PYROLYSIS OF WASTES

By

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Abstract

Results of a BED-UNIDO supported study on the pyrolysis of rice hulls, one of the most abundantly generated waste materials in the Philippines, showed the feasibility of converting these materials into charcoal, pyrolytic oil, and combustible gas.

A manually-operated pyrolytic converter, originally designed at GIT, was locally fabricated and improved to process daily one ton of rice hulls. The design capacity could be attained only at high air flow rates (15 CFM and above). The average daily yields are: char, 15 kg; gas, 44 kg; and oil, 3.5 kg. The per cent energy recoveries from the pyrolytic products range from 80% to 90% for sixty-nine test runs.

One of the most significant improvements on the system is the installation of a by-pass pipe from the reactor top leading to the demister. A higher pyrolytic oil (regardless of quality) and a better oil-water separation was effected resulting in two kinds of oil—low water condenser oil for possible fuel use, and a high water demister oil for use as a wood preservative, for economical reasons.

The most promising use of a pyrolyzer is by integrating it with a rice mill. The pyrolytic products could provide the mechanical power for the mill and the heat to dry the grains and rice hulls. A calculation of the savings earned by installing a pyrolyzer near a rice mill showed that the investment for the additional unit can be paid-off with a period of one year.

The integration of a pyrolyzer with a rice mill is one of the recommendations.

Introduction

It is safe to predict that in the next decade, the uncertainties of oil supply may further escalate the prices of crude oil. To cushion the effects of the oil shortage and oil price increase on the economy, the Philippines has intensified the development of the country's indigenous energy resources, including non-conventional energy sources.

A potential source of energy now being developed in the Philippines is renewable agricultural and forestry wastes, which could be converted into high calorific value fuels. Among these are rice hulls, rice straws, coconut husks, coconut shells, sawdust, and bagasse. Since these wastes

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are regenerated, the accumulation poses a pollution problem and a fire hazard. The utilization of these materials as fuels has been limited in the past because the calorific value is low due to its high water content, and because they are widely scattered, except in places where they accumulate in such large quantities. For the successful utilization of these wastes as fuels, a system must not only overcome these problems, but should be flexible enough to interchangeably use these materials with only minor modifications in design and/or operation.

One of the processes that could be utilized in converting agricultural and forestry wastes into higher value fuels is pyrolysis or carbonization. This is the thermal decomposition of organic matter, either by indirect heating or heating in an oxygen-deficient atmosphere. The products produced are charcoal, pyrolytic oil and a combustible gas, which are all higher-value fuels. They can be used in a variety of ways as energy sources. Any one of these fuels can be maximized according to specific needs in a given place. It is this flexibility that makes pyrolytic systems look attractive in suppyling the energy needs of rural development.

A project to study the feasibility of employing pyrolytic converter systems in the Philippines was undertaken. The following entities were involved in this project: the Bureau of Energy Development (BED), now the Center for Nonconventional Energy Development, UNIDO/UNDP, the Georgia Institute of Technology (GIT), the U.P. College of Engineering (UPCE), the National Engineering Center (NEC), and the National Grains Authority (NGA). BED provided the local funding while UNIDO/UNDP provided financial support for the GIT consultants and engineers. UPCE, NEC and GIT implemented the project while NGA provided for space and personnel support at the field site in Cabanatuan City, Nueva Ecija.

Objectives of the Project

The primary objective of the project is to design, fabricate and demonstrate a manually-operated small-scale pyrolytic converter that can easily be adapted in the Philippine countryside, and can utilize the agri-forestry wastes that may be available in the area.

The other objectives are: to determine the agricultural and forestry wastes in the Philippines; to explore the market potentials for the energy fuel products; and to determine the project costs and returns based on the adapted design.

Agri-Forestry Wastes

Data on the kind, volume and location of agricultural and forestry wastes generated in the Philippines are contained in a report to UNIDO.*

In the design of the pyrolytic converter, rice hull was considered. While the data showed that rice hull is not the most abundant waste in the Philippines, it is concentrated in large quantities at rice mills where they could easily be collected. In addition, the high silica-ash content of rice hull offers a more challenging problem in its utilization as a fuel. Rice hull is a low energy fuel and one of the most difficult waste materials to burn. The successful pyrolysis of rice hulls would make conversion of the other granular wastes into higher-value fuels relatively easier.

The UNIDO/UNDP contract covered the period June, 1978 to June, 1979 and the BED project was for a duration of one year starting October, 1978. Unavoidable delays in fabrication and arrival of gas samplers from the United States, difficulties in attaining the design capacity of the converter, and incomplete data and insufficient number of test runs extended the project into June, 1980.

Field surveys were conducted with two senior staff from GIT in late August and early September, 1978. Construction of the pyrolytic unit at the UPCE shop with a GIT field engineer overseeing, was completed in February, 1979.

A total of sixty-nine test runs were made, twenty of which were jointly conducted and supervised by GIT and UPCE personnel, and the rest under the sole supervision of the UPCE staff. Testing had to be continued to get additional test data and to determine whether further modifications on the design and operation of the pyrolytic converter system were necessary.

The activities and test runs covered by the UNIDO/UNDP contract are contained in the UNIDO Report. The report also contains the engineering drawings, an operation manual, analytical procedure, and discussion of results of the first twenty test runs.

This report discusses the results of the modifications on the pyrolytic converter system and testing conducted from the period July, 1979 to June, 1980.

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*UNIDO Project A-2153 Report: Indigenous Energy Rescurces: Development of A Pyrolytic Converter to Use Rural Wastes in the Philippines (February, 1980).

Report Organization

This report is organized as follows:

I. Introduction — Discusses the significance and objectives of the project.

II. Design and Operation — Presents the technical aspects of the project and the design modifications.

III. Results — Discusses the results of the modifications and testing of the modified pyrolytic converter system.

IV. Economic Analysis — Presents a cost analysis based on test data obtained on the pilot system.

V. Conclusions and Recommendations — Lists down the conclusions and recommendations that evolved from the project.

VI. Appendices — Lists the summary test data, analytical results, and equations used for calculation of yields and energies.

Pyrolytic Converter Design and Process Description

The Philippine pyrolytic converter system, initially designed by Georgia Institute of Technology and patterned after a similar design in Ghana, processes rice hull. The Ghana converter pyrolyzes saw dust. The detailed drawings and functions of the various components of the converter system are contained in the UNIDO/UNDP Report mentioned earlier. The flow diagram of the modified pyrolytic converter system is shown in Fig. 1. The major components of the system include a converter, condenser and demister. The design drawings of these components with their auxiliaries and instruments are shown in Fig. 2.

Converter

The converter has the following functional components: a reactor vessel, an input airflow system, a hopper-feeder system, a char removal system, an agitation mechanism, a gas filter system, and a by-pass pipe system.

a) *Reactor Vessel*

The reactor, a steel vessel consisting of an outside shell and an inner slightly tapered shell, is divided into two zones—the upper

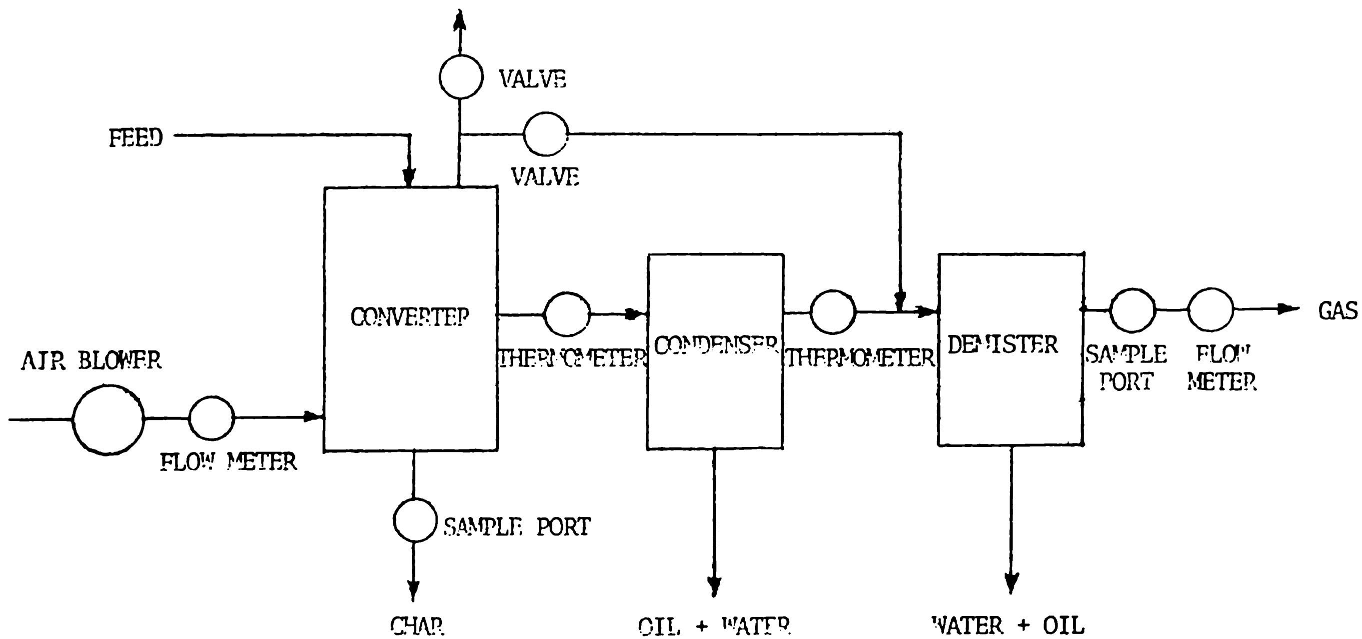

FIG. 1. PYROLYSIS SYSTEM FLOW DIAGRAM.

