**CONTINUOUS PYROLYSIS OF BIOMASS FEEDSTOCKS
IN ROTARY KILN CONVERTORS**

Final Report

By
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August 30, 1979

Work Performed Under Contract No. AS04-77ET04096

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U.S. Department of Energy

Solar Energy

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FUELS FROM BIOMASS PROGRAM
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PROGRAM OBJECTIVES

The main objective of the work herein described was an engineering evaluation of a rotary kiln biomass energy convertor located at The Angelo Industries in Jonesboro, Arkansas. The output capacities, material balances and energy balances were to be the main implements of the evaluation.

A second objective of the work was the development of pyrolytic conversion data for typical biomass materials, but particularly for those found as waste in Arkansas and the Ozark Plateau region of the United States.

A third objective was to make contributions to the design of rotary kiln pyrolytic convertors.

These objectives would be listed as:

- (1) Make an Engineering Evaluation of the Angelo Convertor
- (2) Obtain Pyrolytic Conversion Data for the Biomass Materials of Arkansas and the Ozark Plateau Region
- (3) Develop Engineering Design Data for a General Class of Rotary Kiln Pyrolytic Convertors.

PROGRAM ABSTRACT

The biomass research program at the University of Arkansas has developed three experimental projects or tasks for the attainment of its objectives.

They are:

- (1) Utilization of the Existing Full Scale Convertor for Testing and Data Acquisition at Jonesboro, Arkansas
- (2) Development of a Scale Model Rotary Pyrolytic Convertor (Bench Scale Research Kiln)
- (3) Development of Analytical Laboratory Services for the Analysis of Feedstocks and Products; and for Basic Pyrolytic Process Studies.

The project at Jonesboro, Arkansas, which aimed at testing the Angelo convertor concept through heat and material balances over the available range of operations, could not completely achieve this objective because of the severe mechanical and structural deficiencies in the full scale convertor. Partial instrumentation of the convertor was completed as planned and the total instrumentation package remains in readiness. A program to repair and refurbish the convertor was almost completed as of the end of the program. It is estimated that 75% of the effort needed to obtain the goals of the project has been applied. A limited number of data have been taken in spite of the deficiencies of the machine.

The scale model rotary kiln has been the most successful of the three projects. The kiln has been completed as planned and successfully operated with a number of feedstock materials. Good qualitative data have been obtained on conversion rate capacities, charcoal yields, and off gas combustion product temperatures. In all, about one hundred test runs were made in the scale model

kiln. It remains ready for further testing and development. Overall, about 90% of the results expected with the scale model kiln were attained.

The laboratory services project was designed to provide analytical testing for the other two projects and to do basic studies in biomass material conversion processes. The project delivered the testing services, but was severely restricted in the area of basic studies because of the failure of the main instrument, the gas chromatograph, to operate successfully. An inordinate amount of time was applied in the attempt to utilize the gas chromatograph --time which could have been more profitably applied to other aspects of the project. In all it is estimated that this project attained about 80 percent of its expected goals.

Overall, the programs produced one Master of Science in Chemical Engineering Thesis and provided employment and research experience for four faculty, two staff, two graduate and six undergraduate personnel. Excellent laboratory facilities are available for continued work.

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INTRODUCTION

Background

The United States is now in an era of fuel scarcity. This statement will hardly surprise anyone. What is surprising is the discovery that there are still manufacturing operations wherein combustible biomass by-product materials are considered to be an economic liability. This is because their disposal inflicts an economic cost on the operation that generates them.

Until recently, one such operation was Angelo Industries* in Jonesboro, Arkansas. This small company generates approximately 20 tons per day hardwood scrap as a by-product of the manufacture of shipping pallets. Not having a market for the scrap, the company formerly disposed of them by burning in a conventional sawmill teepee burner. This method of disposal created much smoke and obnoxious fumes and this in turn finally brought the air pollution control authorities down on the company. In an attempt to solve the wood scrap disposal problem, the company secured engineering help and developed a rotary kiln thermal convertor for processing the wood scrap into charcoal and off-gases. This convertor appears to have successfully eliminated the smoke and fumes problem inasmuch as it has received a clean bill of health from the Arkansas State Air Pollution Control Commission.

The charcoal produced by the Angelo convertor is a readily saleable item which brings about 4¢/lb. on the market. The convertor also produces combustible off gases from the thermal decomposition of the wood. These off gases, when burned with secondary air in an afterburner, produce a clean hot combustion product gas that appears to be directly useable in a variety of industrial

*Formerly the A & P Coop Company which was engaged in the manufacture of wooden chicken coops.

operations, either as process heat or as power producing heat. An example of a probable application of the process heat is the kiln drying of lumber at the sawmill that generated the scrap wood in the first place. At the Angelo Industries plant the potentially useful combustion product gases are currently being vented to the atmosphere.

Rotary kilns have long been used in various ore roasting processes, calcining operations, etc., and it seems to be nearly certain that they have been previously applied to the disposal of combustible waste materials. They afford excellent control of the combustion process because the bed is always turning over and being exposed to the combustion air. Specific examples of the applications of the rotary kiln to waste disposal are not known to the authors of this report however, and it appears that the Angelo's may at least be the first to apply a rotary kiln to the manufacture of charcoal. At any rate the Angelo kiln has features that are apparently novel inasmuch as it has been patented in the United States, Great Britain, and Germany.*

The cleanness of the off-gas combustion products and their high temperature ($\approx 2000^{\circ}\text{F}$) along with the production of the very useful charcoal led the Angelos to believe that the convertor had a very wide range of applications, or would have if its performance could be certified by appropriate tests. One of the patented features of the convertor was the method of introducing reaction air to the reacting bed of biomass material. This was done by introducing the air in such a way that it mixed with the off gases and burned before it could come into contact with the reacting biomass and charcoal product. Whether this method of introducing air to the convertor actually increased the yield of charcoal was something that could only be determined by controlled testing.

*U.S. Patent Nos. 3,901,766 and 4,037,543
Great Britain -- No. 1,452,468
Germany -- Not Available

The Angelos also felt that the general utility of their convertor could best be shown by a full scale demonstration project in a commercial setting wherein the process heat from the combustible off gases could be utilized. Consequently the Angelos prepared a proposal to the Energy Research and Development Administration of the United State Government (ERDA) which included among its objectives the above demonstration project.

This proposal was rejected by ERDA for reasons that have not been made clear to the writers of this report. At least a part of the basis for rejection appears to have been a belief on the part of certain personnel at ERDA that the Angelo convertor did not embody sufficiently novel features.

In an effort to get their convertor technically evaluated, the Angelos contacted the University of Arkansas Administration from which the matter was handed over to the College of Engineering and through which it ultimately came to the attention of the project director and his associates. After an intensive but preliminary evaluation of the convertor concept was made, it was determined that the cost of a proper engineering evaluation was far beyond the capabilities of the Department of Mechanical Engineering or the College of Engineering to bear. Consequently, it was decided to apply to ERDA for the funds needed to support the engineering evaluation of the performance of the convertor.

At this point it became evident to the University of Arkansas research team that any series of tests that might be made on the operating Angelo convertor could not adequately evaluate the process concept itself. There were several reasons for this. First, the Angelo convertor was a commercially operating machine that was an economically necessary unit of the overall Angelo production activity. Long periods of idleness for the purpose of instrumentation and especially modification simply could not be financially born by the Angelos. Secondly, it was fairly evident that the convertor, as it then stood, was not a very

very reliable machine as regards its mechanical competence.* It had been assembled from components largely obtained at the salvage yard and there was little compatibility among these components. Thus it was felt that an alternate source of operating test data would be needed, and particularly so if steady state operating conditions were to be reliably attained. Thirdly, the range of operating conditions in the full scale convertor could be changed only at considerable cost in time and money and consequently the operating flexibility needed to evaluate the concept did not exist. Fourth, since it seemed desirable that engineering data be produced which would permit the adequate design of a range of convertor sizes, it was evident that size scaling effects could not be evaluated by tests on the one full scale unit located at the Angelo plant in Jonesboro, Arkansas. Finally, there was not much enthusiasm on the part of the University of Arkansas research personnel to do an in and out test operation at Jonesboro and then be done with it. Thus it was decided that the development of a small, or bench scale rotary kiln convertor was essential to the attainment of the program objectives.

Charcoal

The project director and his associate have maintained a long duration interest in the production of charcoal and its by-products. They had undertaken on their own resources, research aimed at increasing the yield of charcoal while eliminating the air pollution caused by its production. Charcoal, that ancient and excellent fuel, of which there is never enough to meet demand, and for which new fields of applications only await increased production.

Charcoal has the image of being the backyard cookout fuel, and while it serves very well in this application the image is one of luxury and recreation.

*This lack of reliability was grossly underestimated in the preliminary evaluations of the convertor.

This increases the difficulty, for some anyway, of taking charcoal seriously as an important fuel for wide applications. Some familiarity with charcoal history however reveals the fact that charcoal was once the sole reducing agent for the smelting of iron. It would still probably hold sway over coke, since it is better than coke for this purpose, were the supply of charcoal adequate for the needs of the iron smelting industry and its price competitive. Charcoal is easily gasified into a low Btu gas that is suitable for the operation of internal combustion engines. It is useful as an absorbent in the purification of municipal drinking water and in various industrial chemical processes. As a fuel, for direct combustion, its energy release of about 14,000 Btu/lb, matches that of coal. Unlike coal however, its combustion releases very little sulfur and leaves no clinkers. In drying operations, charcoal as fuel is superior to gas or coal because, being almost pure carbon, it produces no water of combustion.

The traditional method of making charcoal by the controlled partial combustion of wood, is very wasteful because all of the liquid and gaseous by-products are vented to the air. This also aggravates the problem of air pollution. In addition, some of the charcoal produced is burned in the kiln itself which lowers the yield of the product. The industrial history of charcoal includes a phase wherein the process was conducted in closed containers by the external applications of heat. By-products could be and were collected from this process. The name of wood alcohol as applied to methanol is the present day remnant of this earlier phase of charcoal production.

What was probably the apex of charcoal production technology in the United States was embodied in the Ford Motor Company plant built at Iron Mountain, Michigan, in the year 1924.* This plant made the conversion from dried wood to charcoal and liquid and gaseous by-products in air tight retorts which

*Industrial and Engineering Chemistry, Vol. 22, No. 4, pp. 812-315.

operated entirely from the exothermic heat produced by the thermal decomposition of the wood itself.

An interesting aspect of this plant is that the combined volume of condensable liquid by-products, all of which are combustible, amounted to 54 gallons per ton of dry wood charged to the process. This amounts to 450 lbs. of liquid by products, which is 22.5% of the dry wood feed weight. By comparison, the technologically modern and highly complex government research plant at Albany, Oregon, only recently achieved a yield of wood oil (syncrude) of 26.4 by using the new LBL (Lawrence Berkeley Laboratories) conversion process.*

There thus exists, in the historical record, the production of charcoal and by-products by a variety of processes varying from the very simple and primitive to the relatively modern and complex. The rotary kiln convertor, in its state of development by the Angelos, represents a favorable combination of simplicity of equipment with good capability of process. Its mechanical simplicity translates into low cost of installation, operation, and maintenance. This low cost is absolutely critical and decisive to the successful utilization of biomass waste in many locations. The process capability of the rotary kiln wherein the off gases are burned to produce process heat or even power heat, indicate a thermal conversion efficiency approaching 100%, since the energy not appearing as process heat is retained in the charcoal as chemically available heat which can be easily stored and utilized as needed.

There seems to be little doubt that the market for charcoal could be expanded greatly from its present position if adequate supplies at a competitive price could be assured. As it now stands, charcoal makers in the

* "Operation of the Biomass Liquifaction facility, Albany, Oregon," Ninth Quarterly Biomass Thermochemical Conversion Contractors Meeting, University of Missouri, Rollo, November 8, 1979.

Ozark region are currently delivering their product to briquetting plants for about 4¢ per pound. At the same time, operators in the chicken broiler industry, which geographically coincides with the charcoal industry, are paying as high as 12¢ per pound for propane gas to heat their brooder houses. Under this condition, charcoal is about 2.00 times as cost effective as propane gas. In addition, it is also a renewable resource that is far more easily stored than propane gas. There are no overriding reasons why the same vehicles that deliver feed to the brooder houses cannot also be used to deliver the charcoal fuel. Thus, in most respects, the charcoal will be as easy to handle as is propane. As mentioned previously, there is also a growing market for metallurgical charcoal and activated carbon. If the fuel market were opened to charcoal the need for it could be expanded indefinitely.

It appears that continued research and development of the production and utilization of charcoal and its by-products would impinge on many of the current concepts being investigated for the liquifaction and gasification of biomass material. In other words the technology of the gasification and liquifaction of biomass can be approached through the research and development of charcoal production, as well as by the direct approach. The charcoal route has the advantage, however, that it is already a working economic process (albeit for the most part a rather primitive one) on which an expanded and modernized technology may be based.

ORGANIZATION

The biomass pyrolytic conversion program at the University of Arkansas is organized around three separate but mutually supportive projects. One of these projects involved the testing and evaluation of a full-scale rotary convertor; designed, constructed, and operated by the Angelo Industries of Jonesboro, Arkansas. A second project involved the continuous pyrolysis of biomass material in a bench scale rotary convertor. This research type convertor is flexible in operation and can be operated, in one of its modes, as a scale model of the full sized convertor at Jonesboro. The third project was designed to provide analytical and testing services for the other two projects and also to develop basic biomass pyrolytic process data in a stationary closed retort convertor which can be applied to the steady flow process in the rotary convertor.

SCALE MODEL ROTARY KILN CONVERTOR

Theoretical Considerations

When a solid carbonaceous material is subjected to heat under conditions which result in the internal energy of any portion of the material rising above some minimum level,³ the material undergoes a decomposition process known as pyrolysis. This process produces a highly condensed carbonaceous residue called char* and a variety of volatile products called off-gases. In the presence of ample oxygen, the pyrolysis products can undergo further decomposition; combustible volatiles are capable of supporting flaming combustion while the char can react by glowing combustion. The end products of the combustion are carbon dioxide, water, and ash as shown in Figure 1. If, however, the amount of oxygen is limited to less than the stoichiometric amount required for the complete combustion, partial oxidation occurs, and both pyrolysis and combustion products are formed.

The basic processing principle of the rotary kiln device under consideration is this partial oxidation concept. After ignition, primary air is supplied in limited amounts to the kiln where oxygen reacts with a portion of the combustible off gases and some char material. In order to minimize the combustion of the char material, the air is directed toward the upper portion of the kiln enhancing the combustion of the off-gases. The exothermic nature of the combustion and of the pyrolysis itself supplies the energy required to dry the feed material and to raise it to the temperature at which the pyrolysis begins to occur. The partially oxidized off-gases are then passed into an afterburner where additional or secondary air is introduced. It is in this afterburner section where complete combustion of the gases can occur.

³See Literature Cited at the end of this section.

*Charcoal is the name given to char obtained by the pyrolysis of wood.

FIGURE 1. FORMALIZED DIAGRAM FOR THE PYROLYSIS AND COMBUSTION OF CARBONACEOUS MATTER

The thermal and chemical phenomena involved in this process are very complicated due primarily to:³

- (1) the non-homogeneous nature of most solid carbonaceous feedstock materials.
- (2) the simultaneous phase change and chemical reaction.
- (3) the strong dependence of the physical and chemical properties of the reactants and products on temperature.

Much study has been directed toward the theoretical understanding of these influences.^{5,6,7,8} However, in systems and processes in which simultaneous influences of many physical phenomena occur, strict theoretical methods of analysis are exceedingly difficult and often yield results not useful for engineering design applications. One method of attacking such a problem in which no explicit mathematical equation is available is that of dimensional analysis. This method has the advantage that it may be applied when only macroscopic knowledge of the system is available. Also, it is very valuable in guiding experimental work, and it offers a sound way of comparing results obtained under widely diversified conditions.

This method requires the selection of the fundamental factors influencing the problem. These factors are the independent variables that actually control the process being considered. The variables must be determined by the judgment of the investigator in light of such knowledge of the mechanism as is available. Through the principles of dimensional analysis, it is possible to group many of these variables into a smaller number of dimensionless groups.

