENTS	OFF - GAS: PER-CENT COMPOSITION [3]
WATER	Percent	6.1	1.2	14.7	N_2	40.3
ASH	Percent	2.8	7.1	-	CO	23.2
ACID INSOLUBLE ASH	Percent	0.5	1.0	-	CO_2	19.3
VOLATILES		-	12.2	-	H_2	9.84
					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	42.7	11.5	30.8	C_3H_6	0.1
HEATING VALUE	kcal/gm	4.727	6.959	6.281		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

TABLE B-11

LABORATORY ANALYSIS

TEST 15

	UNITS	FEED	CHAR[2]	OIL[1]	OFF - GAS NON-CONDENSIBLE COMPONENTS	OFF - GAS PER-CENT COM-POSITION[3]
WATER	Percent	6.1	0.9	18.1	N_2	47.0
ASH	Percent	2.8	10.2	-	CO	11.1
ACID INSOLUBLE ASH	Percent	0.5	3.0	-	CO_2	26.1
VOLATILES		-	11.0	-	H_2	0.5
					CH_4	3.33
CARBON	Percent	50.6	78.7	56.8	C_2H_6	0.99
HYDROGEN	Percent	6.1	1.4	6.29	C_2H_4	-
NITROGEN	Percent	0.7	0.7	1.0	C_3H_8	0.20
OXYGEN	Percent	42.7	9.1	35.91	C_3H_6	0.13
HEATING VALUE	kcal/gm	4.727	6.911	5.817		

1. The CHNO analysis and heating value are based on oil having the indicated moisture content.

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

3. Note, this is the volume, not the weight composition.

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	.485	.191	.021	.303	2704
Char	.025	.751	.026	.089	10950
Feed	.017	.486	.061	.437	8372
Water	.770	0	0	.230	0

From the testing the char yield is 21.7 kg, per 100 kg feed; the measured amount of air per 100 kg feed is 36.4 kg and the amount of the moisture is 4.6 kg per 100 kg feed. The energy losses (L) are estimated at 13,608 kcal (54,000 Btu) for each 45.36 kg (100 lb) feed (or about 7 percent).

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

Then variations of plus and minus 10 percent of each of the coefficients in the eight equations are made and the resulting

*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.

values of each of the eight unknowns are determined. Using these results the measured versus the computed values of the oil composition can 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	Percent Measured	Percent Computed	Percent Dif.
C	.657	.837	+ 27.4
H	.071	.0344	- 51.5
O	.242	.185	- 23.6
N	.04	- .056	--

Not only is the difference between the values for C, H and O substantial, but the computed value for N is physically impossible. Clearly, significant inconsistencies between the measured and the computed results are 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	Percent Measured	Percent Computed	Percent Dif.
C	.657	.654	+ .45
H	.071	.043	- 39
O	.242	.268	+ 10.7
N	.04	.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 )= .0189
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= .936796 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= 14540.1
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= .215998 WNO=-5.16229E-2
```

```
NOMINAL W( 6 )= .025
+10% OF NOM W( 6 )= .0275
MG= 57.9196 MO= 25.3716 MW= 36.0388 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= 13591.
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
```

```
NOMINAL W( 13 )= .11
+10% OF NOM 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=-6.98039E-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= .294888 WNO=-.166113

NOMINAL 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

NOMINAL W( 16 )= .017
+10% OF NOM 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

NOMINAL 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= 32.087 MW= 29.7492 HVO= 12608.6
WCO= .664684 WHO= 4.87003E-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 WHO= 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= 24.631 MW= 30.796 HVO= 15086.2
WCO= .916189 WHO= 5.33032E-2 WOO= .303399 WNO=-.172881
-10% OF NOM W(21)= .693
MG= 52.1923 MO= 26.094 MW= 41.0237 HVO= 13423.7
WCO= .856255 WHO= 1.66061E-2 WOO= 7.31996E-2 WNO= .053939

NOMINAL 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

NOMINAL 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

NOMINAL W(25)= 0
+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
-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

NOMINAL 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=-5.20134E-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

NOMINAL W(27)= 13713

```
+10% OF NOM W( 27 )= 15084.3
MG= 58.2455 MO= 22.8399 MW= 38.2146 HVO= 15087.8
WCO= .927253 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= .208677 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= 58.1698 MO= 13.5884 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= 3.45419E-2 WOO= .186084 WNO=-5.60604E-2

NOMINAL W( 32 )= 54000
+10% OF NOM W( 32 )= 59400
MG= 58.0694 MO= 24.9234 MW= 36.3072 HVO= 14369.7
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	.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
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),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
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
```