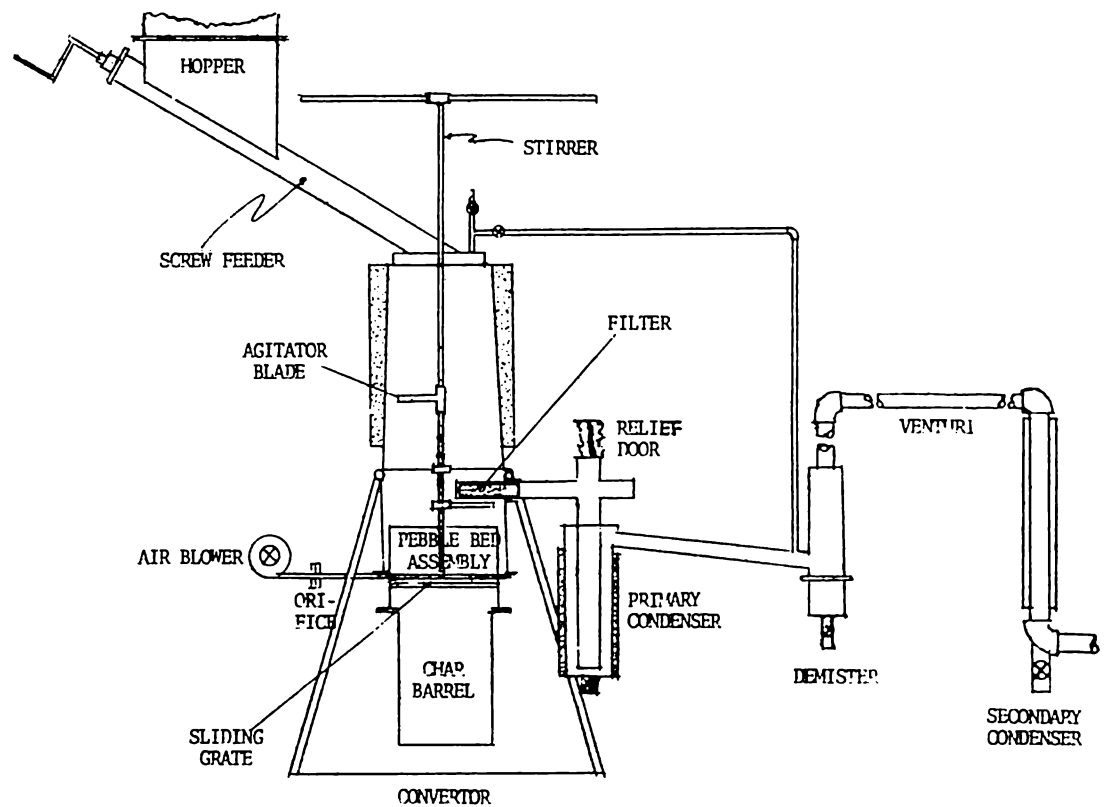

FIG. 2. DETAILED DRAWINGS OF MAJOR UNITS OF PYROLYTIC CONVERTOR SYSTEM.

drying zone, where the unburned rice hull is contained, and the lower pyrolysis zone, where the partial burning of the material takes place.

b) *Input Air-Flow System*

The airflow system consists of a high-speed blower which supplies the air required to sustain the pyrolysis reaction. The air flow is controlled by a primary valve in a main one-inch pipeline. The pipeline contains a calibrated orifice and a pressure gauge. This pipe leads to four horizontal injection pipes, with holes in their upper surface, one in each quadrant of the vessel. Each injection pipe has its own valve which permits the adjustment of air flow to each quadrant to eliminate hot or cool spots that may develop during operation.

The pipes are surrounded by pebbles which serve as heat sink and to further diffuse the air entering the reactor bed.

c) *Hopper-Feeder System*

The hopper has a tapering bottom and is provided with a manually-operated screw conveyor, which conveys the rice hulls into the reactor vessel. Rice hulls in the hopper and feeder form an air lock permitting uninterrupted feeding to the converter. Except on the early runs, when some adjustments had to be made, this system performed satisfactorily well.

d) *Char Removal System*

The char flows through a large center hole in the pebble bed to a grate located directly beneath the bed. The grate consists of two steel plates with matching holes. The bottom plate is fixed while the top plate can slide back and forth by means of a pivoted lever mounted at the side of the reactor. Passage of char is effected by rocking this lever and the char falls into a flanged 55-gallon drum which is securely fastened to the bottom of the reactor with easily loosened bolts for quick changing of barrels.

e) *Agitation Mechanism*

The agitation mechanism consists of a rod with attached paddles. The rod is in the center of the converter, extending above the reactor top with handles for manual operation. This is operated at regular intervals to maintain uniform carbonization and eliminate cavitation in the bed. Initially the rod was a pipe with a small rod inside but this failed on several occasions. The rod was changed to a solid rod with the lower portion made of one foot stainless steel. There are two blades, instead of the original four because of stirring difficulty, attached to the rod—a short one-inch diameter steel rod, two and a half feet from the top, which helps to minimize cavitation and a stainless steel blade positioned just below the filter to even up pyrolysis.

f) *Gas Filter System*

The gas filter system consists of the bed of unburned rice hulls which serves as a filter in trapping most of the particulates, and two concentric pipes—a four inch pipe with a series of holes in the bottom half of the cylinder connected to the wall of the reactor vessel and projecting into the reactor bed above the pyrolysis zone, and a removable smaller pipe with holes over the entire cylinder, wrapped with a fine mesh steel screen, and centered in the larger pipe. Particles which do get through the outer pipe are trapped by the screened inner pipe.

Jet Condenser

The condenser, where most of the oil is collected, consists of a vertical cylinder centrally positioned in a larger cylinder. The inner cylinder is closed at the bottom and one-eighth-inch holes are drilled around the side. The condenser is enclosed in a jacket and the annular space can be filled with either water or rice hulls to aid in maintaining the desired temperature of the condenser.

The gas stream flows out of the holes as a jet and impinges on the side of the larger cylinder effecting condensation of the oil vapors.

Demister

The demister, where the entrained oil and most of the water are condensed, is a two-compartment cylindrical vessel with the upper chamber filled with #10 pebbles.* The pebbles are surrounded by a screen and supported by a flat plate with several holes. Entrained oil and water are condensed as the gas pass through the pebbles and drain through the perforated plate to the lower chamber.

*one-fourth inch diameter.