For the rotary kiln pyrolytic convertor system, the following independent variables were chosen:

$\dot{m}_F$ = Flow rate of feed (dry basis), lb_m/hr

$\dot{m}_A$ = Flow rate of air to kiln, lb_m/hr

$\dot{m}_C$ = Flow rate of char product, lb_m/hr

r = Characteristic dimension of feed particle, ft

P = Power input to agitate solids bed in kiln, ft lb_f/hr

N = Rotational speed of kiln, RPM

R = Pyrolysis rate, lb_m char/ft³hr

H = Depth of solids bed, ft

D = Inside kiln diameter, ft

z = Kiln length, ft

g_C = Dimensional constant 32.2 lb_m ft/lb_f s²

A dimensional analysis of the above process variables, as shown in Appendix A, yields the following functional relationship:

$$\frac{\dot{m}_C}{\dot{m}_F} = \psi \left\{ \left(\frac{z}{D} \right)^k \left(\frac{H}{D} \right)^l \left(\frac{r}{H} \right)^m \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right)^n \left(\frac{RzD^2}{\dot{m}_A} \right)^\theta \right\} \quad (1)$$

The functional dependence of each group can now be determined experimentally by variation of any one variable within that group. Below is a list of each group, group name, and the most easily manipulated variable called the adjustable parameter.

<u>Dimensionless Group</u>	<u>Name of Group</u>	<u>Adjustable Parameter</u>
$\dot{m}_C/\dot{m}_F$	A=Efficiency No.	$\dot{m}_F$
z/D	Equipment No.	z
H/D	Depth No.	H
r/H	Size No.	r
$Pg_C/\dot{m}_F N^2 D^2$	C=Power No.	N
$RzD^2/\dot{m}_A$	B=Damkohler No.	$\dot{m}_A$

The experimental program described in the next section was formulated to ascertain the functional dependence of the efficiency number $\dot{m}_C/\dot{m}_F$, a measure of char conversion, on the power number and the Damkohler number. Effects

of the equipment, depth, and size numbers were not determined by this investigation.

Experimental Program

1. General Considerations

The primary objective of this investigation was the development of a correlation of charcoal yields with the operational parameters of the rotary kiln system. Other objectives were to examine various modes of operation ranging from maximum charcoal production to complete combustion and to determine the flexibility of the system in processing various types of waste materials.

Noting the objectives, as outline above, an overall experimental program was formulated. The first task was to provide a facility to evaluate the process at less cost and with greater flexibility than by using the existing full-scale convertor. Therefore, a scale model rotary kiln system was designed and constructed by the project staff. This model was designed to duplicate the retention time, bed agitation characteristics, and length-to-diameter ratio of the full scale convertor at Jonesboro.

In general terms, the experimental program consisted of obtaining sufficient data to establish a suitable correlation for the prediction of charcoal yields in terms of the system variables, i.e. the dependence of the efficiency number on the power and Damkohler numbers. Specifically, this required the measurement of charcoal yields over a range of wood waste feeds rates, air rates, and speed of rotation of the kiln. Also, data such as temperatures and pressures were obtained so that mass and energy balances could be calculated for each run.

The primary feed chosen for this investigation was a locally available wood waste material. This material was a mixture of hardwoods (mostly oak and ash) with the size of particles ranging from wood flour to chips approximately

3 x 1 x 1/8-inches. Other feeds were chosen on the basis of their availability and their inherent waste disposal problems. These feeds were of both agricultural and manufacturing origin and included rice hulls, cotton gin waste, macadamia nut shells, and particle board scraps.

2. Description of Equipment

The equipment used in this investigation consisted of a rotary kiln, an afterburner, and the auxiliary components required to establish and measure flow rates, temperatures, and pressures. A schematic diagram of the experimental apparatus is shown in Figure 2 with photographs of the system and kiln included as Figures 3 and 4. Waste materials to be converted are fed continuously into a rotating kiln convertor. The rotation of the kiln and gravity cause this material to move toward the discharge end during which time it is converted to char and off gases. Primary air is introduced in limited amounts countercurrently to the feed. Partially oxidized gases pass into the afterburner where secondary air is introduced. Further combustion occurs, and the products exit to the atmosphere via a stack. Char product discharges to a water-jacketed screw conveyor for removal to storage.

The kiln shell was made of 1/4-inch thick low carbon steel plate rolled into a hollow cylinder 41 inches in length and 26 inches in diameter. Two 8-inch wide by 5/8-inch thick steel bands called riding rings were welded around the circumference of the shell as shown in Figure 4. Two kiln seal rings (34-inch OD and 3/8-inch thick) were also welded around the kiln shell.

The inside surface of the shell was lined first with two layers of 1/8-inch thick insulating paper. Castable refractory, three inches of A. P. Green's Castable-22 followed by three inches of MC-22, was then poured over the paper. As a result of this arrangement of insulation, the outside shell temperature

FIGURE 2. SCHEMATIC OF EXPERIMENTAL APPARATUS

FIGURE 3. PHOTOGRAPH OF SCALE MODEL APPARATUS

FIGURE 4. PHOTOGRAPH OF THE SCALE MODEL ROTARY KILN

never exceeded approximately 200°F during any operation. A stainless steel ring with vanes was mounted inside the feed end of the kiln to prevent the accumulation of feed material as it entered. Six inches from the discharge end of the kiln, a 1-3/4 inch high circumferential dam, hand-molded with MC-22, was required in order to ensure adequate retention times. The last six inches of the refractories at this end were tapered at a 45 degree slope to allow the char product to discharge into a drop chute.

The kiln was supported by four low carbon steel cylinders, called trunnions, six inches in diameter and four inches wide. Each pair of these trunnions was mounted on a 1½-inch diameter shaft which was supported by two roller bearings. The bearings were attached to plates which could be moved in a horizontal plane and rotated about a vertical axis to ensure alignment for the kiln-trunnion system and to provide proper mating of the end seals to be described later.

One of the trunnions on the feed end was driven by a variable speed direct current motor connected to a speed reducer which consisted of a gear box and sprocket-chain drive. This arrangement resulted in speed control of the kiln from one to eighteen revolutions per minute.

The stationary end closures for the kiln, called hoods, were constructed of ¼-inch steel plate. The feed hood was 38 inches in diameter with two layers of filler paper, followed by two inches of Castable-22; then two inches of MC-22 refractory. Two 4-inch stainless steel pipes passed through the face of this hood. One of these was horizontal and provided for the exit of the off gases; the other was at a 30 degree angle from vertical and comprised the entrance for the feed material.

The char-end hood incorporated a tapered drop chute for the exit of the char product. This hood was also lined with paper and four inches of refractory. Three 5/8-inch stainless steel pipes passed through the face of this hood to

allow the introduction of air into the kiln. Each of these pipes was fitted with two outlets which introduced air toward the upper portion of the kiln in a direction opposite the direction of the rotation of the kiln. The char hood also was equipped with a one inch diameter "peep hole" which was used during the ignition procedure and for observation of the kiln interior during operation. Water sprays were mounted in the tapered portion of this hood. These sprays could be used to quench the hot char product as needed.

Each hood was supported by a system of rollers which moved on a steel frame. This allowed relatively easy access to the inside of the kiln. The roller system incorporated adjusting screws so that the position of each hood relative to the kiln could be changed to ensure proper alignment.

A positive seal between the rotating kiln and each hood was necessary in order to obtain the data required for mass and energy balances. Several kiln manufacturers and kiln users were consulted about the materials problems associated with moving parts at elevated temperatures and about different methods of effecting a positive seal. The design used for this apparatus was a composite of the information obtained from those sources. The seal material used was carbon, chosen for its immediate availability and demonstrated success.

Each seal consisted of eight (1 x 3 x 13-inch) carbon segments independently mounted on a steel ring. The carbon was backed by a 1/8-inch thick cushion of asbestos paper. The carbon surfaces mated with the rotating kiln seal rings to effect the seal between the moving parts as shown in Figure 4. The carbon ring was free to move against a spring-loaded retaining surface on each of the hoods. The small passage between this surface and the carbon ring required the use of 1/2-inch asbestos rope packing. This seal prevented leaks from occurring as the carbon seal moved back and forth against the compression springs.

The afterburner was a 20-inch OD cylinder 78 inches in length. Six inches of Kast-0-lite 30 refractory lined the inside surface. An opening was made at one end to allow for the delivery of the off gases from the kiln. Eight pairs of stainless steel pipes entered the afterburner horizontally to provide the air required for the complete combustion of the off-gases.

The combustion products exited the afterburner through a double-walled, stainless steel six-inch ID stack. Silica powder and mineral rock wool filled the space between the stack walls. It was found that it was necessary to provide a forced draft by placing an air jet in the uppermost section of the stack. Later, a four foot water jacketed section of stack was added immediately above the afterburner making the overall stack height 12½ feet.

Feed material was stored in a 10 gauge steel cylinder five feet in height and 3½ feet in diameter with a conical bottom. Initially, it was planned to use a vibrator to shake the feed from the tank into a variable speed screw conveyor. Problems with the feed material bridging in the tank prevented this scheme from being used. Successful operation was achieved by mounting a variable speed six-inch diameter screw three feet in length directly into the conical portion of the tank. This screw along with two four-bladed vertically rotating stirrers provided a very dependable and steady flow of feed which could be varied from 10 to 140 pounds of wood waste per hour. Feed material from this screw dropped into a four-inch diameter constant speed screw conveyor with a U-trough and cover. This conveyor was ten feet in length and carried feed material up to the drop chute attached to the feed hood.

Char product discharged to an eight foot long four inch diameter water jacketed screw conveyor. This conveyor system was specially designed with a close clearance (1/8-inch) between the screw and the jacket to ensure transportation of small particles of char product. The conveyor discharged into a 30

gallon char storage bin which rested upon platform scales for measuring char production.

Air was supplied by an air compressor to a small surge tank controlled at approximately 11 psig. Seven rotameters provided the metering of the air flow to both the kiln and the afterburner. Stack gas flow rates were measured with a velocity metering kit comprised of an 18-inch stainless steel pitot tube and an inclined manometer. Stack gas analysis was achieved with an Orsat analyzer. Pressure in the air surge tank was measured with a Bourdon-type gauge while pressure in the afterburner was measured with a vertical water manometer. Positive displacement meters monitored the flow of water to the char conveyor, the lower stack section, and the water sprays. Temperatures within the system were measured using ceramic insulated type-K thermocouples connected to a multipoint recorder.

3. Operating Procedures

In general, data were taken for feed rates ranging from 30 lb/hr to 90 lb/hr (wet basis). Satisfactory kiln operation was achieved at feed rates up to 140 lb/hr. However, the off gas production at rates above 90 lb/hr overloaded the afterburner causing combustion to occur in the stack with resulting damage. Air flow to the kiln was incrementally varied so that a range of charcoal yields could be examined. Air to the afterburner was supplied in greater than stoichiometric amounts to ensure complete combustion of the off gases as evidenced by low carbon monoxide concentrations in the stack gases. Speed of rotation of the kiln was changed from 2 to 8 to 14 rpm for each feed rate-air rate pair.

Flow of feed material was initially set at approximately 60 lb/hr (wet basis). Air flows to the kiln and afterburner of 30 scfm and 100 scfm, respectively, were used. Kiln speed was set at two rpm. By inserting a natural gas-air burner through the "peep hole," ignition of the feed material was

achieved. The burner was left in the kiln for one hour, or until the outside surface of the kiln shell was warm to the touch. This warm-up period was found to be necessary in order for steady state operation to be achieved.

After the warm-up period, the burner was removed and the kiln air flow was set at the desired rate. Once steady state operation was achieved (as evidenced by constant temperatures in the system) the data outlined in Table I were recorded. Feed and char samples for each run were collected and sent to the analytical laboratory for determination of moisture content, heats of combustion, and proximate analysis.

TABLE I. DATA RECORDED FOR EACH EXPERIMENTAL RUN

<u>Data</u>	<u>Method of Measurement</u>
Flow Rates: Feed	Bucket/Stopwatch
Air	Rotameters
Stack Gas	Pitot Tube
Char	Bucket/Stopwatch
Kiln Speed	Stopwatch
Pressures: Air Tank	Bourdon Gauge
Afterburner	Water Manometer
Temperatures: Water Inlet	Type-K Thermocouples
Water Exit	
Afterburner Inlet	
Afterburner Exit	
Kiln Gaseous Portion	
Kiln Solid Bed Portion	
Inlet Air	
Stack Gas	
Stack Gas Analysis	Orsat Analyzer

Experimental Results

In order to determine the dependence of the efficiency number on the power number and the Damkohler number, the data from forty experimental runs using wood waste feed material were examined. Experimental data, mass and energy balances, and correlation groups for each of these runs are presented in Appendix B.

Efficiency number data as a function of power number and Damkohler number are presented graphically in Figure 5. A summary of the data that were correlated is shown in Appendix C.

A proximate analysis of each charcoal sample produced from wood waste was made. Typical results of this analysis were:

85% Fixed Carbon
11% Volatiles
4% Ash

This is a high quality char as evidenced by the high fixed carbon content (see page 61).

The experimental program also demonstrated wide versatility of the rotary kiln convertor in processing other types of waste materials. Successful experimental runs were made using cotton gin wastes, rice hulls, macadamia nut shells, and particle board scraps. Table II includes some typical data for these feedstocks. No quantitative analysis of this data was performed. Significant qualitative observations made during these runs include:

(1) The fibrous fraction of the cotton gin waste was completely incinerated (combusted) while the woody fraction was converted to char.

(2) Operations involving cotton waste feed rates greater than 50 lb/hr were hampered because of blockage of the kiln due to the agglomeration of the fibrous material.

FIGURE 5. CORRELATION OF EXPERIMENTAL DATA

TABLE II. SELECTED DATA FOR VARIOUS FEED MATERIALS

<u>Feed Material</u>	<u>Feed Rate</u> (lb/hr)	<u>Air Rate to Kiln</u> (lb/hr)	<u>Kiln Speed</u> (rpm)	<u>Feed Conversion</u> (lb char/ 100 lb feed)
Rice Hulls	60	25	2	17*
Cotton Gin Waste	25	90	6	10
Macadamia Nut Shells	30	31	2	42**
Particle Board Scraps	45	120	2	5

* Approximately half of this solid product was silica

** Incomplete Conversion

(3) Cotton waste could not be fed to the kiln via the feed conveyor system; hand-feeding was necessary. No problems were experienced with the other feedstocks transported by the conveyor system.

(4) Complete conversion of the macadamia nut shells to char was not achieved.

(5) Runs with particle board and rice hulls were successful in producing a char product.

(6) All feedstocks (excluding the macadamia nut shells) could easily be completely incinerated through adjustment of the system variables, specifically air rate to the kiln and kiln speed.

Discussion of Results

The experimental program resulted in the data summarized in Appendix B. Wood feed rates of 30 lb/hr to 90 lb/hr (wet basis) were examined. The moisture content of the wood ranged from 6.4 to 30.3 percent. Char yields of 0.007 to 0.171 lb. char product/lb wood (dry basis) were measured. Heating values (dry basis) for the wood feed and char product averaged 8010 Btu/lb and 11960 Btu/lb, respectively. Mass balances performed for each run were all within eight percent of closure. Energy balances were close on most runs but were off as much as 60% for those runs in which the afterburner temperatures were low.

Correlation of charcoal yield with the operational parameters of the rotary kiln pyrolytic convertor was established in the form of the following equation resulting from a dimensional analysis of the process:

$$\frac{\dot{m}_C}{\dot{m}_F} = \Psi \left\{ \left(\frac{Z}{D} \right)^k \left(\frac{H}{D} \right)^l \left(\frac{r}{H} \right)^m \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right)^n \left(\frac{RzD^2}{\dot{m}_A} \right)^\theta \right\} \quad (1)$$

The derivation of this expression is given in Appendix A.