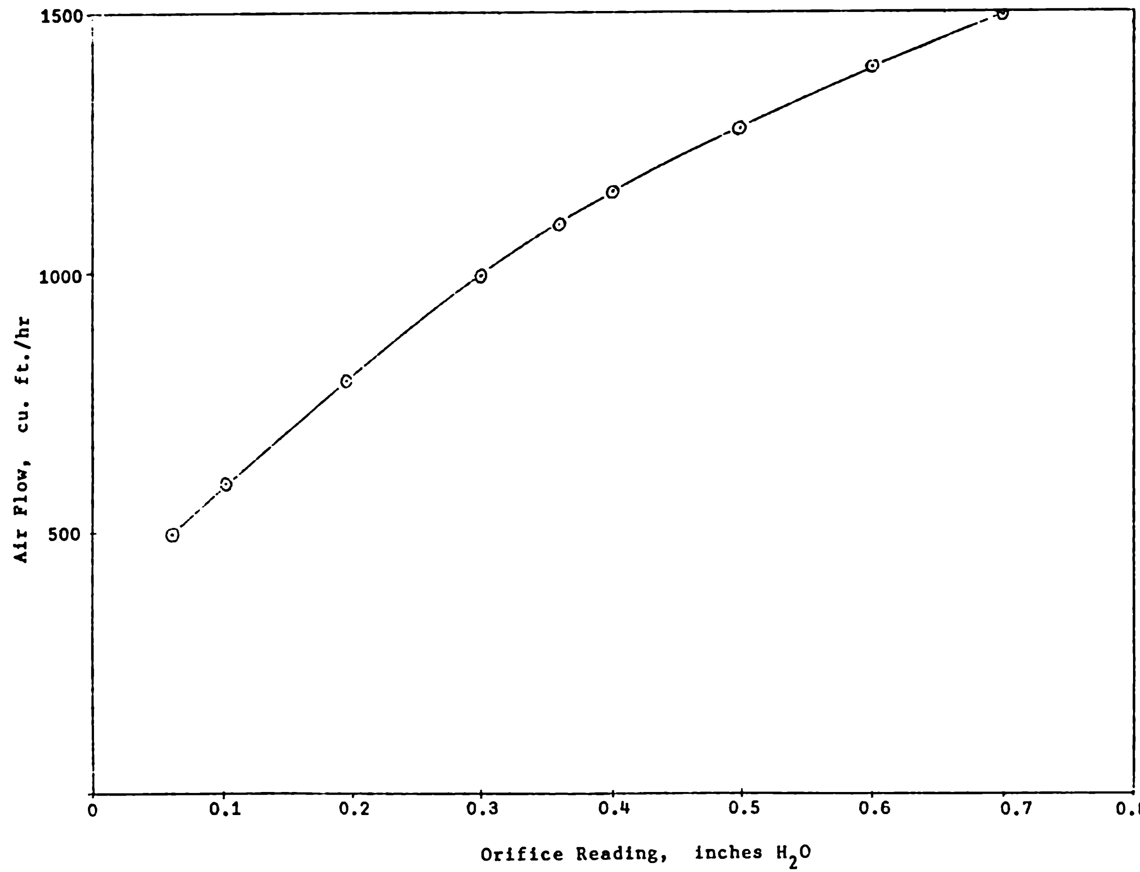

FIG. 3 Air Flow VS. Orifice Reading

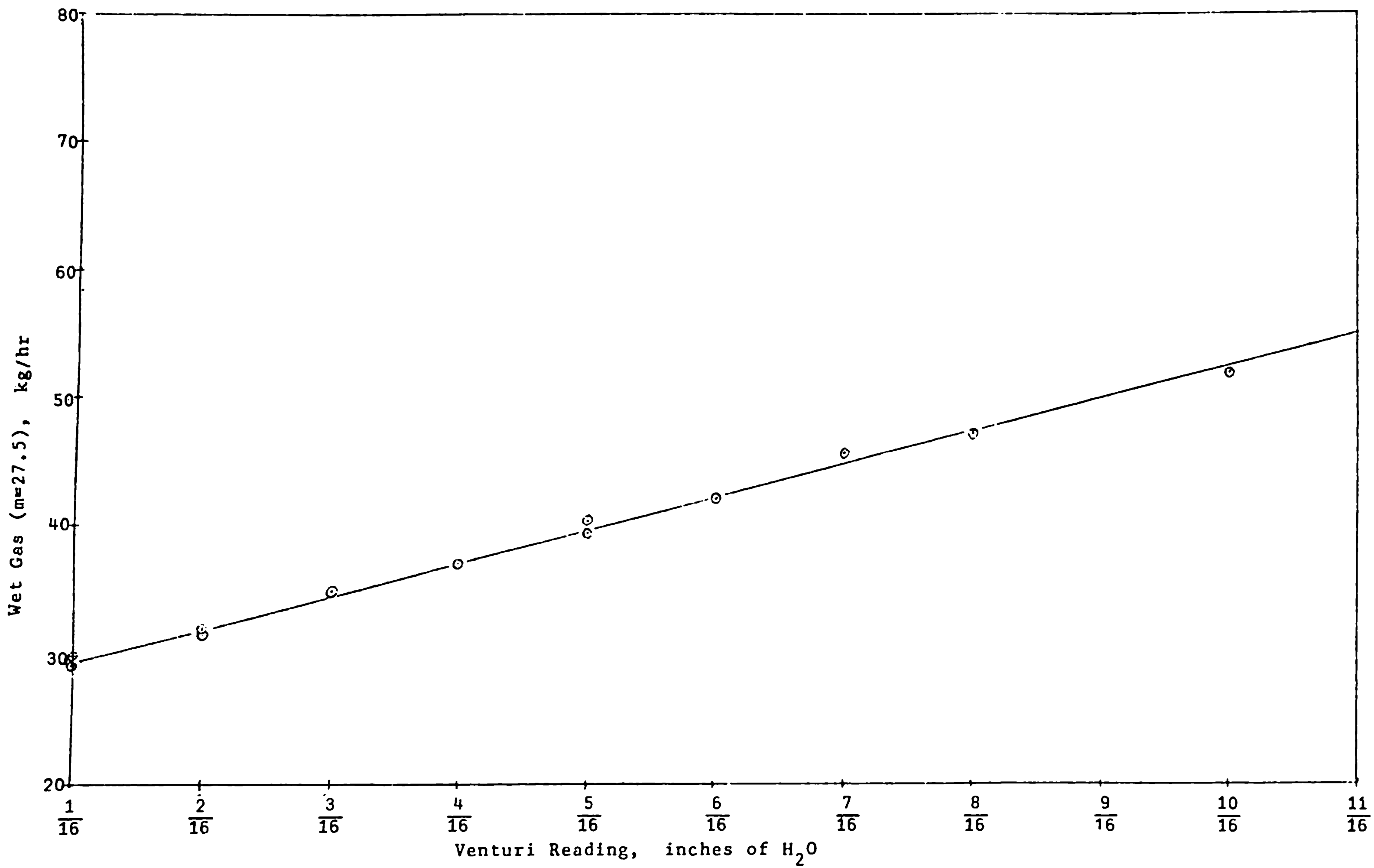

FIG. 4 Wet Gas VS Venturi Reading

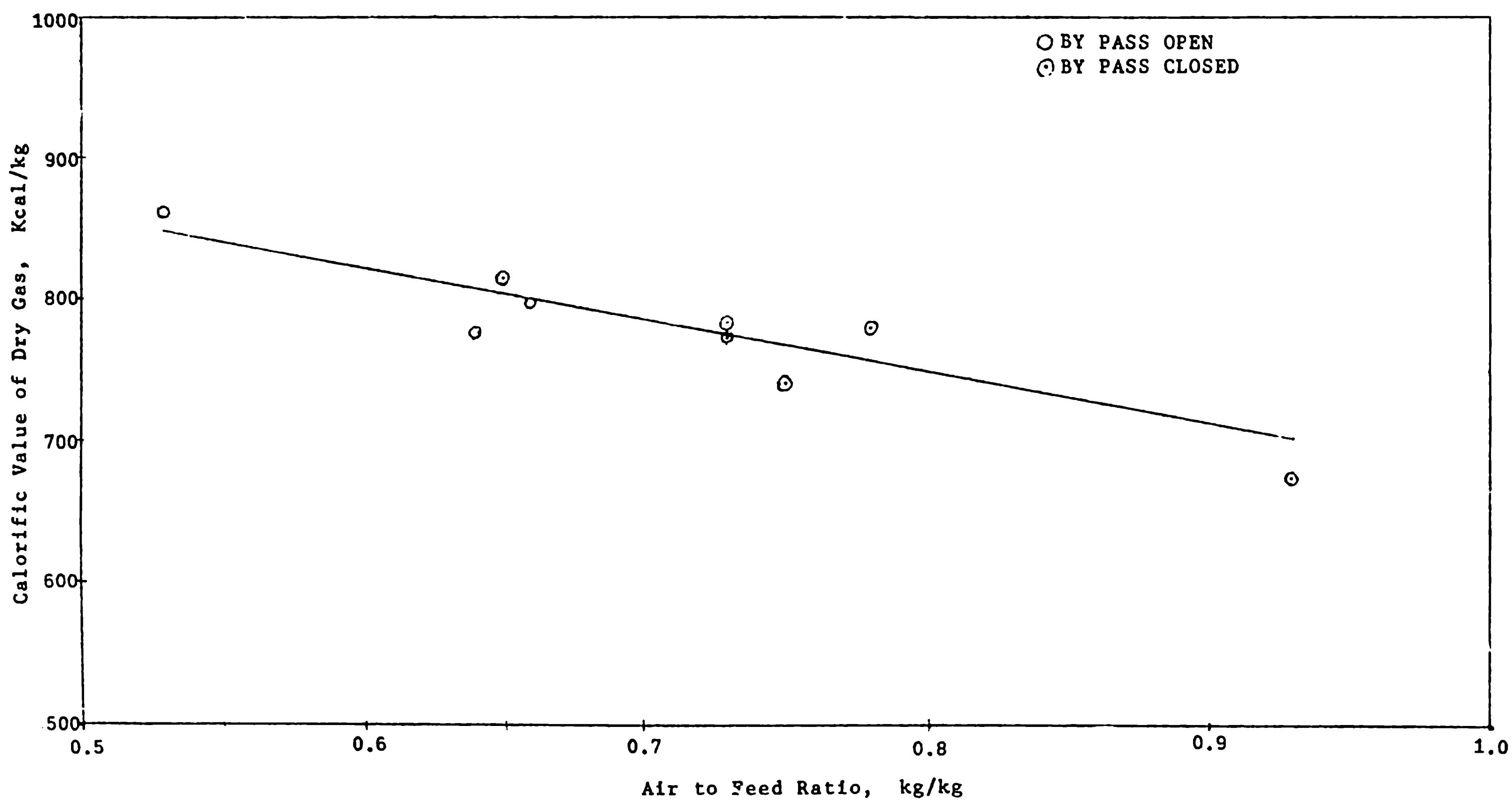

FIG. 5 Calorific Value of Dry Gas VS. Air to Feed Ratio

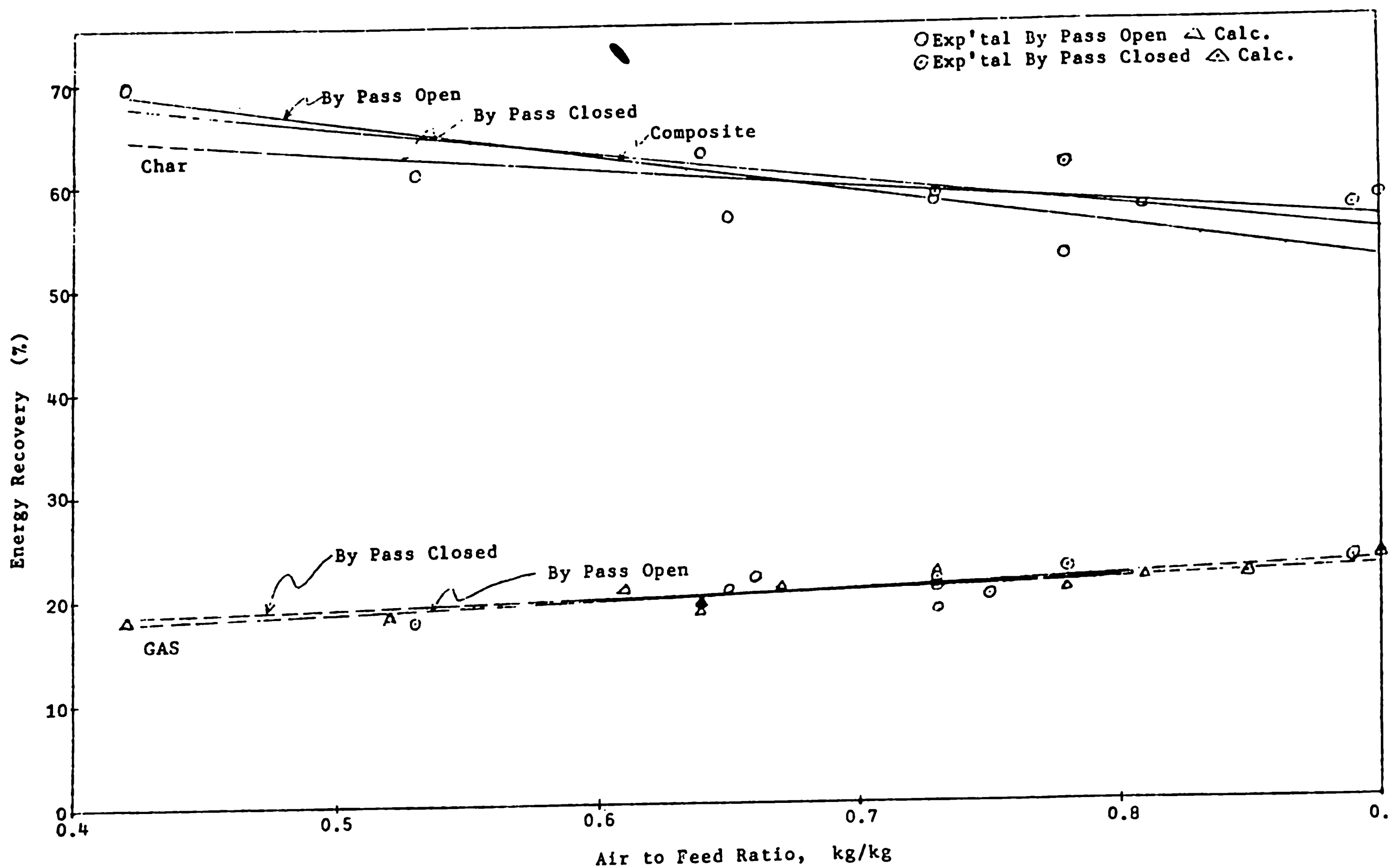

FIG. 6 Percent Available Energy in Char & Gas VS. Air to Feed Ratio

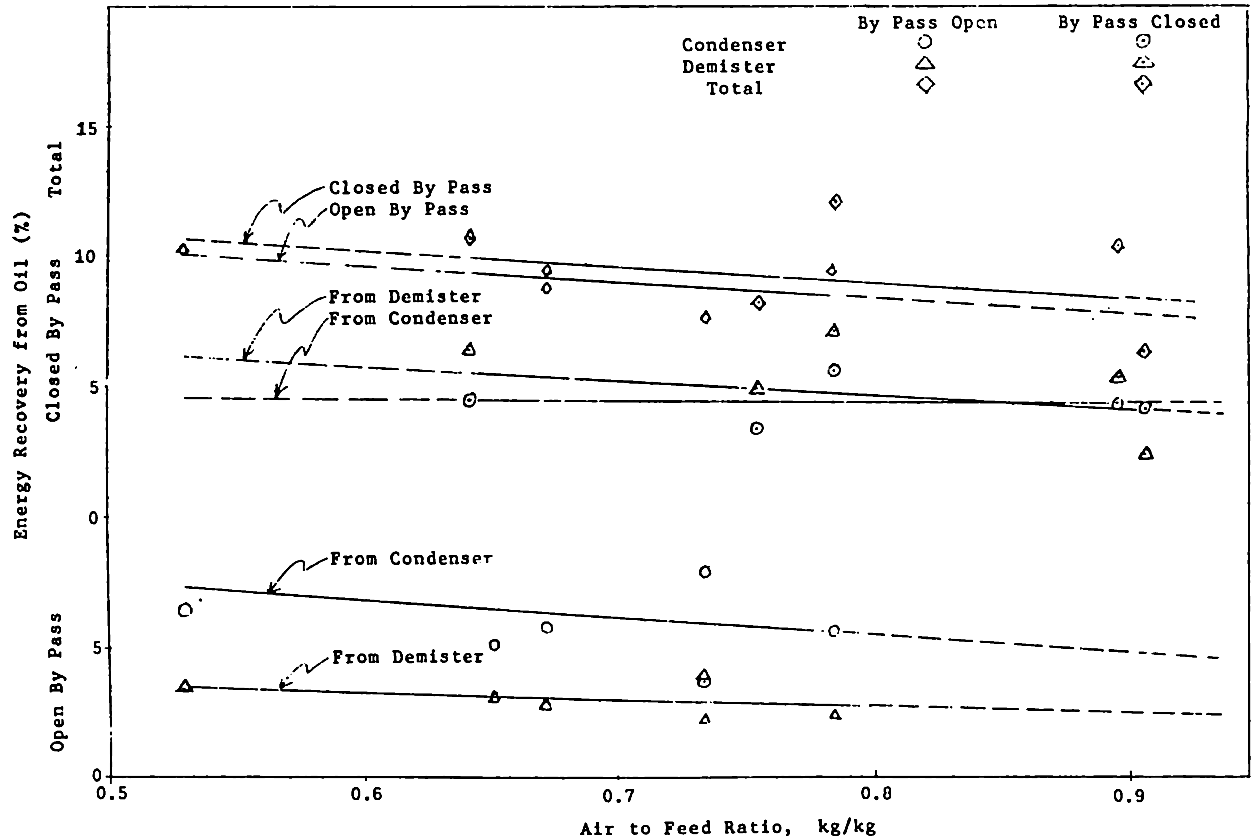

FIG. 7 Percent Available Energy in Pyrolytic Oil VS. Air to Feed Ratio

During the early tests, iron filings, and later on, larger-sized pebbles were used, when much water still appeared in the exiting gas. The use of #10 pebbles substantially reduced the water content of the gas.

Instrumentation

The quantity of air introduced into the converter to produce a chemical reaction which generates heat required for pyrolysis is measured by means of an orifice. The calibration curve of the orifice is shown in Fig. 3.

The amount of gas produced during pyrolysis is measured by means of a venturi located after the demister. The calibration curve is given in Fig. 4.

Temperatures in the combustion-zone are measured by thermocouples around the converter, six inches below the filter and located at the following points:

Thermocouple (T_1) — below the filter
" (T_2) — at grate handle
" (T_3) — at blower
" (T_4) — opposite the filter

Another thermocouple (T_5) is located just beside the filter to indicate the temperature of the gas entering the filter. Dial thermometers, before and after the condenser, and a gas sample tap are provided on the off-gas pipe.

Pressure relief ports are located at the converter top and at the condenser. The ports are spring loaded and adjusted to open when the pressure in the system reaches 10 inches of water (0.4 psig). A pressure gauge was also provided in the reactor vessel.

A calibrated rod is located at the reactor top to measure the bed depth of the material in the reactor.

An open hole with a 1/4-inch valve, six inches from the top of the char barrel, is used to determine if the barrel needs to be changed.

A char probe, located below the grater, is provided for obtaining char samples.

Process Description

The converter system operates as a semi-continuous, self-sustaining pyrolysis process. The feed (rice hulls) is dried to a moisture content of 8-9 percent and is manually fed to the hopper. It is conveyed to the converter with the aid of a manually-operated screw conveyor. The feed in the hopper and screw forms a seal, permitting introduction of feed without stopping the input of air. A limited amount of air is introduced into the converter to partially burn the feed and provide heat required for pyrolysis. The process is initiated by the insertion of burning charcoal to the converter partially filled with the feed.

The converter is divided into two main zones, the pyrolysis zone with temperatures ranging from 400-800°C, located below the off-gas port, where carbonization of the feed takes place, and a vaporization zone, located above the port, where the feed is further dried and preheated by the hot gas.

The feed flows downward by gravity as the mass is reduced in the pyrolysis zone by the action of a manually-operated agitator and by the periodic removal of char at the bottom of the converter. A grate mechanism placed below the pyrolysis allows the char to drop into a char barrel. A water by-pass placed at the top of the converter carries the water vaporized from the fresh feed directly to a demister where the vapor is condensed. The gases come out of the converter just above the pyrolysis zone, through the off-gas port. The gases then go to a condenser and demister where the condensables are separated from the non-condensable gas. The temperature of the gases entering and leaving the condenser are maintained between 150-180°C and 90-120°C, respectively, to minimize water condensation in the condenser. Water and the remaining condensables condense in the demister. A temperature reading of over 180°C on the gas entering the condenser indicates that too much combustion is taking place. To lower the temperature, the lever is rocked to allow the passage of char.

Results

A total of sixty-nine test runs, including the first twenty runs which were conducted jointly with the UNIDO consultants, were made with varying operating times per run, ranging from two hours to twenty-four hours. Air flow rates per run range from seven to sixteen cubic feet per minute. Runs one to eighteen were carried out at a temporary site located on the campus of the University of the Philippines in Diliman, Quezon City. The bulk of the tests were carried out at the NGA compound in Cabanatuan City.

The results are discussed under four categories: design modifications, process operations, product yields of pyrolysis, analysis and calorific values of pyrolytic products, and utilization of pyrolytic products.

Design Modifications

Several modifications were made on the pyrolysis converter system to improve its operation. These are:

a) *Reactor Vessel*

Two holes were drilled on the top cover of the vessel. One of the holes which is two inches in diameter, normally plugged during operation, is used for poking the bed whenever cavitation or compacting of the feed occurs. The other hole, which is one inch in diameter, serves as inlet to a by-pass pipe system, which is discussed in Section (d).

b) *Char Removal System*

A one-inch end section of the fixed grate was cut off to prevent jamming of the grate which occurred during the early test runs due to accumulation of char at the edge of the lower plate.

Additional 3/8" support rods were installed to the barrel to keep the flange from getting deformed due to the weight of the full barrel. Any deformation of the flange results in gas leakage.

c) *Gas Filter System*

The steel filter was replaced by stainless steel when several of the steel screens melted because of recurring high temperatures.

The diameter of the filter pipe was enlarged to 3.5 inches to effect better oil and gas separation by slowing down the gas velocity.

d) *The By-Pass Pipe System*

The by-pass pipe system, a significant improvement to the design of the pyrolytic converter system, effects collection of a more concentrated oil in the condenser and a more aqueous solution in the demister.

The by-pass is an uninsulated one-inch diameter pipe starting out from the top of the reactor and leading down into the demister. This connection allows water from the freshly fed charge, which is vaporized by the heat produced in the pyrolysis zone, to flow directly to the demister. Condensation of the water vapor occurs in the pipe forming a temporary water seal which prevents blow-back of the gas entering the demister from the condenser. Partial cooling of the pebbles is also effected by the condensed water.

The by-pass pipe is provided with two gate valves and a check valve. One valve which opens to the atmosphere, is normally closed during operation. It is opened, but only for a short period, right after feeding rice hulls to the converter, whenever the moisture content of the charge exceeds ten per cent. The other valve, which leads to the demister, is opened during normal operation. It is kept closed to simulate converter operations without a by-pass. The check valve insures no backflows to the converter.

The pipe diameter of the by-pass is important. Too large an opening could result in backflows, when operating without a check valve, and more pyrolytic oils by-passing the condenser. Too small an opening could result in clogging of the line by entrained tars defeating the purpose of the by-pass to effect better separation of oil and water.

e) *Jet Condenser*

The original sixty 1/8" holes were made one hundred twenty 1/16" holes to effectively condense more of the oil vapors in the off-gas.

f) *Demister*

The present demister is not adequate when the converter operates with an open by-pass. This is evidenced by the presence of water still condensing in the gas. Instead of redesigning the demister, which would require a major refabrication effort, a secondary condenser was installed after the demister on the straight pipe going down.

In future pyrolytic converter systems with a by-pass, the capacity of the demister should be increased to take into account the added input of water from the by-pass.

g) *Instrumentation*

A venturi meter was installed on the off-gas line located after the demister to measure the non-condensable gas.

The 1/4" diameter stainless steel thermocouple wells were changed to 1/2" diameter stainless steel pipes to prevent the thermocouple wires from getting stuck in the wells.

Process Description

The pyrolysis of rice hulls has proven to be difficult, but manageable. The processing of this material is particularly sensitive to temperature changes in the bed and to the moisture content of the fresh charge. Non-uniform temperature distribution tends to occur in the bed resulting in hot spots, which accelerate gasification reaction with consequent channelling in these regions. This can be avoided by proper management of airflows, char removal, and agitation cycle.

In rice hull processing, the feeding of drier materials becomes important for it makes temperature control easier and results in products with higher fuel values. Wet feeding, unless the water vapor is removed fast enough through the by-pass, tends to form compaction of the solid charge, hindering the downward flow of the material. During rainy days, it is necessary that a drier feed must be used.