The equipment number (z/D) and the depth number (H/D) were constant for each experimental run. Effects of the size number (r/H) were not considered in the determination of the correlation. Therefore, the equation above was simplified to:

$$\frac{\dot{m}_C}{\dot{m}_F} = f \left\{ \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right)^n \left(\frac{RzD^2}{\dot{m}_A} \right)^\theta \right\} \quad (2)$$

Data were taken for operations in which one group was held constant while the adjustable parameter in the other group was varied. This procedure was then repeated holding the second group constant while the adjustable parameter of the first group was varied.

The first step in the evaluation of equation (2) was the determination of the exponents n and θ . To accomplish this, an assumption of the functional form of the equation was required. It was assumed that the equation could be written as:

$$\frac{\dot{m}_C}{\dot{m}_F} = (\text{constant}_1) \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right)^n \left(\frac{RzD^2}{\dot{m}_A} \right)^\theta \quad (3)$$

Taking the logarithm of equation (3) for a constant Damkohler number gives:

$$\ln \frac{\dot{m}_C}{\dot{m}_F} = \text{constant}_2 + n \ln \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right) \quad (4)$$

Values of $\ln(\dot{m}_C/\dot{m}_F)$ were plotted versus values of $\ln(Pg_C/\dot{m}_F N^2 D^2)$ for each of three constant Damkohler numbers. A least-square fit was obtained for each set of data giving the least-square slope which is seen from equation (4) to be the

* R is determined by trial and error basis using Figure 5.

value of $\underline{n}$. The average of the least-square determinations was taken as the value of $\underline{n}$. This value was calculated to be 0.10.

To obtain $\underline{\theta}$, the logarithm of equation (3) was taken at a constant power number:

$$\ln \frac{\dot{m}_C}{\dot{m}_F} = \text{constant}_3 + \underline{\theta} \ln \frac{RzD^2}{\dot{m}_A} \quad (5)$$

The procedure described above was repeated by plotting $\ln (\dot{m}_C/\dot{m}_F)$ versus $\ln (RzD^2/\dot{m}_A)$ for each of the three constant power numbers. The average slope or $\underline{\theta}$ was calculated to be 0.31.

Equation (2) could then be written as:

$$\frac{\dot{m}_C}{\dot{m}_F} = f \left\{ \left(\frac{Pg_C}{\dot{m}_F N^2 D^2} \right)^{0.10} \left(\frac{RzD^2}{\dot{m}_A} \right)^{0.31} \right\} \quad (6)$$

The final correlation was presented in the form of a plot of $(\dot{m}_C/\dot{m}_F)$ versus $(Pg_C/\dot{m}_F N^2 D^2)^{0.10} (RzD^2/\dot{m}_A)^{0.31}$ on log-log paper as shown in Figure 5. The correlation coefficient for this plot was calculated to be 0.81.

This correlation is applicable for use in the design of rotary pyrolytic convertors. The convertor size is based on the design feed rate and feed variables including particle size, shape, and moisture content. Exact specification of the reactor retention time based on a knowledge of these feed variables was beyond the scope of this work. However, for most of the feedstocks used in this investigation, a retention time of 8 to 10 minutes (duplicating that of the existing large kiln) may be assumed and the appropriate bed volume calculated. The correlation may then be utilized to estimate char yield as a function of kiln speed and air rate to the kiln, thus providing design information required for kiln power drive and speed requirements. Auxiliary equipment including the air blower and piping could then be specified.

The experimental program demonstrated that each of the feed materials tested could be processed using this pyrolytic conversion scheme. Production of char was achieved for each of the feeds. It was not possible to get complete conversion of the macadamia nut shells. Char was formed on the edges of the shells indicating that longer retention time would be required for this feed.

Rice hulls, macadamia nut shells, and scraps of particle board presented no materials handling problems. The feed delivery system incorporated in this apparatus was not suitable, however, for gin waste due to its loose and bulky nature. Once the gin waste reached the kiln itself successful operation was possible for feed rates up to 50 pounds per hour. The fibrous portion of the gin waste material was incinerated while the woody portion was converted to char. At feed rates greater than 50 pounds per hour, the feed material tended to form a large "ball" which obstructed flow through the kiln. This situation could be alleviated rather easily by decreasing the feed rate and allowing the combustion of the fibrous material to reduce the size of the obstruction.

Conclusions and Recommendations

The conclusions drawn as a result of this investigation are:

(1) Charcoal yield from wood waste processed in the rotary kiln pyrolytic convertor is a function of the air rate to the kiln and the speed of rotation of the kiln.

(2) This functional relationship was determined by the correlation of the experimental data. The resulting correlation, presented in graphical form as Figure 5, is useful in design applications.

(3) The rotary kiln pyrolytic convertor demonstrated that it can be utilized for processing a wide variety of feedstocks either by the partial oxidation-pyrolysis method or by complete incineration.

Results of this investigation indicate several points requiring further study:

- (1) The effect of feed particle size and shape on char yields should be determined.
- (2) The effects of equipment number and depth number should be established.
- (3) Utilization of the hot off gases for predrying of feed material should be investigated.
- (4) Quantitative results relating char yields and system variables for feeds other than wood waste are needed for the development of design data for these applications. The problems associated with the handling of materials and the unique characteristics of each individual feed material should be addressed.
- (5) Composition of the off gases should be evaluated for possible recovery of chemicals and or conversion to a low Btu gas.
- (6) Improvements of the mechanical design of the system should include a weigh-feeder and star valves for the char and feed conveyors.
- (7) The experimental data thus far measured should be reexamined to determine if additional results can be obtained.
- (8) As more information and understanding of the rotary kiln pyrolytic process is obtained, efforts should be directed toward analysis of the basic physical and chemical phenomena involved.
 - a. The effects of kiln temperature and gas velocities on the reaction rate should be determined.
 - b. The kiln retention time should be measured.
 - c. The effects of flow pattern and velocities of the air as it enters the kiln should be studied.
 - d. Gas samples at various locations within the kiln should be obtained and analyzed.
 - e. The effect of feedstock moisture should be examined.

Literature Cited

1. Angelo, James F., "Pollution Free Combination Carbonization Apparatus and Furnace," U.S. Patent No. 4,037,543, July 26, 1977.
2. "Thermochemical Conversion of Biomass Residues," A technical seminar presented by Department of Energy, Golden, Colorado, November 30 - December 1, 1977.
3. Havens, J. A., "Thermal Decomposition of Wood," Ph.D. Dissertation, University of Oklahoma, Norman, Oklahoma, 1969, p. 5.
4. Goldstein, Irving S., Wood Technology: Chemical Aspects, American Chemical Society, Washington, D.C., 1977, p. 63.
5. Tran, Dung Q. and Rai, Charanjit, "A Kinetic Model for Pyrolysis of Douglas Fir Bark," AICHE Symp. Series, No. 157, Vol. 72, 1976, pp. 100-111.
6. Chislovskii, V. V., "Mathematical Modeling of High Temperature Pyrolysis," International Chemical Engineering, Vol. 18, No. 1, 1978, pp. 144-149.
7. Havens, J. A., "Pyrolysis of Wood: A Thermoanalytical Study," J. Fire & Flammability, Vol. 2, Oct. 1971, p. 321-333.
8. Stepanov, A. V., "Modeling of the Pyrolysis Process in Tubular Coils on a Digital Computer," International Chemical Engineering, Vol. 18, No. 1, 1978, p. 141-144.

Nomenclature for Scale Model Kiln

A	efficiency number
B	Damkohler number
C	power number
n,θ	exponents of the correlating groups
D	inside kiln diameter
g _c	gravitational constant
H	depth of solids bed in kiln
$\dot{m}_A$	mass flow rate of air to kiln
$\dot{m}_C$	mass flow rate of char product
$\dot{m}_F$	mass flow rate of feed material (dry basis)
N	rotational speed of kiln
P	power input to agitate solids bed
R	pyrolysis rate
r	characteristic dimension of feed particle
Z	the product $(RzD^2/\dot{m}_A)^{0.31} (Pg_c/\dot{m}_F N^2 D^2)^{-0.10}$
z	kiln length
θ	"a function of"
ψ	"a function of"
f	"a function of"

FULL SCALE ROTARY KILN CONVERTOR

Objective

The objective of this project was the acquisition of operating data from the existing large scale convertor with various feedstocks and sufficient variations of the carbonization process in order to:

1. Aid in the evaluation of the process as concerns:
 - (a) pyrolytic conversion performance
 - (b) economics
2. Provide scaling for a bench scale rotary convertor.

The A & P Company of Jonesboro, Arkansas was awarded a subcontract for this project. They were to supply operating and maintenance personnel to operate the convertor as set forth by the project leader. The total amount of the subcontract was for \$98,588. Of this amount \$93,588 was budgeted to provide four full time operating and maintenance personnel, one full time engineer, a full time on site manager, and one clerk bookkeeper. Five thousand dollars was budgeted for emergency repairs, copying, and telephone expenses. The University was to provide the instrumentation, expertise in its installation and usage, and other personnel as needed to attain the project objectives.

At the inception of the project it was thought that the operations at Jonesboro would consist primarily of the design, purchase, and installation of an instrumentation system for the acquisition of data for performing material and energy balances. Need for repair of portions of the existing convertor was evident but was thought to be a secondary problem which could be handled as the instrumentation proceeded. Unhappily, the reverse situation has been the case. Repair of the existing unit has tended to become the primary chore

in order for the unit to remain operational and for effective testing. These problems will be addressed in the material to follow; as well as the planned instrumentation and preliminary data.

General Process Description

A cutaway sketch of the principal parts of the convertor is shown in Figure 6. The sketch can be thought of as cylinder that has been sliced down its length with a view into the side. Rotation of the vessel is into the paper on top and out of the paper at the bottom.

The input solids to the device are presently waste oak woodchips and sawdust from a pallet manufacturing operation. Until March of 1979 the input was from a chicken coop manufacturing operation at the same location. The waste is brought to the convertor from storage bins by means of a series of screw conveyors and dropped into the bottom of the rotating vessel as shown in Figure 6. The drop chute passes through the forward portion of the afterburner, producing some slight predrying effect.

The refractory lined cylindrical rotating vessel is slightly inclined to the horizontal ($\approx 1^\circ$). Thus, the chips move toward the lower end of the vessel as they are agitated by its rotation. In the usual mode of operation they are dried and heated to a pyrolysis or charring temperature as they traverse the vessel. A portion of the off gases produced by the charring are burned within the vessel with the remainder flowing to the afterburner. The energy for drying and raising the waste to the pyrolysis temperature is supplied by this burning, burning of a small portion of the chips themselves, and by the exothermic heat of the pyrolysis reaction. The resulting char at the lower end of the vessel is lifted by scoops and dropped through a pipe to a screw conveyor.

FIGURE 6. SCHEMATIC VIEW OF PROCESS

Air is introduced to the process via a fan and stationary air pipe. The pipe is shown in Figures 6 and 7. It is supported at the hot or char end of the vessel by a large header pipe. It is supported at its other end inside the afterburner. This end of the pipe is sealed. Air enters the vessel through a series of holes as shown in Figures 6 and 7. The resulting turbulent flow is countercurrent to the direction or rotation of the vessel. It provides the oxygen for combustion of a portion of the pyrolytic offgases described above, and for the small portion of input solids that are usually burned. The resulting countercurrent "fireball" provides good heat transfer to the refractory lining and the product bed. The amount of air introduced is presently controlled by a throttle on the fan inlet. Thus, theoretically, if the correct amount of air is introduced, all the solid input can be burned and the device can be said to be operating in an incinerator mode. The usual method of operation is to restrict the air input so that only partial oxidation occurs and the device can be said to be operating in a pyrolysis mode or partial oxidation mode. The very reactive charcoal of the bed tends to be protected from excess oxidation by this air induction scheme.

The majority of the off gases generated within the rotary vessel flow to the afterburner in its usual mode of operation. It is intended that they be mixed with air and burned there. The air for this combustion currently flows through air leaks between the vessel and afterburner and through leaks in the afterburner itself. If the moisture content of the wood is high or the off gas generation is particularly heavy, combustion takes place in the lower portion of the stack via air leaks in the stack.

After the off gases are burned, either in the afterburner and/or the stack, the products of combustion exit the stack with no visible pollutants.

As presently configured there are rudimentary, nonfunctional air seals at both ends of the rotating vessel. The unit currently processes about 20 tons per 24 hour day on a dry basis, with a typical char conversion rate of 15%.

FIGURE 7. AIR INDUCTION

Detailed Description of Components.

The convertor can be thought to consist of the following parts: (1) refractory lined rotating cylindrical vessel, (2) air injection system and air pipe, (3) afterburner, (4) air seals, (5) stack and, (6) input and output conveyors (materials handling equipment).

1. Rotary vessel

The vessel can be thought to consist of its outer shell, refractory lining, and riding rings or tires.

The shell in use now is half of a railroad tank car. A portion of the unused half is still on site. The shell from the tank car is constructed in three overlapping sections. The sections are riveted together with a double row of 1" diameter rivets. The overall length of the shell is 16 feet with a nominal outside diameter of 88 inches. It is presently lined with a castable refractory that is approximately 4" thick.

Failure of the vessel in several modes led to an insurmountable instrumentation problem in performing the mass and energy balances necessary for the attainment of the project objectives. The vessel would not rotate about a common centerline. In other words it shifted drastically in both the radial and longitudinal directions as it rotated. This made it impossible to construct adequate air seals. Without these seals an unknown and unmeasurable amount of oxygen was being introduced into the process at the two ends of the vessel. This runout or wobble problem arose from inadequate design and construction when the vessel was fabricated initially. The tires or riding rings were only 1" thick and were connected rigidly to the vessel. The loads from them were transmitted to the vessel in such a manner as to cause the vessel itself to buckle. In addition, the tires themselves have failed repeatedly. Subsequent repair efforts accentuated the initial wobble problem and lead to dynamic or shock loads being introduced with rotation. This led to even more frequent failures.

A significant investment of time was made in analyzing these mechanical problems. A detailed discussion and analysis of them was included in the 6 month technical progress report. That portion of the report is included for

convenience as Appendix D. The results of this analysis were incorporated into the design of an improved vessel. It features floating riding rings or tires that are nominally 3 inches thick as opposed to the original one inch thickness. The "cold" clearance between vessel and tires is one eighth inch on the radius to allow for thermal expansion and the mechanical loads are transmitted from the tires to the vessel through reinforcing bands that are two feet wide and three quarters inch thick. The tires or riding rings are located 31.5" from the end of the vessel as dictated from stress analysis.

The cylindrical portion of the vessel was rolled from 3/8" thick plate and its outer diameter is 84" with the length being 16 feet. The slightly smaller diameter was chosen so that the trunnion locations would not be changed appreciably with the use of thicker riding rings. The weight of the original vessel was approximately 30,000 pounds. Using a thicker refractory lining with a smaller diameter vessel maintained that weight. The vessel is also equipped with three inspection ports along its length to allow for process sampling. An abbreviated working drawing of the redesigned vessel is shown in Figure 8.

The request for bids on this redesigned vessel was issued on 22 July, 1978. The bid responses varied from \$17,620 to \$42,276. The low bid was accepted after a visit to that bidders shop facilities to determine his capabilities for carrying out the desired fabrication. Due to the technicality of the low bidder not signing his bid; the request for bids was reissued with the result that a purchase order was issued to the original low bidder on 2 October, 1978. A twelve week delivery time was promised.

The vessel has been fabricated and delivered to the Jonesboro site after considerable delay due to difficulty in fabrication of one of the riding rings. The plate from which the riding ring was rolled "laminated" during the rolling

FIGURE 8. PORTION OF WORKING DRAWING OF REVAMPED VESSEL

operation. In other words, it separated into layers. The plate was subsequently reordered twice before a successful rolling of the ring was achieved. Another delay occurred when the fabricated riding rings were machined to meet the radial tolerances of the design. The machine shop under subcontract to the fabricator machined one ring to a thickness of 2-7/16 inches. Financial compensation for this mistake was sought from the fabricator in the form of a reduced price and/or time on site helping with the installation of the vessel. The latter arrangement was negotiated to save time, with the result that there are to be three men furnished by the fabricator to aid in the installation. The thicker or stronger tire was placed on the heavy or char output end of the vessel and it was delivered by the on site personnel.

It must be emphasized that this redesigned vessel is not the best possible vessel attainable, as might be ordered from old line rotary kiln manufacturers such as Combustion Engineers or Allis Chalmers. Its design is a compromise between such a vessel and budgetary constraints. It is adequate, however, for the attainment of the projects goals.

The vessel is to be lined with a 6 inch thick layer of castable refractory atop two layers of insulating paper. The request for bids for this refractory was issued on 3 July, 1978, and a purchase order for 24,000 lb. of Morcocast HSEC castable was issued on 31 August, 1978. The purchase order included 400 stainless steel anchors to secure the refractory to the kiln walls. The refractory weighs about 128 lb/ft³ and has a thermal conductivity of 6.6 Btu/ft²/hr/°F/in. thickness at 1000°F. It is a high strength castable which is comparable to the A. P. Green product called MC-22. The latter may be more familiar to the reader. Its pyrometric cone equivalent is 15-16 with an equivalent temperature at 2606°F - 2716°F. The refractory vendor (Christy Firebrick) is to furnish 3 days of supervision for the refractory pouring.

The insulating paper to be used is a Babcock and Wilcox product called Kaowool ceramic fiber paper. Its thermal conductivity is $0.4 \text{ Btu/ft}^2/\text{hr}/^\circ\text{F}/\text{in}$ thickness at 600°F and its uncompressed thickness is one eighth inch. Both the castable refractory and insulating paper are on site awaiting installation. Fifty bags (500 lbs.) of the castable refractory have been used by the Jonesboro personnel for repairs of the existing convertor. It is to be replaced at their expense.

The heat transfer rate through the refractory (6" thick), two inches of insulating paper (taken to be $3/16$ " thick when compressed), and steel ($3/8$ " thick) was calculated to be 320,000 Btu/hour for the 16 foot long kiln. The outside shell temperature was calculated to be 370°F . Each of these results was arrived at by assuming an interior process temperature of 2000°F . This figure is conservative in that preliminary measurements indicate that the maximum temperature that may be expected is 1800°F . The rotational rate was taken to be 3 revolutions per minute. A computer program was written to obtain the results given above. The program solves the fourth order equation in the outside skin temperature that results from considering conduction, convection, and radiation. The solution is found using the Newton-Raphson method. This program facilitated a rapid evaluation of several combinations of refractories and refractory thicknesses, insulating papers, rotational rates, and kiln lengths.

As stated above the redesigned vessel and the materials for its relining are on site. The vessel has not been installed to date because of the reluctance of the on site personnel to proceed with the installation at their cost. It is estimated that this cost would be \$2,395 for materials such as welding rod, steel for trunnion relocation, char buckets, and crane and mixer rental. The time for installation is estimated as 1 month if one man is used

for the long term job of welding in the refractory anchors. This time would obviously be cut considerably if more labor were employed. The estimate also includes afterburner installation and curing of the refractories of both afterburner and vessel. Labor cost are estimated at \$1,000 for one man for one month.

2. Air injection system

The stainless steel air injection pipe shown in Figures 6 and 7 is 8" in diameter. It is insulated with $\frac{1}{2}$ " of Kaowool Ceramic Fiber on its exterior. Air flows down its interior from an 18" diameter header pipe which is connected outside the kiln to a 30" diameter paddle wheel fan with six paddles that are $8\frac{1}{2}$ " x 8". The fan is powered by a 10hp motor and turns at 1100rpm. The fan outlet is 11" x 11" and its inlet is $14\frac{3}{4}$ inches in diameter. The flow thru the fan is controlled by a vane in its inlet as shown in Figure 6. With the vane open or parallel to the flow, the convertor functions as an incinerator and as the vane is closed the partial oxidation or pyrolysis mode is initiated as explained previously. The pipe is supported on the char end by the header pipe and inside the afterburner at its other end. It is closed at the afterburner end.

The air from the fan and header flows out holes that are cut in the side of the air injection pipe as shown in Figure 7. At the inception of the project the pipe had ten $1\frac{1}{2}$ " diameter and four 1" diameter holes that had been cut in it by torch. The air exit area was thus 20.8 in.^2 . There were no nozzles used and the larger holes were located at the afterburner end of the vessel. The original air pipe collapsed during the project and was replaced in March of 1978 with a pipe of the same diameter but with thirteen $1\frac{1}{4}$ " pipe nipples (1.38" inside diameter) and five $1\frac{1}{4}$ " holes for air exit. This gave an exit area of 25.4 in.^2 . The five $1\frac{1}{4}$ " holes were concentrated at the afterburner end.

The original air pipe that collapsed was braced on its inside by several rods welded across it. This added to the weight carried by the pipe without substantially stiffening it. This inadequate design, as well as the many leaks that had been burned in the pipe, caused it to collapse. The leaks also caused much of the char output to be burned and actually caused the char lift buckets to melt at one time. The replacement air pipe was stiffened by the addition of angle iron to its top exterior and installed with its bottom 15" from the refractory surface instead of 6" as with the original pipe. The new pipe has been functioning well and it is hoped that it can be used with the redesigned vessel discussed previously. Because of delays in further funding of the project this may not be possible.

The air flow rate thru this induction system obviously depends upon the degree to which the convertor is being operated toward the pyrolysis side or incinerator side of its capabilities. Taking a typical flow rate of 800 cfm thru the fan from the preliminary data and a coefficient of discharge of 0.61 for use in the orifice equation yields a velocity of 75.6 ft/sec out the pipe nipples and the holes with the corresponding flow rates being 0.785 and 0.644 ft³/second.

It is hoped that a zone air injection scheme can be implemented if additional funding is provided. At least three individually controllable zones of air injection would be set up. For example, the air injection rate near the char end of the process could be attenuated as compared to that near the solids input end. This should make the converter more controllable and efficient, and aid in the attainment of the project objectives.

3. Afterburner

The present afterburner in use is a 42" diameter by 5 foot long hollow cylindrical shell. It is made of ½" thick steel and has no refractory lining.

It is near collapse. Stack draft draws air thru leaks in the afterburner shell to supply combustion air for burning of the off gases. The measurement of the combustion airflow thru the numerous leaks is impossible.

This afterburner is to be replaced with a 54" diameter by 56" long 10 gauge cylinder whose interior is to be lined with 6" of insulating castable refractory. The refractory to be used is a Morcolite insulating castable (2450°F) which is equivalent to the A. P. Green product called Kastolite - 25. It has a thermal conductivity of approx. 3.0 Btu/sq ft/hr/°F/in thickness at 1200°F and is to be laid atop two layers of insulating paper with stainless steel anchors (89) as discussed previously.

The afterburner is to be constructed in two sections to facilitate installation. Each section will be cylindrical with one section being 20" long and the other 36" length. The two sections will be flanged and bolted together with the short section flanged and bolted to the stack. The other end will be free to expand into the vessel as thermal expansion takes place. The weight will be supported from the concrete floor and will be 3000 lb. The afterburner shell will support the air seals on its end of the vessel.

Combustion air to burn the off gases is to be supplied by a blower that is already on site and owned by the subcontractor. It was tested and found to be adequate for supplying combustion air thru a measuring venturi and four 6" diameter stainless steel pipes. These pipes will introduce the combustion air at the upstream end of the afterburner, perpendicular to its longitudinal centerline. They will be equally spaced around the circumference of the afterburner shell.

Writing a balanced equation for the process reaction that produces char and burns the off gases completely to carbon dioxide and water yields a total air requirement of 1222 scfm for both the partial oxidation reaction and the

off gas burning. Then by making a conservative estimate that 80% of this must be supplied to the afterburner; one finds the required combustion air to be 978 cfm. With the four 6" pipes mentioned above, this produces a velocity of 21 ft/sec in each. These calculations are based on a 20 ton/day input (dry) and a 15% char conversion rate. This data is typical for the Jonesboro unit. The fan that is on site and that was tested will supply 1000 ft³/min of air at about 0.6 in. H₂O. This slightly exceeds the pressure loss due to piping and the measuring venturi.

The purchase order for the refractory and anchors of the afterburner was issued on 17 November, 1978. A shop drawing of the steel shell and a description of it was completed with the request for bids and the resulting purchase order being issued on 1 November, 1978. Both these items were delivered in December of 1978. The air pipes, drop chute, and insulating paper are also on site. The subcontractor (A & P Coop) has made no effort to proceed with the afterburner construction even though furnished with detailed drawings. University personnel have constructed a circular form for use in pouring the refractory during their trips to Jonesboro.

Afterburner and vessel installation should be accomplished simultaneously but if the afterburner is considered alone it is estimated that the additional cost of its installation is \$50 for supports and \$250 for labor (1 man for one week).

4. Airseals

There is one seal on each end of the rotating vessel. The one on the char output end is mounted on the air injection system header pipe. The one on the input solids end is mounted on the afterburner.

The seals in use are totally ineffective and are more of a cosmetic ornament than anything else. They are to be replaced with seals of the design shown in Figure 9. Considerable time was spent in investigating several different configurations of seal design. The result shown is felt to be the best compromise between cost, as compared to commercially available kiln seals, and the achievement of the project objectives. An assembly drawing of the seal for each end with a parts list for each is attached as Appendix E.

Air may be drawn from the outside into the process; or gases may escape from it in the radial and longitudinal directions. Thus there must be two sealing surfaces. In the design of Figure 9 the asbestos rope (D) provides the seal against leakage in the longitudinal direction while the seal material (A) rubbing against (B) blocks flow in the radial direction. The latter also allows for rotation of the convertor by providing a sliding contact seal surface. The tangential or rubbing velocity at the radial midpoint ($32 \frac{3}{8}$ in. radius) of the afterburner end rubbing surface will be 773 inches/min. This is based on a rotational rate of 3.8 revolutions/minute which is the nominal rate of the Jonesboro convertor. The prototype unit on campus was run at rubbing velocities that ranged from 201 in/min to 1407 in/min with a velocity of 804 in/min being the most common. The carbon on steel rubbing surface used there worked very well with good wear characteristics. Thus a carbon on steel rubbing surface is planned for the Jonesboro unit if funds allow. If not, a cement-asbestos on steel surface will be employed. An interface pressure of 0.3 lb/in^2 is planned at the rubbing surfaces. Longitudinal relative movement of the kiln and seal

FIGURE 9. SEAL DESIGN

mounting due to thermal expansion is allowed at the longitudinal seal while radial motion is accommodated at the rubbing surface of the radial seal.

The seals are one of the most significant items needed to bring the convertor at Jonesboro to a state of operation commensurate with the achievement of the project objectives. As mentioned previously, an unknown and unmeasurable amount of air is leaking into the process thru the useless seals currently in place. This makes the attainment of accurate energy and mass balances impossible. The seals are the only large item remaining to be constructed and installed before long term data acquisition can begin in earnest.

The estimated cost of the seals of the design shown in Figure 9 is \$5000 for both ends, as opposed to \$14,000 for the best commercially available units.

5. Smokestack

The smokestack in place at the start of the project was a 34.75' high by 42" ID steel cylinder with a $\frac{1}{2}$ " wall thickness resting on a concrete slab and connected directly to the afterburner as shown in Figure 6. The stack was not refractory lined. The burning of the offgases was completed in the portion of the stack immediately above the afterburner (3-4 feet) as explained previously. As a result that portion of the stack was subjected to overheating and a tendency to buckle locally. It was hoped that the existing stack could be lined with refractory. Before this could be accomplished the operators allowed the overheating to become so severe as to cause the stack to tilt dangerously toward collapse.

Operations were continued by spraying cooling water on the stack exterior at the hot spots until a replacement stack could be designed,

purchased, and put in place. Figure 10 shows a portion of the drawing that was sent out for bids on the replacement stack. Upon receipt of bids the spark arrestor and insulating castable shown on this drawing were dropped from the specifications to save money. The insulating castable was replaced by insulating firebrick. The outer 10-gauge steel shell temperature was to be limited to 350°F with a stack interior temperature of 2000°F. This specification was met in practice. The design of the stack was such that it was capable of withstanding standard design wind loads of 25 pounds per square foot ($\approx$ 118 mph) with no guy wire supports. Three guy wires were used for safety purposes however, and to prevent first mode oscillations that might be excited by Von Karmann wind vortices. These calculated results were found by using a drag coeff. of 0.7 and an air density at 60°F. The maximum normal stresses in the steel outer shell due to the weight of the stack (164 lb/ft) and a design wind load of 25 lb/ft² were calculated to be 3514 psi in compression and 2930 psi in tension. The maximum shear stress was found to be 356 psi. The bracing around the access door was designed with a resulting safety factor of 2.59 for the design criteria set forth previously. Column buckling of the newly designed stack was calculated to be outside the realm of possibility. The new stack weighed 5904 lbs and replaced a stack that weighed approx. 8000 lbs.

The requisition or request for bids for the newly designed stack was issued on 28 February, 1978. The resulting bids were modified by telephone by dropping some of the specifications to save money, as stated above. The purchase order for the stack was issued on 10 May, 1978, and the stack was installed by the on site personnel in August of that year.

FIGURE 10. SMOKESTACK

The replacement stack performed well for two months until the sub-contractor started using input solids that had been heavily contaminated with dirt. This caused a glassy like brown slag to form on the walls of the afterburning portion of the stack. The resulting stresses that arose from differing thermal coefficients of expansion between the slag and firebrick lining caused the latter to spall when the stack cooled and was then reheated. Severe damage to the lining occurred.

Operations were continued by thermocouple monitoring of the stack gas temperatures and by paying closer attention to the contamination level of the input solids. The temperature was controlled by allowing excess air to be admitted through the stack access door.

Portions of the stack lining which had suffered the worst damage were cleaned and patched with a castable refractory. This patching proved unsatisfactory in that the castable would not adhere to the firebrick surface. It was then concluded that the bottom two sections should be relined with a thick super duty firebrick that could withstand higher stresses should they ever arise again.

Stack draft calculations were made for a smaller inner diameter stack (37" versus 43") based on temperature data obtained earlier. These calculations indicated that using the smaller diameter would cause no problems. Calculation of the outer steel skin temperatures with different lining systems was carried out with the results shown below. They were based on an inside temperature of 2000°F.

<u>Lining System</u>	<u>Outside Shell Temperature</u>
2.5" of Kaiser M-20 insulating firebrick. This was what was in the stack before its deterioration.	332°F
1" of M-20 insulating brick. This was about what was left after the deterioration occurred.	518°F
4.5" of super duty firebrick.	620°F
4.5" of super duty firebrick backed by two layers of Fiberfrax 970-J insulating paper.	507°F
4.5" of super duty firebrick backed by 1" of Insul Block 1900 insulating block.	386°F

These temperatures and draft calculations; as well as cost estimates obtained by phone; led to the decision to reline the bottom 24' of the 36' stack with a 4.5" thick super duty firebrick backed by 1" of insulating block. The thermal conductivity of the firebrick was approx. 10 while that of the insulating block was 0.93. This relining scheme was implemented by the subcontractor in the spring of 1979, at his cost (approx. \$4000) and the stack has been operating well since then.

6. Materials handling equipment

The input solids (wood waste) and output solids (charcoal) were handled by screw conveyors at the start of the project as listed in the table below.

TABLE III. ORIGINAL CONVEYORS

<u>Input</u>
1. 12" diameter, 18 foot long screw conveyor from hammer mill to bucket elevator

2. 6" diameter, 15 foot long screw conveyor from one storage bin to other
3. 9" diameter, 13 foot screw conveyor from under bin to inclined screw
4. 9" diameter, 16 foot inclined screw conveyor feeding kiln drop chute, 33° inclination

Output

5. 9" diameter, 50 foot long water jacketed inclined screw to truck
= 48° inclination

These conveyors were in need of constant repair to maintain continuity of operation as set forth in the six month technical progress report. This was especially true of the char output conveyor whose angle of inclination was much greater than normal design criteria would dictate. They were also marginal as to their ability to handle feedstocks other than the wood chips being used. After some time designing a replacement system, writing specifications, and obtaining bids; the original conveyor system was replaced by the items shown in the Table below.