On the basis of the results of the test runs with operating times ranging from 2 to 24.5 hours, air flow rates from 7 CFM (13.9 kgm/hr) to 16 CFM (32.00 kgm/hr), and air-to-feed ratio from 0.42 to 1.6, the following summarize the best conditions for satisfactory performance of the pyrolytic converter system processing rice hulls:

1. The pyrolytic converter system is to be operated with a by-pass.

2. The filter is located twelve inches above the pebble bed.

3. Two blades properly positioned, are adequate to effect uniform pyrolysis reaction over the entire bed and to minimize cavitation.

4. The movable grate plate should be the upper plate, but with an opening at the edge of the lower plate.

5. The pebbles in the demister have to be as small as practically possible. One-fourth inch diameter pebbles are satisfactory.

6. A moisture content of 8-9 per cent is satisfactory, but should still be lower during humid or rainy days.

7. A slow starting with low air flow (10 kgm/hr) is recommended to spread combustion uniformly over the bed.

8. The bed depth is fifty-one inches from the pebble bed, placing the surface of the bed about twelve inches from the top. At this level the weight of rice hulls is about seventy kilograms.

9. Agitation is to be done every fifteen minutes for 3 to 5 minutes.

10. Char removal through the grate is to be done oftener but for shorter periods.

11. The temperature of the filtered gas entering the condenser is from 300-320°F and the temperature at the exit is 205-215°F.

Product Yields of Pyrolysis

A summary of all test runs is given in Appendix A. The analyses of product samples, which could be done, are shown in Appendix B. The product yields and calorific values were calculated using equations developed in Appendix C.

Fluctuations in operating temperatures encountered during many test runs resulted in large variations in product yields, which on an hourly basis range as follows: char, 2.3-30 kgm; gas, 24.1-48.0 kgm; condenser oil, 0.03-1.9 liters; demister oil, 0.7-3.1 liters when operating without or with closed by-pass; and condenser oil; 0.6-2.1 liters; demister oil, 0.7-3.1 liters when the by-pass is open.

The char produced ranges from 16.5% to 68.7% of the feed. A high percentage yield of char is an indication of incomplete carbonization, while a low value means ashing of a portion of the charge during pyrolysis. The product yields, most notably the gas, generally increased with increasing air flow rates.

Only a few runs (Runs 46-47, and 67) could meet the design capacity of one ton rice hull per day. These occurred at air flow rates of 15 CFM and above, corresponding to an orifice reading of 0.25 in. of H_2O. The data for these runs with almost identical configurations are summarized in Table 1.

Test runs of short duration (<2.5 hrs), because stabilization of the operation has not yet been attained, and high per cent char (>50%), be-

Table 1: Pyrolytic Product Yields[a]

RUN NO.	RUN TIME Hrs.	AIR FLOW CFM	FEED kgm	$\frac{AIR}{FEED}, \frac{kgm}{kgm}$	CHAR kgm	OIL[b] li	GAS kgm	% CHAR	% OIL	BY PASS
46	6.2	15	986	0.73	290	95.3	1010	29.4	11.1	open
67	5.	15	1152	0.61	390	74.9	1130	31.3	7.5	open
Avg	5.6	15	1069	0.67	325	85.1	10.70	30.4	9.2	open
47	6.	15	1118	0.64	341	66.7	1097	30.4	6.9	close

a — Daily basis (24 hours per day)
b — Regardless of quality

cause of the presence of substantial quantities of unburned charge, were disregarded in the evaluation.

In runs 62-65, the by-pass was found to be clogged.

Analysis and Calorific Values of Pyrolytic Products

Rice Hull

Rice hull has a high ash content ranging from 20-26% (dry basis). The ash consists mostly of silica. The moisture content of rice hull when it comes from the milling process is from 9-10%. The moisture content increases to about 13% when the rice hull is exposed to the atmosphere for quite some time. It should be dried to 8-9% H_2O before feeding it into the pyrolytic converter.

The average calorific value of the rice hull is 4719 kcal/kg on a dry and ash-free basis.

Char

The char varied in the values of its components depending on the extent of carbonization. On a dry basis, the volatile matter ranges from 2-9%; fixed carbon, 30-54%; and ash, 40-57%. The ash content of the char is unusually high and one factor accounting for this is iron contamination from the converter.

The average fuel value of the char on a dry and ash-free basis is 9,917 kcal/kgm.

Gas

As shown in Appendix B, the dry gas composition is as follows: carbon dioxide, 7-14%; oxygen, 1.5-7%; carbon monoxide, 13-19%; hydrogen, 1-7%; and methane, 2-5%. The average molecular weight is 27 kgm/kgmole. The calorific value of the gas ranges from 720-850 kcal/kgm on a dry basis.

Oil

It can be seen from Appendix B that the water content of the oil varies widely from 15 to 87%. However, for test runs where the by-pass is open, the water accumulated in the demister oil, ranging from 70-79%, while the water content in the condenser oil ranged from 15 to 32%.

The calorific value of the oil on a dry and ash-free basis is 7696 kcal/kgm.

The manner of oil sampling is important. Oil sampled from the bottom layer of a container after long standing contains less water than samples directly obtained from the system (See Runs 38, 41, 49 & 50).

Two options are available for effecting better separation of oil and water. One, is to closely control the temperature of the streams entering and leaving the condenser. The surface temperature of the condenser must be at least 205°F to remove most of the oil, while leaving the water as vapor in the gas stream. The other is to operate the pyrolytic converter with a by-pass.

A comparison of runs with open or close by-pass at the same air flow rate is given in Table 2. Results showed a more concentrated oil yield in the condenser and watery oil in the demister. The percent energy recoveries from selected runs are shown in Table 3 and plotted in Figs. 6-7.

To determine the suitability of the oil as fuel, the properties were determined on a composite sample containing 56% H_2O. The results are given in Table 4.

It has been observed that the oil sample will not burn because the water content was too high. Commonly used fuels have much lower water content, from traces to 2% by volume. The boiling point and the flash point are high. Flash points of common liquid fuels range from 38 to 65%. However, burning tests showed that when the water content was about 30%, the oil, if preheated, ignited and, if provided with a wick, supported a flame, but only for a short duration. This is because a hard crust of solid formed on the wick which prevented the oil to flow freely. The insoluble portion of the tar in benzene, which in this case consists mostly of entrained char fines, is rather high and the silica ash in this char could have caused the formation of the crust on burning.

Table 2. COMPARISON OF RUNS WITH BY-PASS CLOSE AND OPEN AT THE SAME AIR FLOW RATE

TEST NUMBER	ORIFICE RDG. (in.)	AVERAGE/HOUR FEED, kg.	AIR, kg.	CHAR, kg.	GAS, kg.	Oil, liters[a] CONDENSER	DEMISTER	TOTAL	BY-PASS		Proximate Analysis of Liquor % H_2O	% VM	% FC	% ASH
39	0.1	21.6	19.9	7.6	29.9	0.84	1.10	1.94	close	Condenser	20.0	94.1	3.8	2.1
										Demister	79.0	94.5	4.3	1.2
40	0.1	22.0	19.9	8.6	29.9	1.36	1.23	2.59	open	Condenser	74.0	93.2	0.8	6.0
										Demister	85.5	94.8	4.1	1.1
57	0.15	43.8	23.2	20.8	40.4	1.35	2.50	3.80	open	Condenser	32.2	97.5	1.7	0.8
										Demister	69.5	98.0	1.5	0.5
58		31.3	22.9	14.0	35.8	0.52	1.69	2.21	close	Condenser	60.4	88.7	3.5	7.8
										Demister	65.7	97.1	2.0	0.9
41	0.2	28.6	26.6	10.0	35.5	0.74	1.40	2.11	close	Condenser	20.6	96.2	3.1	0.7
										Demister	41.0	95.7		2.0
42		34.3	26.6	13.0	38.5	0.88	1.40	2.28	open	Condenser	15.4	95.4	3.6	1.0
										Demister	76.3	96.1	0.2	3.7
47[b]	0.25	46.7	29.8	14.2	45.7	1.02	1.76	2.78	close	Condenser	23.0	97.6	1.1	1.3
										Demister	37.0	97.8	1.1	1.1
52		40.9	29.7	20.0	40.4	1.85	1.28	3.13	open	Condenser	30.0	75.3	20.2	4.5
										Demister	72.0	86.2	10.8	3.0

a — Regardless of quality.
b — Oil samples collected after run.

Table 3. PERCENT ENERGY RECOVERIES FROM PYROLYTIC PRODUCTS

		RICE HULL[a]		CHAR[b]			OIL[c]						GAS[d]			
Test							CONDENSER			DEMISTER						
TEST NUMBER RUN	AIR/FEED, kg/kg	Kg/hr.	KILOCALORIES / hr	Kg/hr	KILOCALORIES / hr	PERCENTAGE	Kg/hr	KILOCALORIES	PERCENTAGE	Kg/hr	KILOCALORIES / hr	PERCENTAGE	Kg/hr	KILOCALORIES / hr	PERCENTAGE	TOTAL %
							BY-PASS CLOSED									
38	0.78	27.5	99,571	10.3	(61,188)	(61.4)	1.07	(4,282)	(4.3)	1.35	(4,580)	(4.6)	28.2	(22,165)	(22.2)	(92.5)
40	0.90	20.1	73,145	8.1	42,445	58.0	0.58	2,924	4.00	0.29	1,539	2.1	23.7	(16,946)	(23.2)	(87.3)
41	0.93	26.2	94,852	9.8	49,387	52.1	0.97	(3,984)	(4.2)	1.36	(3,604)	(3.8)	28.2	19,091	20.1	(80.2)
47	0.64	42.7	154,783	13.3	(93,643)	(60.5)	0.78	6,849	4.4	1.82	9,697	6.2	36.4	(29,520)	(19.1)	(90.2)
50	0.89	30.5	110,425	14.3	63,072	57.1	0.87	4,451	4.1	1.32	6,849	6.2	33.8	25,519	23.1	90.5
58	0.73	28.6	103,818	13.5	60,791	58.6	0.34	1,832	1.8	0.95	5,118	4.9	28.5	22,430	21.6	86.9
59	0.75	36.1	131,188	18.7	(76,745)	(58.5)	0.44	2,370	1.8	0.91	4,908	3.7	34.7	25,782	19.7	(83.7)