TABLE IV. REPLACEMENT CONVEYORS

Input

1. 14" diameter, 18 ft long screw conveyor from hammer mill to bucket elevator
2. 12" diameter, 16 ft long screw feeder allowing both bins to feed simultaneously
3. 12" diameter, 19 ft long screw conveyor from under bins to inclined screw, with gate
4. 12" diameter, 24 ft long inclined conveyor feeding kiln drop chute, 21° inclination

Output

5. 9" diameter, 30 ft long water jacketed screw conveyor to bucket elevator, 8° inclination, with gate
6. 12" x 35" x 22' centrifugal discharge bucket elevator to elevate char vertically and discharge to truck

This arrangement eliminated one variable speed drive, allowed both feed bins to feed simultaneously, and resulted in an overall design that was not marginal.

As can be seen from the table above, two of the replacement screw conveyors were designed with "gates." This means that the bottom of each can be opened at one point and the conveyed solids will drop thru the resulting opening. This was done so that the flow rates of solids in and solids out could be measured simply and cheaply by means of stopwatch and platform scales. This scheme has worked quite well after overcoming the initial hurdle of training on site personnel to obtain this data.

Instrumentation

The planned instrumentation is summarized in the table below.

TABLE V. OVERALL INSTRUMENTATION

<u>Quantity</u>	<u>Method of Measurement</u>
Flow Rates	
solids---feedstock in and char out	scales and stopwatch
gases ---air to kiln air to afterburner stack gases	orifice meter plenum venturi pitot probe station
liquids---char cooling spray char conveyor cooling	rotameter rotameter
Temperatures	
solids, liquids, and gases	Thermocouples connected to potentiometric recorders and pyrometers, optical pyrometer, and liquid bulb thermometers
Composition	
stack gases and off gases	Orsat analysis and stack gas train effluent analyzer on site, gas chromatograph analysis of interior gas samples returned to campus if possible
solids	moisture content on site and further analysis on campus (usually a proximate analysis)

As already mentioned the flow rates for solids in and out of the convertor will be determined by measuring the time necessary for a quantity of material to fall onto a set of platform scales. The gas flows will be measured as indicated with orifice meter, venturi meter, and pitot probe station. The orifice meter is under construction, the venturi meter is on

site and the stack sampling apparatus (temperature, velocity, and gas sampling) is on hand. Liquid flow rates will be measured with rotameters which are on site.

The majority of the temperature data will be obtained by means of thermocouples connected to indicating devices. Figure 11 shows the proposed stations at which temperature data will be obtained.

A detailed breakdown of that instrumentation is shown in Table VI. Thermocouples 1 and 2 are located in the water flowing from the jacketed screw conveyor and the char output of that screw conveyor, respectively. Thermocouples 3 and 4 are in place to measure the temperature of the incoming water to the jacket of the char conveyor and to the char cooling spray. Thermocouple 5 is located in the hot char stream flowing to the output screw conveyor.

Thermocouples 6 thru 10 are to be located in the bed of char and wood chips from one end of the vessel to the other. Thermocouples 11 thru 15 are to be used to measure interior gas temperatures. These thermocouples (6-15) will be attached to the central air pipe for physical positioning. Their junctions will then be placed in the appropriate locations and lead wires run out through the central air pipe. The temperatures so measured will be used to relate the reaction rate to the bed temperature and determine reaction zones of the process. Thermocouples 16 thru 20 are to be used to measure afterburner and stack gas temperatures.

Some of the thermocouples have been installed (1-5), others await permanent installation (6-10, 20), and some must be purchased (11-19). These last thermocouples were intended to be platinum-rhodium (type R). A precipitous price increase brought about a cancellation of the purchase order for them and they will be reordered as chromel-alumel (type K).

FIGURE 11. THERMOCOUPLE LOCATIONS

TABLE VI. DETAILS OF TEMPERATURE INSTRUMENTATION.

STATION	ESTIMATED TEMP. RANGE	THERMOCOUPLE	LEADWIRE	INDICATOR
1 cooled char out (see Figure 11)	100-400°F	400-8J12 12" long, 14 gauge stainless steel tube	14, 16 gauge = 45' do not exceed 116' with 14 gauge	5S-PYR-J500-4Z (one) 10 ohm external resistance pyrometer
2 jacket water in	40-80°F	1600-J 1.5 hose clamp type 20 gauge	14 gauge = 45' do not exceed 58' with 14 gauge	5S-PYR-J300-HZ (one) 5 ohm resistance pyrometer
3 jacket water out	40-180°F	1600-J 1.5 hose clamp type 20 gauge	14 gauge = 35' do not exceed 58' with 14 gauge	5S-PYR-J300-HZ (one) 5 ohm resistance pyrometer
4 spray cooling water	40-80°F	1600-J 1.5 hose clamp type	14 gauge = 35' do not exceed 58' with 14 gauge	5S-PYR-J300-HZ (one) 5 ohm resistance pyrometer
5 char out before cooling spray	700-1300°F	400-8K12* 12" long, 14 gauge stainless steel tube	14 gauge = 35'	Honeywell potentiometric (one) circular chart recorder
6 outer skin temperature	150-600°F	1800-K6 3/8" dia. washer 24 gauge	14 gauge = 40' do not exceed 68'	5S-PYR-K1000 (two) 10 external resistance pyrometer or manual potentiometer
11 interior temperatures	1000-2000°F	900-14K12 12" long, 14 gauge two hole ceramic insulation	16 gauge = 40'	Honeywell series 152 circular chart recorder (4), Honeywell class 15 four point strip chart recorder, Antek model 285 two channel strip chart recorder, manual potentiometer, handheld pyrometer, and optical pyrometer.
16 afterburner interior	1000-2000°F	900-8K24 24" long, 8 gauge two hole ceramic	16 gauge = 90'	
20 stack	700-1800°F	900-8K24 24" long, 8 gauge two hole ceramic	14 gauge = 120'	

NOTE: Thermocouples and pyrometers listed are from Modutec Company

* J-iron-constantan
K-chromel-alumel

The indicating devices are all on site, checked out, and operating properly. The Honeywell recorders (5) were purchased as reconditioned instruments to save money and to date have been performing well. Two of them were purchased for use with platinum-rhodium thermocouples. They have been converted for use with chromel-alumel thermocouples because of the necessity of reordering, as mentioned above.

Gas samples will be taken from the interior of the kiln and returned to campus for analysis by means of sample pipes running along the central air induction pipe.

In summary then, all the instrumentation is on hand except for the orifice meter and the thermocouples and leadwire that must be reordered. The orifice meter is being constructed locally. The manometers for use with the venturi and orifice meter have been purchased and delivered. The materials for construction of apparatus for sampling gases and solids inside the convertor are yet to be purchased. It is estimated that a maximum of \$1500 would be needed to totally complete the instrumentation necessary for the attainment of the project objectives.

Preliminary Data

Typical preliminary data is shown in the table below.

TABLE VII. PRELIMINARY DATA

Char temperatures	1100°F exiting kiln 110°F at bucket elevator
Air flow thru fan to kiln	850 Scfm
Char cooling spray H ₂ O	11 Gallon/hr, 50°F
Char conveyor jacket H ₂ O	225 Gallon/hr 50°F in, 104°F out
Feedstock moisture content	30% - High 4% - Low 25.5% - Average
Char Moisture	53% 2% 34%
Feedstock flow rates (dry basis)	2392 $\frac{\text{lb}}{\text{hr}}$ 883 $\frac{\text{lb}}{\text{hr}}$ 1577 $\frac{\text{lb}}{\text{hr}}$ 18.9 tons/day
Char output rates (dry basis)	382 $\frac{\text{lb}}{\text{hr}}$ 103 $\frac{\text{lb}}{\text{hr}}$ 231 $\frac{\text{lb}}{\text{hr}}$ 2.77 tons/day
Per cent char yield (dry basis)	23.6% - High 9% - Low 14.6% - Average
Stack gas velocity	34 $\frac{\text{ft}}{\text{sec}}$ at 1500°F (Measured 15' up stack)

The table below (Table VIII) gives the proximate analysis of the char output of the convertor. The proximate analysis of the typical product from a Missouri kiln is shown for comparison.

TABLE VIII. PROXIMATE ANALYSIS OF CHAR

	#20	#22	#28	Typical Missouri Kiln
Moisture (As Received Basis)	52.7%	32.3	49	4.7
Volatile Matter	4.95%	8.33	5.78	21.5
Ash	4.76%	5.14	5.67	1.8
Fixed Carbon	90.29%	86.52	90.71	76.7
Higher Heating Value (Btu 16)	12720	12490	12770	~11000

Figure 12 shows preliminary temperature data at various locations in the process. Table X is a table of solids flow rates, moisture contents, and approximate air flow rates to the kiln. The air flow rates of this table were determined by on site personnel using a Birams anemometer. The flow rates of the wood in and char out were determined by means of stopwatch and scales as mentioned before.

The moisture contents given in Table IX were determined by on site personnel using a drying oven and a triple beam balance. Their results agree very well with those obtained on campus as a check. A comparison is shown below.

TABLE IX. COMPARISON OF ON SITE AND LABORATORY MOISTURE CONTENTS

Lot No.	Laboratory	On Site
Char 20	52.7%	53 %
22	32.3	34
28	49	49.3
Wood 19	24.0%	23.3 %
21	27.4	27.33
27	28.1	28

TEMPERATURE LOCATIONS

1	1110°F	(CHARCOAL)	11	1786°F	(INSIDE CHARCOAL)
2	70°F	(AIR IN)	12	1668°F	(SAME)
3	450°F	(SKIN TEMP.)	13	1668°F	(SAME)
4	411°F	(SAME)	14	NO DATA RECORDED	
5	411°F	(SAME)	15	1225°F	(AFTERBURNER)
6	342°F	(SAME)	16	1707°F	(SAME)
7	1668°F	(INSIDE WALL)	17	1592°F	(STACK)
8	1630°F	(SAME)	18	1110°F	(STACK)
9	1377°F	(SAME)	19	587°F	(STACK)
10	NO DATA RECORDED

FIGURE 12. KILN TEMPERATURES

TABLE X. WOOD INPUT AND CHAR OUTPUT FLOW DATA

August and September 1978

Date	Time	% Moisture	lb hr	Tons/Day	% Char Yield	Kiln Air Flow
8/10/78	9:00 am	30	1615	19.38	23.6	
	9:05 am	33	382	4.58		
8/11/78	9:30 am	4	2392	28.7	10.7	
	9:40 am	38	255	3.06		
8/16/78	11:45 am	0.4	1374	16.49	9.6	
	11:30 am	18	133	1.59		
8/16/78	1:30 pm	27	1990	23.88	13.5	
	1:45 pm	19	268	3.22		
8/18/78	9:00 am	36	883	10.6	22.2	
	9:00 am	48.5	196	2.35		
8/18/78	1:30 pm	32	1698	20.37	19.2	700 fpm
	1:30 pm	24	326	3.91		≈ 830 cfm
8/23/78	1:30 pm	27	955	11.46	13.0	630 fpm
	1:30 pm	2.3	124	1.49		≈ 747 cfm
8/28/78	1:15 pm	20	1645	19.74	9.0	750 fpm
	1:30 pm	38.33	148	1.77		≈ 889 cfm
8/30/78	9:30 am	29.66	1150	13.8	9.0	700 fpm
	9:30 am	50	103	1.24		≈ 830 cfm
9/11/78	9:00 am	23.3	1127	13.52	13.7	766 fpm
	9:30 am	53	154	1.85		≈ 909 cfm
9/12/78	11:30 am	27.33	1868	22.42	18.2	790 fpm
	11:45 am	34	339	4.07		≈ 937 cfm
9/12/78	1:30 pm	28.6	1904	22.85	17.3	770 fpm
	1:45 pm	34.3	329	3.95		≈ 913 cfm
9/13/78	1:15 pm	29.5	2115	25.38	13.2	780 fpm
	1:10 pm	37.3	279	3.34		≈ 925 cfm
9/14/78	9:10 am	28	1364	16.37	14.2	
	9:20 am	49.3	194	2.33		

14 3/4" I.D. inlet
to kiln fan

NOTE: Flow rates and yield are on a dry basis.

The linear and quadratic least squares curve fits to this data for percentage char yield versus input moisture content for the month of September are:

$$\text{linear} - \% \text{ yield} = 7.881 + 0.286 X$$

$$\text{quadratic} - \% \text{ yield} = 11.016 - 0.589 X + 0.025X^2$$

in which "X" is the percentage of moisture in the input.

Preliminary Economic Evaluation

BASIS: Nominal 50 TPD Rotary Kiln Converter

CAPITAL INVESTMENT:

Calculated from costs incurred in revamping
the Angelo converter - \$126,500

Installed Cost = (\$126,500) (1.55) = \$196,000

OPERATING EXPENSES:

Labor

Operate 5 days/week, 3 shifts/day, 1 operator
per shift: Cost = (3) (\$20,000) = \$60,000

Utilities

Electric Power - 25 kw
Cost = (25 kw) (52 x 120 hrs) (\$0.04/ kw hr) = 6,200

Maintenance

Estimate @ 10% of installed cost = 19,600

Depreciation

Straight-line with 11-year life = 17,800

TOTAL OPERATING EXPENSE = \$103,600

CREDITS:

Charcoal Sales

* Conversion @ 18% \$75/ton
Income = (50) (52 x 5) (0.18) (\$75) = \$175,500

Waste Disposal Savings

Estimate @ \$1.50/ton
Income = (50) (52 x 5) (\$1.50) = 19,500

TOTAL INCOME** = \$195,000

PROFITABILITY:

Net income = \$195,000 - 103,600 = \$91,400

Net income after 50% taxes = 45,700

Return on original investment = $\frac{45,700}{196,000} \times 100 = \underline{\underline{23\%}}$

* Estimated conversion rate from a new kiln with no air leaks

**Total income does not include value of off gas energy for steam generation
or other use - Potentially \$400,000+/year

Project Expenditures

TABLE XI. EXPENDITURES AT JONESBORO

Instrumentation

Thermocouples & lead wire -----	\$ 784.68
Temperature indicating devices -----	4,827.68
Orsat analyzer and stack gas train -----	2,860.60
Plenum venturi -----	585.00
Manometers and air velocity measurement -----	540.80
Rotameters, thermometers, scales and other instrumentation -----	2,885.26
	<u>\$12,484.02</u>

Equipment

Rotating kiln -----	\$17,620.00
Smokestack -----	8,675.00
Conveyors of bucket elevator -----	13,940.00
Refractory & anchors -----	3,744.39
Insulating paper, afterburner shell, instrument building, steel, and misc. supplies -----	3,199.04
	<u>\$47,179.03</u>

Subcontract (A & P Coop)

Direct Labor

1 on site manager ----- (full time 12 mo.)	\$20,000.00
1 on site engineer ----- (full time 12 mo.)	\$15,000.00
3 Converter operators ----- (full time 12 mo., 1 per shift at \$5.00/hr)	\$31,200.00
2 Maintenance men ----- (Half time 12 mo. @ \$6.00/hr)	\$12,480.00

1 Clerk-bookkeeper ($\frac{1}{4}$ time) -----	\$ 2,000.00
Labor Overhead @ 16% -----	\$12,908.00
Telephone -----	\$ 300.00
Repairs and material handling -----	\$ 4,500.00
Copying -----	<u>\$ 200.00</u>
	\$98,588.00
	<u><u> </u></u>
TOTAL	\$158,251.05

In addition to these expenditures \$5575 (estimated) worth of government surplus equipment was delivered to the subcontractor for use at his site. The University contributed \$175 of miscellaneous supplies in the way of thermocouple wire (50'), insulating paper, and sodium silicate.

A more detailed breakdown of the project expenditures is given in Appendix F.

Conclusions and Recommendations

It was thought that the operations at Jonesboro would consist primarily of the design, purchase, and installation of an instrumentation system for the acquisition of data. This data would be used to make an engineering evaluation of the specific unit at Jonesboro as well as provide scaling for the bench scale convertor on campus. From the latter would come more general conclusions concerning this rotary kiln biomass conversion process. Need for repair of the existing convertor at Jonesboro was evident at the inception of the project but was thought to be a secondary problem which could be accomplished as the instrumentation was installed. Unfortunately the reverse situation turned out to be the case and repair of the existing unit became the primary chore as reported above.