BY—PASS OPEN

42	0.78	31.4	113,728	12.5	59,483	52.2	1.22	6,542	5.8	0.55	2,848	2.5	30.5	(23,180)	(20.4)	(80.9)
44	0.73	33.1	120,335	12.0	(69,794)	(58.0)	0.82	4,387	3.7	0.90	4,772	4.0	33.4	(26,052)	(21.6)	(87.3)
45	0.67	32.0	116,087	12.6	(69,652)	(60.0)	1.28	6,849	5.9	0.64	3,463	3.0	30.5	(24,440)	(21.0)	(89.9)
52	0.73	37.4	135,907	19.0	82,807	60.9	2.13	10,928	8.0	0.59	3,001	2.2	32.5	25,220	18.6	89.7
54	0.81	26.4	95,324	13.4	54,444	57.1	1.44[c]	(5,243)	(5.5)	0.30[d]	(2,669)	(2.8)	27.4	(20,550)	(21.6)	(87.0)
56	0.66	32.0	116,987	13.2	(70,116)	60.4	0.46	(7,661)	(6.6)	0.73	(3,714)	(3.2)	32.1	25,776	22.2	(92.4)
57	0.53	40.1	145,345	20.1	88,261	60.7	1.78	9,543	6.6	1.00	5,233	3.6	29.9	25,864	17.8	88.7
64	0.64	27.9	102,402	16.2	(62,465)	(61.0)	0.45	(6,861)	(6.7)	1.17	(3,277)	(3.2)	22.1	17,238	16.8	(87.7)
68	0.65	36.6	132,715	17.5	75,516	56.9	1.28	6,852	5.2	0.80	4,268	3.2	33.4	27,351	20.6	85.9

a — Tabulated on dry basis.
b — Corrected to 30% H_2O content.
c — Calculated on dry basis.
d — Tabulated on wet basis.
Values in parenthesis calculated from Figs. 5, 6, & 7.

Table 4: PROPERTIES AND ANALYSIS OF PYROLYTIC OIL

Water	56%
pH	3.2
Specific gravity (15.5°C)	1.12
Boiling point	94°C
Flash point	110°C
Total acids	2.6%
Alcohol as methanol	0.5%
Total tar	40.9%
Solubility of tar in benzene	31.5%

Plots in Figs. 5-7 show the variation of the calorific value of the gas, the percent available energy in the pyrolysis products with air-to-feed ratio. The points are somewhat scattered due to the temperature fluctuation from run to run. The best lines through the points were drawn using the least squares method.

As shown in Fig. 5, the calorific value of the dry gas decreases by about 5% with every tenth increase in air-to-feed ratio. The decrease is expected due to increase in nitrogen content in the gas. At an air-to-feed ratio of 0.67, the calorific value of the dry gas is 800 kcal/kgm. No significant differences in calorific value were observed between operations with open and close by-pass.

Fig. 6 shows the energy recoveries of the char and gas at varying air-to-feed ratios. The available energy in the char decreases by about 3% per one-tenth increase in air-to-feed ratio, while that of the gas increases slightly by about 1%, although there is a decrease in the unit calorific value of the gas. This is because increasing air-to-feed ratio increases also the quantity of gas produced.

Results of the test runs showed that the yields of these two products are significantly affected by the operation of the by-pass.

The percent available energy in the pyrolytic oil collected from the condenser and demister operating with open and close by-pass is shown in Fig. 7. It can be seen from this figure and Table 2 that as compared to the system without a by-pass, the condenser oil from the system with a by-pass show about 31 to 58% increase in energy recovery and this oil can directly be used as fuel. The oil from a converter without a by-pass will still have to be processes to reduce the water content, before it can be used as fuel.

Utilization of Pyrolysis Products

The labor-intensive U.P. NEC-BED pyrolytic converter, designed for rural use, converts rice hulls into higher calorific-value fuels. For the rural community to benefit from these fuels, they must be suitable and convenient to use.

The gas has to be utilized as soon as it is produced since it will be uneconomical to store it. Otherwise, it has to be flared for health and safety reasons. The gas can be used to dry palay and the rice hulls, to provide mechanical power for the pyrolytic converter, or to generate power to run a rice mill.

A number of test runs showed that a pyrolytic gas burner can replace the kerosene burner which is normally used in drying palay in a flat-bed dryer. When drying palay, because of the smell, the gas has to be burned in a furnace. The heat generated heats a cylinder through which hot air is sucked towards the dryer. In rice hull drying the gas can be used directly.

A 6 feet wide by 12 feet long flat-bed drier, commonly used in the farm was used for the comparison tests. The grain compartment is 18 inches deep and can hold up to 40 cavans of wet palay. The drier also includes a fan and engine to force the drying air through the grain, and a kerosene burner to heat the drying air.

It takes about 6 hours to dry the rice hulls from a moisture content of 13% to 8.5%, using the kerosene burner. At a blower rate of 75 CFM, the average temperature on the bed is 110°F. The kerosene consumption is 3 liters per hour. The drying time is 3-3.5 hours when the kerosene burner is replaced with a gas burner using the gas from the converter operating at an air flow rate of 15 CFM which corresponds to an orifice reading of 0.25 inches of H_2O. However, the temperature on the bed is about 145°F which is too high for palay drying. To maintain a temperature of 110°F on the bed, the converter should be operated using an air flow rate of 7.5 CFM ($\Delta P = 0.02$ inches of H_2O).

The granular char, if it is to be used for residential cooking and ironing, has to be briquetted using locally available binders like starch, molasses and sorghum. A manually operated briquetting machine has to be designed and built out of local materials to provide a low cost means of briquetting.

Two kinds of oil can be produced from the converter with a by-pass; namely, a condenser oil which, because of a relatively lower water content, can be used directly as fuel, and a demister oil which could be more economically used as a wood preservative because of its high water content.

The oil may be used as a substitute for kerosene or bunker oil, but as previously discussed, the oil affects wicking action and has to be further refined. The oil is acidic. Neutralization or blending with other oils would counteract its acidic properties.

Economic Analysis

It is often difficult to carry out a meaningful cost analysis without reference to particular cases, and a valuation of the material used. Furthermore, data on prices and costs of materials and services continue to increase, while social and other related benefits may not be quantifiable.

The following economic analysis is based on integrating a pyrolyzer with a rice mill and comparing costs of using alternative fuels. A typical barangay level rice mill has a milling capacity of 100 cavans (4.4 tons) palay* operating for 12 hours a day. The power requirement is 21 BHp. Normal milling produces 20-24% of rice hulls. A one-ton pyrolytic converter operating at an air-to-feed ratio of 0.67 can recover the energy (See Figs. 6-7) from the rice hull as follows: char, 60%; gas, 20%; and oil (30% H_2O), 6.5%.

The following summarizes the energy recoveries from a daily capacity of 100 cavans:

Rice hull (cal. value of 3626 kcal/kg)		=	3.51 Mkcal
Charcoal	= (0.6)(3.51)	=	2.11 "
Gas	= (0.2)(3.51)	=	0.70 "
Oil	= (0.065)(3.51)	=	0.23 "
	Total	=	3.04 Mkcal or 912 Mkcal/yr.

A 21 Hp engine operating for an hour will produce at its shaft: 21 Hp-hr X 641.7-kcal/Hp-hr = 13,476 kcal. Assuming an engine efficiency of 16%, the engine will consume energy at a rate of 84,225 kcal/hr

*13% H_2O content.

or 303 Mkcal/yr for an estimated annual operating time of 50 weeks, operating for 72 hours weekly. If diesel fuel, which has a fuel value of 10,833 kcal/kg, density of 0.88 kg/liter, and a unit price of ₱2.50/liter, is used the annual expense for operating the engine is ₱63,726.

In the Philippines, the moisture content of newly harvested palay ranges from 20-26%, which is too wet for milling or storage. The grain moisture should be reduced to 13%, which takes 6-8 hours drying time in a flat bed grain dryer, depending upon moisture content. The water evaporated daily in the drying process is 543 kg from palay and 49 kg from rice hulls, or a total of 592 kg. The energy required to vaporize this quantity of water is 96 Mkcal per year. Assuming a burning efficiency of 75% for the pyrolytic gas, the energy required is 128 Mkcal per year. Using the results of the drying tests, the annual kerosene consumption in drying the palay from 23% to 23% H_2O, and the rice hull from 13% to 8.5% H_2O is 15,750 liters and 2,727 liters, respectively or a total of 18,477 liters. At the price of kerosene of ₱2.50 per liter, the annual expense for kerosene is ₱46,193.

The blower of the drier is run by a gasoline engine which, from an actual test run, consumes a liter of gasoline per hour operating time. In drying the palay and rice hulls to the desired water content, the annual gasoline consumption would be 5,250 liters and 900 liters, respectively, or a total of 6,150 liters. At the current price of gasoline of ₱4.75 per liter, the annual expense for blower operation is ₱29,213. The energy required in the operation of the blower, assuming a 20% engine efficiency is 9.96 Mkcal. The equivalent pyrolysis fuel (16% utilization) is 62.3 Mkcal annually.

There is still available from the pyrolysis fuels energy amounting to 912 − (128 + 303 + 62) = 419 Mkcal/yr. At 15% utilization, this is equivalent to 20 kwatss of lighting.

The annual energy savings in integrating a pyrolyzer with a 100-cavan rice mill is ₱139.00. With this saving, the investment cost of installing and operating a pyrolyzer which is about ₱70,000, could be paid-off within a period of seven months.

Conclusions and Recommendations

Conclusions

The results of this project have led to the following conclusions:

a. Pyrolysis could be utilized in converting rice hulls into higher value fuels with proper operational management.

b. Pyrolytic converters can be designed, locally fabricated, and manually operated in the Philippines to meet rural needs.

c. The design capacity of the prototype model can be met only at higher air flow rates with tendency to gasification.

d. A by-pass pipe system can improve performance of the converter system insofar as oil yield and better oil-water separation are concerned.

e. The pyrolytic products, except for the oil, can be readily and conveniently utilized as fueld with minimal processing.

f. Two kinds of oil can be produced; namely, condenser oil for use as fuel and demister oil for use as a wood preservative.

g. Integrating a pyrolyzer with a typical barangay rice mill can pay-off the investment for a pyrolyzer within a period of one year.

Recommendations

The following recommendations are presented:

a. A bigger capacity of 2-3 MT per day be designed, fabricated and tested to determine performance and economics on a larger or pilot plant scale, before widespread application of pyrolytic converter units be undertaken. Engineering and design details of larger-scale facility appear to be needed.

b. A one-tone pyrolytic converter be integrated with a typical barangay level rice mill (100 cavans per day) to demonstrate its utility and to determine its economic viability.

c. Either the existing prototype pyrolytic converter in Cabanatuan or another prototype, which has to be constructed, be utilized for testing other rural wastes as feed stocking and research on the use of the pyrolytic products.