The materials handling equipment system has been redesigned and replaced. A new smokestack has been designed, purchased, and installed. A replacement afterburner has been designed and all materials for its construction are on site. A revamped rotary vessel has been designed, purchased, and is on site awaiting installation. The only major items remaining to bring the unit at Jonesboro to an operational state ready for installation of a full instrumentation system are the air seals. They have been designed but not purchased. The estimated cost of these air seals is \$5,000 while the cost of installation of the afterburner and vessel is estimated is \$3,400, including labor (one man for one month).

Partial installation of the instrumentation system has been accomplished and the remainder, except for a few minor items, is on hand awaiting usage. The majority of this is internal vessel instrumentation which cannot be put in place until the revamped vessel is installed. Even though the full instrumentation package is not in place, preliminary data has been obtained as discussed

above. Adequate air seals must be installed to insure that air flow rates into the kiln are anything other than estimates.

It is estimated that 75 percent of the effort needed to reach the project objectives at Jonesboro has been applied. The remaining 25 percent would involve mostly time and labor. The expense of items remaining to be purchased are minor as compared to the monies already expended. If the project were refunded the most pessimistic estimate is that within 6 months the remaining items of equipment and instrumentation could be installed and operating successfully. From that time it is estimated that 2-3 months, at the most, would be necessary to acquire the data necessary for the attainment of the project objectives.

It appears that the economics are favorable for the use of this rotary kiln biomass processing system for pollution-free use and disposal of agriculture and forest waste products in the production of charcoal and process heat and/or steam. This is especially true in Arkansas and the Ozark Plateau Region where there are many small industries, and some not so small, producing significant quantities of biomass materials while at the same time requiring process heat and/or steam.

From qualitative observation of the Jonesboro unit and from quantitative data from the bench scale campus unit it can be stated with certainty that this process is very flexible as concerns operating conditions and feedstocks. It can be operated easily in various modes ranging from complete incineration to pyrolysis conditions. The products may be completely oxidated flue gases, gaseous and liquid fuels, solid char fuel, or a combination of these. The solid char fuel has been largely overlooked in the search for new energy sources. It is storable, readily transportable, has a relatively high heating value, and presents no great problems in firing.

Investigation of this biomass convertor concept should continue. The goal of such an investigation should be the optimization of its outputs as related to its operating variables, physical dimensions, and feedstocks. The first step in this investigation should be the completion of the project using the existing kiln at Jonesboro. This would provide the data for proper scaling of the scale model convertor and allow its use as a proper experimental vehicle for the optimization investigation. The project at Jonesboro is so near fruition that a relatively small expenditure of funds would lead to its successful conclusion. Experiments with the scale model convertor on campus should continue concurrently with the completion of the Jonesboro project. These experiments should have as their goal the completion of the work already begun in utilizing feedstocks other than wood with the convertor in its present configuration. Work should then begin on utilizing the process as a gasifier for the production of low to medium Btu fuel gases. Attention should also be directed toward the production of liquid fuels utilizing the rotary kiln concept.

LABORATORY SERVICES AND BASIC PYROLYTIC STUDIES

This project was expected to produce much useful basic data on the pyrolytic process as applied to biomass materials. The fact is, however, that the project never fully recovered from the loss of Dr. Lea, who had organized the project and had laid out the experimental program. Much time was devoted by Dr. Lea's replacement in the attempt to bring the gas chromatograph into the picture as the main analytical instrument for pyrolysis products. This is now viewed as a tactical error and that the time and effort would have been better utilized by concentrating on the traditional process analytical methods such as moisture content, heats of combustion, proximate analyses, etc. Even so, a fair amount of data in these categories was obtained.

Sample particle size studies were made using a closed retort with dried red oak cubes as input. The smaller cubes were one inch on the side while the large cubes were two inches. The char exhibited about 20% linear shrinkage, pyrolyzing to about 1000°F. during a 40-minute run. Approximately 75% of the original sample weight was lost during 1000°F. pyrolysis. That is to say, char yields were typical of the values traditionally found for undried wood.

The mass of the closed retort, 5.6 kg masked the temperature variations in the 62 gram wood sample used for each run, even though the thermocouple was in close proximity to the wood mass. A larger wood sample is needed to observe differences in the time - temperature profile as obtained between reactions with small cubes and large cubes. Once the effects of surface to volume ratio for these simple geometrics are known, further project studies can be planned. It is anticipated that differences and yields in reaction products--liquids, gases, and solids--will be found as the particle size varies.

Some additional data was taken on rice hull char produced in the closed retort. This data is reported in Table XII as SPEC 1 and SPEC 2. The SPEC 1 data indicates that rice hulls will produce about 26% ash when burned completely. Rice hull char was produced by heating the hulls in the closed retort at 900°F. for 25 minutes. The carbon, volatiles and ash for this char were similar to that of the char produced in the scale model rotary kiln (runs 3-15-5, 3-15-6, 4-12-6, 4-12-7).

The primary result of this project was then the furnishing of laboratory analyses for the scale model rotary kiln and the full scale convertor at Jonesboro. Feed and product analyses for the scale model kiln are given in Table XII. Run identification numbers generally refer to the date the run was made and the sample number on that date.

It should be especially noted that rice hulls are a rather anomalous material in the biomass category. The rice char sample was 47% ash as compared to typically 5% ash for oak charcoal. This is apparently due to the very high silica content of 20% that is reported for unprocessed rice hulls. The high ash content of rice hull char points toward a low combustion heating value, but the material appears to have other uses for which it may be more valuable than as a fuel.

It is estimated that a total of 400,000 ton/year of rice hulls are produced in Arkansas alone.

TABLE XII. FEED AND PRODUCT ANALYSES

<u>Sample I.D.</u>	<u>Type</u> Ch-oak charcoal W-oak wood	<u>% Moisture</u> (wet basis)	<u>% Carbon</u>	<u>% Volatiles</u>	<u>% Ash</u>	<u>Heat of Combustion</u> BTU/lb (dry basis)
11-21-1	Ch	0.71				11,700.
11-21-2	Ch	0.86				11,550.
11-21-3	Ch	0.62				11,500.
11-21-4	Ch	1.29				11,000.
11-21-5	Ch	0.21				11,300.
12-5-2	Ch	0.87	64.19	32.51	3.30	
12-5-3	Ch	1.02	67.19	27.70	5.12	
12-5-4	Ch	4.15	65.37	31.84	2.80	11,290.
12-5-5	Ch	4.68	65.17	30.12	4.71	11,780.
12-11-2	Ch	3.15	68.07	27.85	4.08	11,730.
12-11-3	Ch	2.36	70.75	23.11	6.14	11,510.
12-11-4	Ch	3.03	64.77	29.95	5.28	11,320.
12-13-F1	W	6.50				7,605.
12-13-F2	W	6.39				7,813.
12-13-1	Ch	2.69	66.21	26.46	7.33	11,660.
12-13-2	Ch	2.83	64.94	30.95	4.11	10,730.
12-13-3	Ch	2.98	61.26	34.21	4.53	10,870.
12-13-4	Ch	3.41	65.26	30.03	4.71	11,600.
12-13-5	Ch	2.04	63.32	32.33	4.35	10,400.
12-13-7	Ch	3.52	67.50	28.78	3.72	11,000.
12-13-F1	W	7.16				7,596.
12-13-F2	W	25.73				7,595.
1-25-1A	Ch	0.08	59.33	35.61	5.06	

<u>Sample I.D.</u>	<u>Type</u> Ch-oak charcoal W-oak wood	<u>% Moisture</u> (wet basis)	<u>% Carbon</u>	<u>% Volatiles</u>	<u>% Ash</u>	<u>Heat of Combustion</u> BTU/lb (dry basis)
1-25-3	Ch	1.37	62.17	34.78	3.05	10,500.
1-25-F1	W	13.78				7,698.
1-30-1	Ch	1.80	51.38	46.66	1.96	9,949.
1-30-F1	W	14.25				7,570.
1-30-F2	W	27.45				7,777.
2-6-1	Ch	2.28	67.20	28.06	4.74	11,120.
2-6-2	Ch	2.31	72.50	21.88	5.62	11,070.
2-6-3	Ch	2.47	79.98	13.80	6.22	12,260.
2-6-4	Ch	2.66	75.75	15.21	9.04	11,405.
2-6-5	Ch	3.55	70.30	23.04	6.65	11,090.
2-6-6	Ch	2.65	71.42	24.39	4.19	11,500.
2-6-F1	W	24.31				7,555.
2-13-F1	W	24.40				8,431.
2-15-1	Ch	6.24				10,060.
2-15-2	Ch	3.37	56.71	36.99	6.30	10,396.
2-15-3A	Gin Waste Char	32.09				
2-15-3B		55.33	46.08	33.02	20.91	9,283.
2-15-4		28.69	52.69	26.35	20.96	9,353.
2-15-F1	W	30.34				8,790.
2-15-F2	W	9.14				
2-20-1	Ch	5.52	56.74	35.35	7.91	10,230.
2-20-2	Ch	5.62	59.45	34.06	6.50	10,330.
2-20-3	Ch	4.23	65.78	26.16	8.06	11,610.

<u>Sample I.D.</u>	<u>Type</u> Ch-oak charcoal W-oak wood	<u>% Moisture</u> (wet basis)	<u>% Carbon</u>	<u>% Volatiles</u>	<u>% Ash</u>	<u>Heat of Combustion</u> BTU/lb (dry basis)
2-20-4	Ch	3.15				11,390.
2-20-5	Ch	1.30	66.84	27.32	5.83	11,920.
2-20-6	Ch	2.92	70.98	19.21	9.81	12,650.
2-20-F1	W	14.35				7,564.
2-22-1	Ch	1.85	72.00	16.05	11.95	12,060.
2-22-2	Ch	1.53	73.32	18.10	8.57	11,100.
2-22-3	Ch	1.74	67.24	21.77	10.99	12,060.
2-22-4	Ch	2.66	61.70	27.00	11.29	11,310.
2-22-5	Ch	1.56	68.07	20.53	11.40	12,330.
2-22-6B	Ch	1.96				11,520.
2-22-8	Ch	4.00				11,030.
2-22-9	Ch	3.63				11,930.
2-22-10	Ch	2.79				12,270.
2-22-11	Ch	1.75	72.44	21.34	6.21	11,470.
2-22-F1	W	7.65				8,237.
2-22-F2	W	14.26				8,206.
3-13-1	Ch	2.00	59.43	32.18	8.38	11,050.
3-13-2	Ch	1.16	68.48	23.81	7.72	10,740.
3-13-3	Ch	1.79	68.92	23.25	7.83	12,300.
3-13-5	Ch	2.11				12,140.
3-13-6	Ch	2.09				12,230.
3-13-7	Ch	1.46	67.18	21.65	11.17	11,180.
3-13-F1	Macadamia Nuts	18.97				8,327.
3-15-1	Ch	0.89	71.69	21.06	7.25	11,500.

<u>Sample I.D.</u>	<u>Type</u> Ch-oak charcoal W-oak wood	<u>% Moisture</u> (wet basis)	<u>% Carbon</u>	<u>% Volatiles</u>	<u>% Ash</u>	<u>Heat of Combustion</u> BTU/lb (dry basis)
3-15-2	Ch	1.27	71.02	22.21	6.76	12,730.
3-15-3	Ch	1.47	68.35	22.59	9.06	11,250.
3-15-4	Rice Hull Char	2.03				
3-15-5		2.86	27.24	18.11	54.66	5,222.
3-15-6		2.53	34.18	10.72	55.10	5,077.
3-27-1	Ch	3.88	49.60	31.88	18.52	8,828.
3-27-2	Ch	5.77	61.01	26.59	12.40	9,940.
3-27-3	Ch	5.08	59.64	25.74	14.62	9,340.
3-27-4	Ch	2.50	64.83	28.49	6.68	10,870.
3-27-5	Ch	3.67				12,370.
3-27-F1	W	12.90				7,621.
3-27-F2	W	22.32				8,289.
4-12-1	Ch	1.26				11,920.
4-12-6	Rice Hull Char	1.94	28.80	18.35	52.86	
4-12-7		1.60	32.82	13.04	54.13	
4-12-F1	Rice Hulls	15.86				7,916.
SPEC 1	Rice Hulls	7.37			25.93	
SPEC 2	Rice Hull Char		28.27	24.88	46.85	

APPENDIX A

DIMENSIONAL ANALYSIS

Assume that the production of char product is a function of the following variables:

$$\dot{m}_C = \Phi \{ \dot{m}_F, \dot{m}_A, R, r, N, H, D, z, P, g_C \} \quad (A-1)$$

and that this function is represented by:

$$\dot{m}_C = \Psi \{ (\dot{m}_F)^a (\dot{m}_A)^b (R)^c (r)^d (N)^e (H)^f (D)^g (z)^h (P)^i (g_C)^j \} \quad (A-2)$$

In terms of the dimensions of the respective quantities, (A-2) is written as:

$$\frac{M}{t} = \Psi \left\{ \left(\frac{M}{t} \right)^a \left(\frac{M}{t} \right)^b \left(\frac{M}{tL} \right)^c (L)^d \left(\frac{i}{t} \right)^e (L)^f (L)^g (L)^h \left(\frac{LF}{t} \right)^i \left(\frac{LM}{Ft^2} \right)^j \right\} = \frac{\text{mass}}{\text{unit time}} \quad (A-3)$$

Equating the exponents of M:

$$1 = a + b + c + j \quad (A-4)$$

Equating the exponents of t:

$$-1 = -a - b - c - e - i - 2j \quad (A-5)$$

Equating the exponents of L:

$$0 = -3c + d + f + g + i + j + h \quad (A-6)$$

Equating the exponents of F:

$$0 = i - j \quad (A-7)$$

Solving equation (A-4) for a, and substituting the resulting expression in equation (A-5) yields:

$$b = 1 - 1 + b + c + j - c - e - 3j \quad (A-8)$$

or simply:

$$e = -2j \quad (A-9)$$

Solving equation (A-6) for h:

$$h = 3c - d - f - g - 2j \quad (A-10)$$

Equation (A-2) can now be written in terms of b, c, d, f, g, and j and like terms collected:

$$\frac{\dot{m}_C}{\dot{m}_F} = \psi \left\{ \left(\frac{\dot{m}_A}{\dot{m}_F} \right)^b \left(\frac{Rz^3}{\dot{m}_F} \right)^c \left(\frac{r}{z} \right)^d \left(\frac{H}{z} \right)^f \left(\frac{D}{z} \right)^g \left(\frac{Pg_C}{\dot{m}_F^N z^2} \right)^j \right\} \quad (A-11)$$

Rearranging,

$$\frac{\dot{m}_C}{\dot{m}_F} = \psi \left\{ \left(\frac{z}{D} \right)^k \left(\frac{H}{D} \right)^l \left(\frac{r}{H} \right)^m \left(\frac{Pg_C}{\dot{m}_F^N D^2} \right)^n \left(\frac{RzD^2}{\dot{m}_A} \right)^\theta \right\} \quad (A-12)$$

NOTE: See SCALE MODEL ROTARY KILN for definition of symbols.

APPENDIX B

SAMPLE COMPUTER PRINTOUT OF EXPERIMENTAL DATA

Nomenclature

Basis: 1 hour

Run # - Refers to specific run for the given calendar date
Speed (RPM) - Kiln rotational speed
Feed (lb) - Moist feed
% H₂O - Moisture content
Wood (lb) - Dry feed
Char (lb) - Char production
Conv (lb) - Conversion, lbs/100 lbs on a dry basis

Air in kiln: K1 - Refers to air inlet location nearest char discharge
K2 - Refers to air inlet location in kiln mid-section
K3 - Refers to air inlet location nearest kiln feed end

Aftb A1 - Refers to air inlet location nearest afterburner inlet
A2 - Refers to air inlet location in afterburner mid-section
A3 - Refers to air inlet location nearest afterburner exit

Other - Refers to air into system from other locations, chiefly from feed pipe.