Appendix A. SUMMARY OF TEST RUNS

Test Number	Readings (in.)		Feed		Char Collected		Oil Collected, l			Hrs. of Operation	Average/hr.							Filter		No. of Blades	Size No. Pebbles in	By-Pass	Air/Fuel	Air Temp.	
														— Oil, l —											
	Orifice	Venturi	Burned, kg.	% H_2O	Wt., kg.	% of Feed	Condenser	Demister	Total		Air, kg.	Feed, kg.	Char, kg.	Condenser	Demister	Total	Gas, kg.	Diam., in.	Port No					Dry Bulb, °C	Wet Bulb, °C
1							3.4	0.95	4.35	2.5				1.36	0.38	1.74		2.25	1	4		w/o			
2							9.5	1.4	10.9	4				3.8	0.56	4.36		2.25	1	4		w/o			
3							8.8	1.1	9.9	2				4.4	0.55	4.95		2.25	1	4		w/o			
4	0.10																	2.25	1	4		w/o			
5	0.18						0.15	0.15	0.3	5				0.03	0.03	0.06		2.25	1	4		w/o			
6	0.13			10			6.85	1.45	8.3	3.5				1.96	0.40	2.36		2.25	1	2		w/o			
7	0.08			8			2.45	0.95	3.4	3.5				0.7	0.27	0.34		2.25	1	2	8	w/o			
8	0.20		159	10	45.45	28.58	3.73	1.10	4.83	3.5		45.45		1.07	0.31	1.38		2.25	1	1	8	w/o			
9	0.04			10			0.63	0.20	0.83	4				0.16	0.05	0.21		2.25	1	1	8	w/o			
10	0.03			10			3.0	2.4	5.4	5				0.6	0.48	0.54		2.25	1	1	8	w/o			

Appendix A. (continued)

23	0.04		415	9	68.6	16.5	20.4	14.54	34.9	21.5	15.2	19.3	3.2	0.95	0.68	1.63		3.5	1	1	8	w/o	0.79
24	0.03		410	8	138	31.4	16.2	12.16	28.36	22.5	14.2	19.5	6.1	0.72	0.54	1.26		3.5	1	1	8	w/o	0.73
25	0.03			8	53		7.3	6.25	13.55	8			6.6	0.91	0.78	1.69		3.5	1	1	8	w/o	
26	0.03			9	22		3.8	2.9	6.7	2	18.0		11.0	1.9	1.45	3.35		3.5	1	1	8	w/o	
27	0.20		220	10	60	27.3	3.06	3.03	6.09	5.5		40.0	11.0	0.56	0.55	1.11		3.5	1	1	8	w/o	
28	0.20		170	10	52	30.6	2.7	3.7	6.4	3		56.6	17.3	0.9	1.2	2.1		3.5	1	1	8	w/o	
29	0.20		227	8.5	48	21.1	9.3	9.8	19.1	5.5	26.6	41.3	8.73	1.7	1.8	3.5		3.5	1	1	8	w/o	
30	0.10			11			3.95	3.6	7.44	5				0.79	0.72	1.51		3.5	1	1	8	w/o	
31	0.20		120	8.5	30	25.0	2.35	3.0	5.25	3	26.6	40	10	0.78	1.0	1.78		3.5	1	1	8	w/o	0.66
32	0.20		150	11.5	50	33.3	9.9	9.8	19.7	6	26.6	25	8.3	1.65	1.63	3.28		3.5	1	1	8	w/o	1.06
33	0.10	3/16	160	8.5	35	21.9	11.5	9.4	20.9	7	19.6	22.8	5	1.64	1.34	2.98	24.4	3.5	1	2	8	w/o	0.87
34	0.2	8.5/16	200	9.0	55	27.5	8.25	10.0	18.25	6	26.6	33.3	9.16	1.38	1.67	3.05	38.5	3.5	1	2	8	w/o	0.80
35	0.1	4/16	125	9.5	25	20.0	5.2	3.1	8.3	3.5	19.9	35.7	7.14	1.48	0.88	2.36	35.8	3.5	1	1	10	o	0.56
36	0.1	3/16	180	8.5	70	38.8	14.4	10.7	25.1	7	19.9	25.7	10	2.06	1.52	3.58	24.1	3.5	1	2	10	o	0.77
37	0.1	2/16	180	8.5	60	33.3	6.4	11.2	17.6	6.5	19.9	27.7	9.2	0.98	1.72	2.70	32.4	3.5	1	2	10	o	0.72
38	0.15	3/16	330	8.5	117	35.4	10.55	14.0	24.55	11	23.3	30	10.6	0.96	1.27	2.23	35.4	3.5	1	2	10	c	0.78
39	0.1	1/16	259	8.5	92	35.5	10.15	13.25	23.4	12	19.9	21.6	7.6	0.84	1.1	1.94	29.9	3.5	1	2	10	o	09.2

Appendix A. (continued)

40	0.1	1.1/16	540	8.5	210	38.9	33.45	30.15	63.6	24.5	19.9	22	8.57	1.36	1.23	2.59	29.9	3.5	1	2	10	o	0.90		
41	0.2	3.3/16	230	8.5	80	34.8	5.95	11.15	17.1	8	26.6	28.6	10	0.74	1.4	2.14	35.5	3.5	1	2	10	c	0.93		
42	0.2	4.3/16	240	8.5	92	38.3	6.15	9.7	15.85	7	26.6	34.3	13	0.88	1.4	2.28	38.5	3.5	1	2	10	o	0.78	29	25
43	0.1	2/16	170	8.5	86	50.6	5.3	11.95	17.25	7	19.9	24.3	12.3	0.76	1.7	2.46	32.2	3.5	1	2	10	o	0.82		
44	0.2	6/16	290	8.5	100	34.5	4.85	20.6	25.45	8	26.6	36.2	12.5	0.6	2.6	3.2	42.1	3.5	1	2	10	o	0.73		
45	0.15	5/16	105	8.5	40	38	3.15	6.95	10.1	3	23.3	35.0	13.3	1.05	2.3	3.35	38.7	3.5	1	2	10	o	0.67		
46	0.25	6/16	255	8.5	75	29.4	8.05	17.55	24.6	6.2	29.8	41.1	12.1	1.14	2.83	3.97	42.1	3.5	1	2	10	o	0.73		
47	0.25	7/16	280	8.5	85	30.4	6.14	10.6	16.74	6	29.8	46.67	14.2	1.02	1.76	2.78	45.7	3.5	1	2	10	c	0.64		
48	0.30	8.4/16	240	9.5	110	45.8	4.9	14.4	19.3	5-1/6	32.1	46.4	21.3	0.95	2.78	3.73	48.0	3.5	1	2	10	o	0.69	30	29
49	0.30	8/16	200	8.5	82	41.0	5.5	11.75	17.25	5-1/3	32.0	37.5	15.4	1.03	2.2	3.23	47.1	3.5	1	2	10	c	0.85	31	25
50	0.25	6/16	100	8.5	45	45.0	2.15	3.8	5.95	3	29.7	33.3	15.0	0.72	1.26	1.98	42.5	3.5	1	2	10	c	0.89	31	26
51	0.25	10/16	95	8.0	40	42.0	3.25	1.15	4.35	1.5	29.7	(63.3)	26.67	2.16	0.76	2.92	52.0	3.5	1	2	10		0.47		
52	0.25	5/16	235	8.5	115	48.9	10.65	7.35	18.0	5.75	29.7	40.9	20.0	1.85	1.28	3.13	40.4	3.5	1	2	10	o	0.73	31	28
53	0.15	6/16	80	10.5	40	50.0	4.4	1.5	5.9	2.5	23.1	32.0	16.0	1.76	0.5	2.26	42.1	3.5	1	2	10	o	0.72		
54	0.15	6/16	115	8.5	55	47.8	5.0	1.05	6.05	4	23.3	28.8	13.8	1.25	0.26	1.51	42.1	3.5	1	2	10	o	0.81		
55	0.15	4.8/16	225	8.5	95	42.2	6.0	12.0	18.0	6	23.0	37.5	15.8	1.0	2.0	3.0	39.4	3.5	1	2	10	o	0.61	32	25
56	0.15	4.8/16	140	8.5	55	39.3	2.85	8.1	10.95	4	23.2	35.0	13.8	0.71	2.0	2.71	40.2	3.5	1	2	10	o	0.66	31	26
57	0.15	5/16	95	8.5	45	47.4	4.00	5.0	9.0	2-1/2	23.2	43.8	20.8	1.6	2.0	3.6	40.4	3.5	1	2	10	o	0.53		
58	0.15	3.3/16	235	8.5	105	44.7	3.9	12.65	16.55	7.5	22.9	31.3	14.0	0.52	1.69	2.21	35.8	3.5	1	2	10	c	0.73	33	29

Appendix A. (continued)

59	0.25	6.4/16	250	8.5	125	50.0	4.7	10.0	14.7	6-1/3	29.5	39.5	19.7	0.74	1.58	2.32	43.7	3.5	1	2	10	c	0.75	33	27
60	0.02	2/16	180	8.5	75	41.7	5.65	9.4	15.05	5.5	15.0	32.7	13.6	1.03	1.71	2.74	31.9	3.5	1	2	10	c	0.46		
61	0.25	6/16					1.0	5.85	6.85	2.0	29.5			0.5	2.9	3.4	41.2	3.5	1	2	10	o			
62	0.02	1/16	70	8.5	40	57.1	2.25	2.2	4.45	2.0	15.0	35.5	20.0	1.13	1.1	2.23	29.6	3.5	1	2	10	o	0.42	35	27
63	0.25	5/16	138	9.5	70	50.7	2.7	7.8	10.5	3.0	29.6	46.0	30.0	1.08	3.12	4.20	40.4	3.5	1	2	10	o	0.64	32	25
64	0.10	1/16	185	9.5	100	54.0	4.2	14.3	18.5	6.0	19.7	30.8	16.6	0.7	2.38	3.08	30.5	3.5	1	2	10	o	0.64		
65	0.15	5/16	155	8.5	55	35.0	2.25	3.75	6.0	3.5	23.1	44.3	15.7	0.64	1.07	1.07	39.6	3.5	1	2	10	o	0.52		
66	0.02	2/16	175	8.5	70	40	7.15	15.25	22.4	8.0	15.0	21.9	8.75	0.89	1.9	2.79	32.2	3.5	1	2	10	o	0.68	31	24
67	0.25	8/16	240	9.0	75	31.15	4.6	11.0	15.6	5.0	29.5	48.0	15.0	0.92	2.2	3.12	47.1	3.5	1	2	10	o	0.61	33	25
68	0.20	6/16	280	8.5	127	45.3	6.6	13.95	20.55	7.0	26.0	40.0	18.14	0.94	2.0	2.94	42.1	3.5	1	2	10	o	0.65	35	26
69	0.15	4/16					3.0	3.25	6.25	2.5	22.9			1.2	1.3	2.5	37.2	3.5	1	2	10	o		34	26