Stack Gas Orsat - Analysis (Volume fraction) and lbs. of each component

At Stack Conditions: Velocity - Center-line velocity
VBAR - Average velocity across stack cross-section
Reynolds - Stack gas Reynolds Number

Enthalpy Data (BTU)

HIN - Energy of feed stock
HSTACK - Enthalpy of gases passing up the stack
HCHAR - Energy of char
QLOSS - Energy loss from kiln and afterburner surfaces
HCOOL - Energy removed by waterjacket of char conveyor

A - Efficiency Number = lbs char/lb dry feed

B - Damkohler Number = $R_z D^2 / \dot{m}_A$

C - Power Number = $P g_c / \dot{m}_F N^2 D^2$

Z - The Product = $(B)^{0.31} (C)^{0.10}$

Mass In - total mass into system, including feed and air
Mass Out - total mass from system, including char and flue gas
% Diff - difference between mass in and mass out (percentage)

Energy In - total energy into system
Energy Out - total energy from system
% Diff - difference between energy in and energy out (percentage)

DATE 12/ 13/ 78 BASIS ONE HOUR

RUN (#)	SPEED (RPM)	FEED (LB)	ZH2O	WOOD (LB)	CHAR (LB)	CONV (DB)
1	2	45.0	7.2	41.8	1.4	3.5

AIR IN	SCFH AIR	LB AIR	LB O2	LB N2
KILN K1	8.4	37.6	8.7	28.9
K2	0.0	0.0	0.0	0.0
K3	7.8	34.9	8.1	26.8
TOTAL	16.1	72.5	16.8	55.7
AFTB A1	7.0	31.3	7.2	24.0
A2	12.2	54.7	12.7	42.0
A3	0.0	0.0	0.0	0.0
OTHER	58.9	264.8	61.7	203.1
TOTAL	78.0	350.8	81.6	269.2
TOTAL IN	150.5	423.3	98.4	324.8

NOTE: 39 other runs
not included

STACK GAS	ORSAT	LB	AT STACK CONDITIONS:
CO2	0.125	82.5	DENSITY 0.0301 LB/FT3
O2	0.101	48.5	VELOCITY 28. FT/S
CO	0.001	0.4	VBAR 22. FT/S
N2	0.773	324.8	VOLFLOW 15436. FT3/HR
H2O	-----	25.5	MOLWT 29.3
TOTAL	1.000	465.2	REYNOLDS 18781..

ENTHALPY DATA (BTU)

HIN	293738.	A	0.0347
HSTACK	130320.	B	0.4116
HCHAR	16903.	C	93566.
QLOSS	5330.	Z	2.3856
HCOOL	0.		

MASS IN:	468.3	ENERGY IN:	293738.
MASS OUT:	466.7	ENERGY OUT:	152553.
Z DIFF:	-0.3	Z DIFF:	-48.1

APPENDIX C

DATA USED IN THE DETERMINATION OF THE NON-DIMENSIONAL CORRELATION OF FIGURE 5

Run No.	Identification	$\dot{m}_F$	$\dot{m}_A$	N	A	B	C	Z
1	12-11-2	28.1	12.0	8	0.119	5.72	34800	4.89
2	12-11-3	28.1	9.2	8	0.171	10.70	34800	5.94
3	12-11-4	28.1	11.9	14	0.125	6.03	19900	4.70
4	12-13-1	41.8	72.5	2	0.035	0.41	93500	2.39
5	12-13-2	41.8	72.6	8	0.015	0.18	23400	1.60
6	12-13-3	41.8	57.8	8	0.035	0.52	23400	2.23
7	12-13-4	41.8	34.5	8	0.048	1.19	23400	2.89
8	12-13-5	41.8	17.7	8	0.057	2.79	23400	3.76
9	12-13-6	41.8	17.7	8	0.036	1.74	23400	3.25
10	12-13-7	41.8	8.6	8	0.043	4.30	23400	4.30
11	01-25-2	25.9	30.9	2	0.145	2.50	151000	4.38
12	01-25-3	25.9	31.2	8	0.044	0.75	37800	2.62
13	01-25-4	25.9	30.6	13	0.043	0.75	23200	2.50
14	02-06-1	45.4	70.4	8	0.068	0.91	21500	2.63
15	02-06-2	45.4	70.4	2	0.092	1.23	86100	3.32
16	02-06-3	45.4	70.4	13	0.007	0.09	13200	1.25
17	02-06-4	45.4	41.9	13	0.035	0.79	13200	2.40
18	02-06-5	45.4	41.3	8	0.090	2.04	21500	3.38
19	02-06-	45.4	41.3	2	0.104	2.34	86100	4.05
20	02-15-1	20.9	6.1	8	0.144	10.10	46800	6.00
21	02-20-1	21.6	12.9	14	0.106	4.46	21000	4.30
22	02-20-3	51.4	29.1	8	0.146	5.30	19000	4.49
23	02-20-4	51.4	29.1	14	0.066	2.40	10900	3.32
24	02-20-5	51.4	29.1	2	0.146	5.30	76100	5.16
25	02-20-6	51.4	12.5	2	0.130	11.00	76100	6.48
26	02-22-1	77.2	76.2	8	0.079	1.64	12700	3.00
27	02-22-2	51.4	12.5	8	0.086	7.25	19000	4.95
28	02-22-3	51.4	11.9	14	0.049	4.34	10900	3.99
29	02-22-5	38.6	8.4	8	0.136	12.90	25300	6.09
30	02-22-6	38.6	7.8	2	0.130	13.10	101000	7.04
31	02-22-7	38.6	7.8	2	0.130	13.10	101000	7.04
32	02-22-8	38.6	7.6	14	0.028	2.99	14500	3.66
33	02-22-11	77.2	53.7	8	0.097	2.87	12700	3.57
34	02-22-12	77.2	42.1	14	0.122	4.59	7240	3.90
35	03-15-1	78.9	35.0	8	0.076	3.53	12400	3.79
36	03-15-2	78.9	35.0	2	0.076	3.53	49500	4.36
37	03-15-3	78.9	35.0	14	0.057	2.65	7080	3.28
38	03-27-4	46.6	22.4	2	0.113	4.82	83900	5.06
39	03-27-5	46.6	14.3	2	0.054	3.59	83900	4.62
40	04-12-1	50.5	19.3	4	0.119	6.38	38700	5.11

APPENDIX D
ANALYSIS OF VESSEL MECHANICAL PROBLEMS

The vessel can be thought to consist of its shell, refractory, riding rings or tires, trunnions and air seals.

The shell in use now is half of a railroad tank car. A portion of the unused half is still on site. It was measured with the results shown in Figure D-1. The shell from the tank car is constructed in three sections as shown. The sections are riveted together with a double row of 1" diameter rivets. The overall length of the shell is 16 feet with a nominal outside diameter of 88 inches.

The shell is presently lined with MC-22 castable refractory. This is an A. P. Green Company product weighing 128 lb/ft^3 with a thermal conductivity of $4.67 \text{ Btu/ft}^2/\text{hr}/^\circ\text{F/in.}$ thickness at 1200°F . At the onset of the project the best information available was that the lining was 4 inches thick. Later measurements showed that the thickness varied from 3 to 7 inches. In addition the inner surface of the lining is not concentric with the longitudinal axis of rotation. The present condition of the refractory is poor, stemming partly from improper installation techniques, improper refractory selection, and thermal shock stresses resulting from frequent starting and stopping of the convertor's operation. The char output conveyor has been jammed and broken 15 times during this six-month period due to ingestion of larger refractory pieces that have fallen from the lining. This has resulted in a total of 81 hours of downtime. Smaller refractory pieces are continually being conveyed out with the char stream as the inner surface of the lining erodes. Screening of the char stream as it falls from its conveyor yields approximately one handful of small lining particles per hour. Attempts at patching the lining have been made since the inception of the project. Plastic ramming mixes have been tried as well as a patching mix.

View A-A
Rivet Spacing

FIGURE D-1. RIVET SPACING

Neither was successful, probably due to the poor refractory base to which they had to be attached. Breaking out enough of the old refractory to provide an adequate patch base would involve almost as much work as simply starting over and replacing the lining.

The vessel (shell and lining) is mounted inside 1" x 8" riding rings as shown in Figure D-2. It is not known whether the riding rings were round or whether the shell was mounted concentrically within the rings when the convertor was constructed. This would be difficult to do since the shell itself is constructed of three overlapping plates as shown in Figure D-1. There is one ring at either end of the vessel. The center line of each of these is approximately 30" from its respective end. The riding rings are attached to the vessel by means of 8" wide spokes and a 1" x 8" circumferential reinforcing band as shown schematically. The reinforcing band is welded to the vessel. The spokes are welded to the reinforcing band and to the riding ring. This results in the riding ring being attached rigidly to the vessel.

The shell and reinforcing band are subjected to thermal and mechanical stresses. The thermal stresses arise in two ways. First there are thermal stresses due to the temperature gradient through the thickness of the shell. Secondly, as the shell heats it naturally tries to expand. This expansion is constrained by the riding ring since it is rigidly attached to the shell. It is thought that this is the dominant of the two thermal effects. The mechanical stresses arise from the shell having to support its own weight and the weight of the refractory. This gives rise to small beam type stresses along the length of the shell with higher localized stresses under the riding rings where the load is transferred to the rings.

A computer program has been written to determine these beam stresses for various locations of the support along the length of the kiln. Theoretical

f = friction force W = total convertor weight

$$N_1 = \frac{W/2 \sin \theta - f \cos 2\theta}{\sin 2\theta}$$

$$N_2 = \frac{W/2 \sin \theta + f}{\sin 2\theta}$$

FIGURE D-2. VESSEL CONSTRUCTION

analysis shown that the supports or rings should be located $1/5$ of the length of the vessel from its ends if the cylindrical portion of the vessel is open ended and has its ends closed by separately supported hoods or end closures. This is the usual case for most rotating kilns. The unit at Jonesboro has its ends supported directly by the cylindrical portion of the shell. The theoretical analysis becomes more difficult in that case so the computer program was written. The moment of inertia of the shell is large because of its large diameter. Thus the beam stresses are small in any case. The shell is showing signs of failure at its juncture with the circumferential reinforcing band. The worst areas of refractory failure on the interior are under the reinforcing band. A partial solution to this problem would be to make the band wider, thus providing more load carrying surface.

The riding rings are also subjected to thermal and mechanical stresses. The predominant thermal stress occurs because of expansion of the vessel being constrained by the rings. This produces tension stresses in the circumferential direction in the outer fibers of the ring. The predominant mechanical stresses are due to the rings supporting the weight of the vessel and transferring it to the trunnions as shown in Figure D-2. There are also localized contact mechanical stresses that arise at the innerface between trunnion and ring.

Both the thermal and mechanical stresses which the shell and riding rings are subjected to are complex, statically indeterminate problems whose solution is not completely in hand yet. The mechanical stresses are fluctuating in nature so the fatigue failure problem must also be considered. A simplified analysis of the mechanical stresses in the riding ring can be performed, however.

Rotation of the vessel is accomplished by means of a friction drive. One trunnion at the heavy or char end of the kiln is driven by a 7.5 hp electric motor through a wormgear reduction unit and a chain and sprocket arrangement. The

vessel rotation rate is 3-4 rpm. The outer ring diameter is 96" while the trunnion diameter is 13-5/8". Thus the trunnion turns at 21-28 rpm.

Application of the equations of equilibrium from statics yields (from Figure D-2) the following relations for the normal forces at the trunnions:

$$N_1 = \frac{W/2 \sin \theta - f \cos 2\theta}{\sin 2\theta}$$

$$N_2 = \frac{W/2 \sin \theta + f}{\sin 2\theta}$$

in which f is the friction force, W is the total weight supported by four trunnions, and 2θ is the included angle between the trunnions. For the unit at Jonesboro the included angle is approximately 79° . The normal practice is for this angle to be closer to 60° . The slant of the vessel from end to end ($\approx 1^\circ$) was ignored in formulating these expressions and the lining was assumed to be of uniform thickness.

From the above it can be observed that the normal force can be reduced if the included angle is made smaller. Ignoring the friction force for the moment, the normal forces become equal and are equal to

$$N = 0.324W \quad \text{for } 2\theta = 79^\circ$$

$$N = 0.288W \quad \text{for } 2\theta = 60^\circ.$$

Assuming 4" of refractory lining for the vessel and its ends gives a weight of $W = 29000$ lb. Thus, with the kiln not rotating, each trunnion supports $N = (0.324)(29000) = 9396$ lb.

When the vessel is being rotated the friction force is unknown unless slipping impends or occurs between trunnion and ring. In that case the friction force can be taken to be equal to the coefficient of friction between the surfaces times the normal force. Even without knowing the friction force per se, it is evident from the above relations that the trunnion opposite the driven trunnion (N_2) is subjected to largest normal force ($N_2 > N_1$). This has been

confirmed at the Jonesboro operation. The trunnion shaft opposite the driven trunnion has broken twice since the start of the project.

The friction force f could be found by measuring the torque input to the driven trunnion. This has not been done to date but even without this data it is interesting to examine the loads carried by the trunnions. If the friction force is taken to be some fraction of the normal force the following loadings occur:

	<u>$2\theta = 79^0$</u>			<u>$2\theta = 60^0$</u>		
$\frac{f}{N_1}$	N_1	N_2	R	N_1	N_2	R
0	0.324 W	0.324 W	0.324 W	0.288 W	0.288 W	0.288 W
0.1	0.318 W	0.357 W	0.32 W	0.273 W	0.321 W	0.275 W
0.3	0.306 W	0.418 W	0.319 W	0.246 W	0.374 W	0.257 W
0.5	0.296 W	0.492 W	0.331 W	0.224 W	0.418 W	0.25 W
0.7	0.285 W	0.525 W	0.348 W	0.21 W	0.455 W	0.251 W

R is the resultant force acting on the driven trunnion $R = (f^2 + N_1^2)^{1/2}$.

From this table it can be seen that N_2 is always greater than N_1 and that the load carried by the trunnion opposite the driven one (N_2) increases with increasing friction.

Coefficients of friction (f/N_1) have been reported as high as 0.7 and as low as 0.15 for metal on metal. (CRC Handbook of Tables for Applied Engineering Science, 2nd edition.) Since no slipping occurs at Jonesboro, the ratio of f/N_1 must be greater than 0.15. The value of 0.3 will be chosen for use in the material to follow. With this choice:

$$N_1 = 0.306(29000) = 8874 \text{ lb.}$$

$$N_2 = 0.418(29000) = 12122 \text{ lb.}$$

$$R = 9251 \text{ lb.}$$

Due to the ambiguity in defining f/N_1 and the thickness of the refractory lining these loadings are subject to question but should be representative.

An approximation of the load carrying capacity of the riding ring and the mechanical stresses it is subjected to can be found by examining a straight beam with fixed ends. This beam will be taken to model a portion of the ring between two spokes.

It is taken to be $12''$ long. This was the average circumferential spoke spacing at the start of the project. As breakages have occurred spokes have been welded in at various other locations. The load can be thought of as moving across the beam to simulate the ring moving over the trunnion.

The problem above is statically indeterminate but it can be shown quickly by application of Castigliano's theorem that the maximum bending moment in the beam occurs when the load is one-third the beam length from either end. The maximum moment occurs at the end and is $M_L = 0.148 PL$. When the load is one-third the beam length from the right hand end the maximum moment is $M_R = 0.148 PL$. Thus the maximum bending stress occurs over the spokes (at the reactions in the model) and is equal to

$$\sigma = \frac{Mc}{I} = \frac{(0.148 PL)(0.5)}{2/3} = 16000 \text{ psi.}$$

It is a tensile circumferential stress at the outside of the ring.

The stress just calculated is a fluctuating stress. It rises to this value as the ring passes over the trunnion opposite the drive trunnion. It then goes toward zero and rises again to approximately two-thirds this value as the ring passes over the drive trunnion. Thus fatigue must be considered.