Appendix B. Analyses of Pyrolysis Products

TEST NO.	PROXIMATE ANALYSES								GAS ANALYSES				
	LIQUOR				CHAR								
	% H_2O	% VM	% FC	% ASH	% H_2O	% VM	% FC	% ASH	CO_2	O_2	CO	H_2	CH_4
10						10.96	38.29	50.75					
11						3.46	45.32	51.22	11.8	0	23.6	6.9	2.6
14						3.77	41.2	55.03					
16						3.15	36.52	60.33	10.8	8.2	19.6	1.1	1.0
17						4.38	34.42	61.2	8.2	8.0	11.2	0.4	2.4
18						3.42	35.8	60.78					
28									7.6	5.0	15.4	7.3	1.0

Appendix B. (continued)

33										9.2	1.9	28.3	14.75	13.7
34										9.8	0.3	11.05	7.1	11.1
35 —										10.1	3.4	14.0	7.6	12.8
37	Condenser	55.6	94.71	3.46	1.82	4	12	30	58					
	Demister	61.5	96.3	2.2	1.5									
38	Condenser[a]	32.3	95.1	2.05	3.85	3	6	54	40	6.8	7.2	14.8	1.8	5.1
	Demister[a]	35.2	93.8	2.91	3.3									
39	Condenser	20.0	94.1	3.8	2.08	1.92	5	36	59					
	Demister	85.5	94.5	4.3	1.2									
40	Condenser	74.0	93.2	.81	5.98	6	15	38	47					
	Demister	85.5	94.8	4.08	1.06									
41	Condenser[a]	20.6	96.2	3.1	0.7	2.4	7	42	51	11.1	1.9	12.85	6.8	2.6
	Demister[a]	41.0	95.7	2.3	2.01									

Appendix B. (continued)

42	Condenser	15.41	95.4	3.61	9.8	3.95	11.25	33.81	50.99					
	Demister	76.3	96.12	0.21	3.67									
43	Condenser									7.75	4.25	14.2	5.3	2.0
	Demister	87.05	97.68	0.69	1.62									
44	Condenser	17.27	98.44	0.7	.88	4.18	10.02	30.8	60					
	Demister	79.0	97.21	1.72	1.05									
45	Condenser	25.54	97.11	2.1	0.85	5.22	10.11	32.1	58					
	Demister	83.0	96.01	3.8	1.22									
47	Condenser[a]	23.0	07.6	1.15	1.3	6.1	9.87	35.0	54.9					
	Demister[a]	37.0	97.8	1.14	1.1									
48	Condenser	13.2	97.11	1.53	1.35					11.0	2.4	16.2	9.7	3.7
	Demister	33.67	98.32	1.22	0.45									
49	Condenser[a]	20.0	97.65	1.44	0.91					9.6	1.8	15.2	10.6	4.2
	Demister[a]	29.09	98.4	1.21	0.4									
50	Condenser[a]	26.84	87.4	10.3	2.3	4.55	13.4	29.0	57.6	8.2	3.6	17.1	5.14	2.8
	Demister[a]	36.36	85.1	12.2	3.7									
52	Condenser	30.0	75.3	20.19	4.51	5.1	7.9	32.0	56.0	12.5	1.5	13.0	1.3	2.5
	Demister	72.0	86.2	10.78	3.02									

Appendix B. (continued)

54	Condenser					3.2	5.03	36.1	58.87	11.0	0.8	18.2	7.8	3.1
	Demister													
55	Condenser	52.0	88.85	4.1	7.55	4.25	5.1	39.2	55.7	13.2	1.7	19.4	7.2	4.7
	Demister	84.54	94.52	1.37	4.11									
56	Condenser	60.9	89.8	3.41	6.79	4.1	6.1	36.8	57.1	13.5	5.0	18.3	6.7	2.73
	Demister	77.75	97.56	1.49	0.95									
57	Condenser	32.2	97.5	1.7	0.8	3.15	8.98	35.22	55.8	12.4	3.1	18.1	7.1	3.3
	Demister	69.5	98.01	1.52	0.47									
58	Condenser	60.4	88.7	3.52	7.78	3.8	8.5	37	54.5	12.0	4.8	16.5	7.37	2.7
	Demister	65.7	97.08	2.01	0.91									
59	Condenser	63.9	97.3	1.45	1.25	5.01	7.0	40	53.0	10	4.5	17.6	6.02	2.2
	Demister	64.9	97.8	1.2	1.0									
62	Condenser[b]	84.1	90.9	3.0	6.1	5.01	7.2	35.8	57.0	11	0.5	20.0	6.6	1.2
	Demister[b]	86.0	95.0	4.11	0.89									
63	Condenser[b]	75.2	92.65	1.95	5.4	4.29	5.8	34.1	60.1	9.2	0.6	22.0	9.7	1.0
	Demister[b]	80.3	97.78	1.3	.92									

Appendix B. (continued)

64	Condenser[b]	61.0	94.8	2.8	2.4	2.17	5.0	35.0	60.0		11.5	1.5	20.0	8.0	1.2
	Demister[b]	70.0	94.4	1.52	1.08										
65	Condenser[b]	74.2	92.0	3.1	4.9	3.9	8.0	34.8	57.2		10.0	0.5	18.5	6.2	1.0
	Demister[b]	88.0	97.1	1.68	1.22										
68	Condenser	16.89	97.0	2.12	0.88	3.72	7.8	35.8	56.4		12.5	0.5	18.6	6.89	2.51
	Demister	75.59	95.1	3.7	1.2										

a — Oil samples collected after runs.
b — By-pass line found clogged.

Appendix C. EQUATIONS FOR CALCULATION OF YIELDS VALUES

The yields are calculated using the following equations:

1. Air — The air was relatively dry during most of the test runs.

$$A = q_1 \times \frac{492}{460 + {}^\circ F} \times \frac{1}{359} \times 29 \times \frac{1}{2.2}$$

$$= q_1 \times \left(\frac{18.065}{460 + {}^\circ F}\right)$$

The temperature of the air ranges from 28°C to 35°C and

$$\left(\frac{18.065}{460 + {}^\circ F}\right)$$

is approximately equal to 0.033.

$$A = 0.033\, q_1$$

where A = mass air flow rate, kgm/hr

q_1 = volumetric air flow rate, obtained from Fig. 1, cu.ft./hr.

2. Gas — The gas is saturated with water at an average temperature of 72.8°C.

$$WG = q_2 \times \frac{492}{460 + 163} \times \frac{1}{359} \times \left(\frac{m + 0.4 \times 18}{1.4}\right) \times \frac{1}{2.2}$$

$$= q_2 (m + 7.2)(7.14 \times 10^{-4})$$

$$DG = WG \times \frac{m}{m + 7.2}$$

where WG = mass flow rate of wet gas, $\frac{kgm}{hr}$

DG = mass flow rate of dry gas, $\frac{kgm}{hr}$

q_2 = volumetric flow rate of wet gas, cu.ft./hr

= $1600\,(\Delta h) + 1100$ or obtained from Fig. 2.

Δh = manometer reading of venturi, inches of water

m = molecular weight of dry gas, $\frac{kgm}{kgmole}$

3. Oil — The average specific gravity of pyrolytic oil is 1.15.

$$P = q_3 \times 1.15$$

where P = mass flow rate of pyrolytic oil, regardless of quality, $\frac{kgm}{hr}$

q_3 = volumetric flow rate of pyrolytic oil, $\frac{liters}{hr}$

4. Char —

$$C = \frac{W}{H}$$

where C = char yield, kgm/hr

W = char collected for the test run, kgm

H = hours of operating of the test run.

The calorific values of the pyrolytic products are calculated as follows:

1. Gas

The calorific value of the gas can be calculated from its composition and the heat of combustion of gases as follows at 25°C and 1 atm.:

	Gross, kcal/liter
CO	2.767
CH_4	8.703
H_2	2.794

$$(CVG)_G = \left[\frac{\% CO}{100}(2.767) + \frac{\% CH_4}{100}(8.703) + \frac{\% H_2}{100}(2.794)\right] \times \frac{1}{\rho} \times DG$$

where $(CVG)_G$ = calorific value of gas, kcal/hr

ρ = density of the dry gas, $\frac{kgm}{liter}$

2. Oil

The calorific value of pyrolytic oil on a dry and ash-free basis is 7695 kcal/kgm.

$$(CVG)_o = P_1 \times [(1 - \frac{\% H_2O}{100})(1 - \frac{\% Ash}{100})]_c + P_2 \times [(1 - \frac{\% H_2O}{100})(1 - \frac{\% Ash}{100})]_d$$

where $(CVG)_o$ = calorific value of pyrolytic oil, kcal/hr

P_1 = mass flow rate of condenser oil, $\frac{kgm}{hr}$

P_2 = mass flow rate of demister oil, $\frac{kgm}{hr}$

subscript c refers to condenser oil
d refers to demister oil

3. Char

The calorific value of char on a dry and ash-free basis is 9917 kcal/ kgm.

$$(CVG)_C = C \times (1 - \frac{\% H_2O}{100})(1 - \frac{\% Ash}{100}) \times 9917$$

where $(CVG)_C$ = calorific value of char, kcal/hr

C = mass flow rate of char, kgm/hr

Rice Hull: The calorific value of rice hull on a dry and ash-free basis is 4719 kcal/kgm.

$$(CVG)_{RH} = R \times \left(1 - \frac{\% H_2O}{100}\right)\left(1 - \frac{\% Ash}{100}\right) \times 4719$$

where $(CVG)_{RH}$ = calorific value of rice, hull, $\frac{kcal}{hr}$

R = rice hull burned, $\frac{kgm}{hr}$

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