The riding rings are made of a mild steel. Choosing a typical ultimate strength of 60,000 psi and making some approximations as to temperature effects, size effects, and stress concentration yields an endurance limit of about 17,000 psi for a rotating beam specimen. (Mechanical Engineering Design, 2nd edition, 1972, McGraw Hill, J. E. Shigley.) Constructing a modified Goodman diagram for analysis of fatigue failure due to fluctuating stresses (non-reversed) for this material shows that stress calculated above should be in the neighborhood of 25,000 psi for fatigue failure. Fatigue failure is defined here to mean finite life. Further work with the Goodman diagram yields the result that a thermal stress of 24,000 psi superimposed on the fluctuating stress calculated above will produce fatigue failure. It is doubtful that the thermal stresses are of this magnitude, although definitely not negligible.

Dynamic loading has not yet been considered in this approximate stress analysis. At the start of the project tire breakage and repair had occurred. This repair resulted in the riding ring having rough spots in it as well as becoming out of round. As the ring moves over the trunnion shock loads are applied to ring and trunnion due to these discontinuities of repair. The runout or out of roundness also produces dynamic loads. With this in mind the approximate stress calculated above (16,000 psi) should be multiplied by the factor of approximately two for an estimate of the true stress state under sudden loading. (Formulas for Stress and Strain, McGraw Hill, 2nd edition, 1943, R. J. Roark). Thus the mechanical stresses are in the neighborhood of 32,000 psi. Superimposed on this stress are the thermal stresses, giving a resultant

stress that is greater than the projected stress of 25,000 psi that will produce fatigue failure. This situation almost guarantees riding ring failure. Indeed frequent failures have occurred resulting in 156 hours of down time since the start of the project. On site personnel have tried to smooth the rings with a hand held electric grinder with some effect but breakages are still common. The out of roundness or runout of the present ring also presents extreme problems in designing effective air seals as will be discussed later. The solution to this riding ring breakage problem would be to replace or revamp the rings with ones with the following characteristics:

- (1) Rings that are not welded to the vessel or free floating. This is the common practice with most commercial kilns and minimizes the thermal stress problem for the rings. Of course, it gives rise to mounting problems.
- (2) Rings that are thicker to ensure low stress values. Three inches thick has been tentatively chosen as the minimum for this unit.
- (3) Rings that are smooth and round. The common commercial practice is to use forged rings that have been machined.

Another attack on the riding ring thermal stress problem is to minimize heat losses from the convertor itself. The cooler the shell and rings the less thermal expansion.

A synopsis of the stress analysis of the trunnion shaft opposite the drive trunnion is given in Figure D-3. The largest stress occurs at the stress concentration created by the change in diameter of the shaft. This stress is higher than the projected endurance limit for the shaft material. Thus fatigue failure is predicted. This shaft has failed twice at this stress concentration since the inception of the project resulting in 131 hours of downtime. It is interesting to note that this shaft went through about $3.2 (10^6)$ cycles before

The trunnion shaft is made of an unknown cold rolled material. Pick a typical ultimate strength in tension of 100,000 psi.

$$S_e' = \text{rotating beam specimen endurance limit} = 100,000(.5) = 50,000 \text{ psi}$$

$$S_e = k_a k_b k_c k_d k_e S_e' = \text{endurance limit of actual specimen}$$

$$k_a = \text{surface factor multiplier} = 0.75$$

$$k_b = \text{size factor} = 0.75$$

$$k_c = \text{reliability factor} = 0.75 \text{ for } 99\% \text{ reliability}$$

$$k_d = \text{temperature factor} = 0.94 \text{ for } 200^\circ\text{F}$$

$$k_e = \text{stress concentration multiplier} = 0.637 \text{ for section A above}$$

$$S_e = 0.75(.75)(.75)(.94)(.637)(50,000) = 12631 \text{ psi}$$

The maximum bending stress at section A occurs at outer fiber

$$\sigma_A = \frac{32M}{\pi d^3} = \frac{32(6000)(2.5)}{\pi(2\frac{11}{16})^3} = 7871 \text{ psi}$$

$$\text{Due to shock loading } \sigma_A = 2(7871) = 15742 \text{ psi}$$

$\sigma_A = 15742$ is greater than $S_e = 12631$ psi so one can expect fatigue failure or finite life.

FIGURE D-3. TRUNNION SHAFT

failure. This data is from a daily log of operations kept by the on site personnel since the start of the project. Data from many rotating beam specimens of this sort show that if a material will last from 1 (10^6) to 10 (10^6) cycles it will have infinite life or will not fail from fatigue. The calculated stress level and projected endurance limit from Figure D-3 are not very different (15742 psi and 12031 psi respectively). This means that the shaft is on the borderline of having an infinite life, as is verified by the actual life data given above. A very important point to be derived from this analysis is that failure would not be predicted if the shock loading were absent. There would, in fact, be a predicted safety factor of $\frac{12631}{7871} = 1.6$ without shock.

The localized contact stresses between the riding ring and trunnion have been calculated. The interface pressure at the trunnion opposite the drive trunnion was 36000 psi. Values of the surface endurance limit for steels can be obtained from the equation:

$$S_e = 400 H_B - 10,000 \text{ psi}$$

in which H_B is the Brinell hardness number. If the two materials have different hardnesses the lesser value is generally used. Solving for H_B using the calculated interface pressure of 36000 psi for S_e gives $H_B = 115$ as the desired minimum hardness for infinite life with no safety factor. Both the rings and trunnions are mild steels. Their exact composition and heat treatment are unknown. The range of H_B for mild steels is from 95 to about 200. The conclusion then is that the desired value of 115 has been exceeded since little surface fatigue has been observed at Jonesboro.

The convertor shell and tires do not rotate about a common centerline. In other words the shell wobbles as it turns, as previously mentioned. This wobble or runout has been quantified by measuring the radial distance from the shell to a fixed point at eight evenly spaced locations around the outside of the shell.

These measurements were made at the edge of the riding rings on both ends of the convertor. The radial distance from a fixed point to each riding ring was also measured at the same time. These measurements are shown in the tables that follow. The difference between succeeding measurements is the amount that the shell or ring moves radially between successive measurement points. These differences are shown in the table under the column label "Runout." The longitudinal or fore and aft movement of the riding rings during one revolution was also measured and is shown in the table. These measurements were of the distance to the edge of the riding ring at the eight locations mentioned above. They reflect the longitudinal movement of the vessel itself as well as any misalignment of each ring and any small variation in ring width. A plot of the runout is shown for each end of the convertor in Figures D-4 and D-5.

If the shell were located concentrically within the ring the shell runout and riding ring runout should be the same. From the Figures it can be seen that they at least follow the same general trend except in a few locations around the circumference of the vessel. Thus the primary problem seems to lie with the rings themselves being out of round with the location of the vessel within them being a lesser contributor to the problem. As is noted on the Figures, the total shell runout is $1\frac{7}{8}$ " and 2" at the char output end and stack end respectively.

The runout described immediately above leads to almost insurmountable problems in instrumentation of the convertor. Because of it the present air seals are useless, and the design of effective ones is almost impossible. This means that an unknown amount of air is entering the vessel and afterburner at the air seal locations. Preliminary calculations indicate that this air leakage is appreciable. Because of it the mass and energy balances necessary to reach the project objective cannot be performed. Thus the amount of air leakage must

TABLE D-I. RADIAL RUNOUT MEASUREMENTS

SHELL		STACK END		RIDING RING	
Measurement	Runout			Measurement	Runout
8 7/8"	-1 1/8"			4 1/8"	-5/8"
7 3/4	0			3 1/2	1/2
7 3/4	3/8			4	-1/4
8 1/8	-3/8			3 3/4	-1/8
7 3/4	1/4			3 5/8	1/8
8	3/8			3 3/4	7/16
8 3/8	-3/8			4 3/16	-11/16
8	7/8			3 1/2	5/8

SHELL		CHAR. END		RIDING RING	
Measurement	Runout			Measurement	Runout
9 7/8"	-5/8"			5 1/2"	-1/2"
9 1/4	1 1/8			5	1 1/8
10 3/8	-3/4			6 1/4	-1 1/8
9 5/8	3/8			5 1/8	1/2
10	-1/8			5 5/8	-3/8
9 7/8	0			5 1/2	0
9 7/8	-5/8			5 1/4	-1/8
9 1/4	5/8			5 1/8	3/8

TABLE D-II. LONGITUDINAL RUNOUT MEASUREMENTS

STACK END		CHAR. END	
Measurement	Runout	Measurement	Runout
5/8"	-1/8"	3/4"	-1/8"
1/2	-3/8	5/8	-5/8
1/8	1/8	0	1/4
1/4	0	1/4	1/8
1/4	1/4	3/8	0
1/2	-1/4	3/8	0
1/4	1/8	3/8	3/8
3/8	1/4	3/4	0

FIGURE D-4. CHAR END RUNOUT

FIGURE D-5. STACK END RUNOUT

be measured or the leaks must be stopped. The former would be most difficult, expensive, and time consuming if performed to the needed accuracy. The latter route of stopping the leaks is the most desirable. It entails the design and construction of effective air seals. As previously discussed, this is impossible unless the convertor runout is reduced to a manageable level. This in turn means that something must be done about the riding rings and their out-of-round condition.

Proper replacement or revamping of the riding rings and shell could then lead to the following:

- (1) Design and construction of effective air seals so that useful mass and energy balances could be performed.
- (2) Elimination of trunnion shaft and riding ring failures.
- (3) Minimization of convertor shell failure due to mechanical shock loads.
- (4) Minimization of refractory failure due to mechanical shock loads.

The elimination of so many failures would also have a desirable effect not mentioned as yet. It would give the on site personnel enough time away from repair chores to be trained in the use and operation of the planned instrumentation system. Because of the time spent on emergency repairs this important task has been sorely neglected to date.

The simplest route to solve the runout problem discussed above would be to order a new convertor shell and rings from an established rotary kiln or dryer manufacturer such as Combustion Engineering or Allis Chalmers. The riding rings would be forged and machined to be round and smooth. The mounting for the rings around the shell would be machined concentric with the shell so that the ring-shell combination would not wobble more than a few thousandths of an inch per revolution. Because of budgetary limitations this approach cannot be followed.

It is proposed that a shell be rolled from sheet steel to form as true a cylinder as possible instead of the shape of the railroad tank car of Figure D-1. With this basic cylindrical shape from which to work, riding rings could then be fit so as to reduce the total runout problem to manageable proportions. The riding rings would either be forged or rolled from at least 2" thick stock; depending upon budgetary constraints. It is felt that this combination could produce runout of not more than $\pm 1/8$ inch.

This is still a considerable amount of wobble as compared with commercial units but would be small enough to allow for the design of adequate air seals and elimination of failure from dynamic loads. In other words, this approach to the runout problem would be just sufficient for accomplishment of the project's objectives while remaining within budgetary constraints.

The thermal stress problem will be attacked by allowing the riding ring to float, and by installation of a refractory lining that causes the shell to operate at a lower temperature than at present. This will also eliminate the problem of the deteriorated refractory lining. The replacement lining will be either a thicker heavy castable than presently in use or firebrick. A composite or layered system of insulating castable and heavy castable is also being considered. Either approach will be backed with a $1/4$ " (uncompressed) layer of insulating paper to cut down heat losses. The choice of lining will be the best compromise between weight, overall thermal conductivity, and cost. An additional benefit that will result from this approach is that thermocouple instrumentation interior to the rotating vessel can be positioned with more certainty than at present. In other words the distance from the rotating vessel centerline to the refractory wall will not be varying drastically as it does now.

ASSEMBLY DRAWINGS OF SEALS

NOTE: See parts list for dimensions of each part

Rotating Kiln

Stationary Afterburner

Scale: 1" = 2"

Afterburner
54" O.D.

Kiln Nose -- 59" I.D.

FIGURE E-1. SEAL ASSEMBLY DETAILS - FEED END

FIGURE E-1. SEAL ASSEMBLY DETAILS - FEED END

TABLE E-1. PARTS LIST - FEED END.

<u>Part Ident.</u>	<u>Dimensions</u>	<u>Notes</u>
A	67-3/4" O.D. x 59-3/4" I.D. x 1/4"	Ring welded to kiln
B	18, 1/2" Dia. x 4 1/4" long studs	Threaded and with adjusting nuts
C	18, 1" I.D. x 4 1/2" springs	Springs ride over "B" and "D"
D	18, 3.8" Sch 10 x 2 1/2" pipe sections	Welded to "F"
E	Ring, 64 1/2" O.D. x 59-3/4" I.D. x 1/4"	Not attached to kiln; free to move
F	Ring, 67-3/4" O.D. x 59-3/4" I.D. x 3/4"	Not attached to kiln Machined surface to contact seal, "G"
G	Seal Material 67-3/4" O.D. x 61-3/4" I.D. x 3/4"	Seal attached to "H" Moves against "F", radial seal
H	67-3/4" O.D. x 61-3/4" I.D. x 1/4"	Ring welded to "L"
I	Flame Ring 66 1/4" O.D. x 60 1/4" I.D. x 1/4"	Not welded to kiln; free to move
J	Flame Ring 58 1/2" O.D. x 54 1/2" I.D. x 1/4"	Not welded to Kiln; free to move
K	Asbestos Rope Packing	Longitudinal seal
L	Angle Flange 67-3/4" O.D. x 54" I.D. x 1/4" 1" Flange	Welded or clamped to afterburner shell

FIGURE E-2. SEAL ASSEMBLY DETAILS - DISCHARGE END

TABLE E-II. PARTS LIST - DISCHARGE END

<u>Part Ident.</u>	<u>Dimensions</u>	<u>Notes</u>
A	44-3/4" O.D. x 36-3/4" I.D. x 1/4"	Ring welded to kiln
B	12, 1/2" Dia. x 4 1/4" long studs	Threaded and with adjusting nuts
C	12, 1" I.D. x 4 1/2" springs	Springs ride over "B" and "D"
D	12, 3/8" Sch 10 x 2 1/2" pipe sections	Welded to "F"
E	Ring, 41 1/4" O.D. x 36-3/4" I.D. x 1/4"	Not attached to kiln; free to move
F	Ring, 44-3/4" O.D. x 36-3/4" I.D. x 3/4"	Not attached to kiln Machined surface to contact seal "G"
G	Seal Material 44-3/4" O.D. x 38-3/4" I.D. x 3/4"	Seal attached to "H" Moves against "F", radial seal
H	44-3/4" O.D. x 38-3/4" I.D. x 1/4"	Ring welded to "L"
I	Flame Ring 43 1/4" O.D. x 37 1/4" x 1/4"	Not welded to kiln; free to move
J	Asbestos Rope Packing	Longitudinal seal
L	Angle Flange 44-3/4" O.D. x 29-3/4" I.D. x 1/4" 1" flange	Welded to air inlet and char outlet pipe

APPENDIX F

DETAILED BREAKDOWN OF EXPENDITURES AT JONESBORO

TABLE F-I. NON-INSTRUMENTATION MATERIALS AND SUPPLIES BOUGHT FOR USE AT A & P COOP COMPANY

31 August 1979

Item	P. O. Date	Approximate Delivery Date	Cost
75 lb. of Babcock and Wilcox Ceramic Fiber Paper 80 mil 3-25# rolls.	6 Nov 1978	December 1978	\$ 448.50
7' O.D. x 16' long rotating kiln from Trumbo Welding.	2 Oct 1978		17,620.00
2625# Morcolite insulating castable (2450°F) and 89 Type 304 SS anchors, AR-732-4 for afterburner from Christy Firebrick.	17 Nov 1978	December 1978	591.59
24000# Morcicast HSEC castable and 400 Type 304 SS anchors, AR-732-4 for lining kiln from Christy Firebrick.	31 Aug 1978	September 1978	3,152.80
Afterburner shell assembly from Venus Corporation.	1 Nov 1978	December 1978	488.00
140 feet of 1½" x 1½" x 3/16" angle iron for building smokestack ladder.	27 Sept 1978	September 1978	55.19
36' high by 48" O.D. by 43" I.D. insulating firebrick lined smokestack from Environmental Enterprises.		July 1978	8,675.00
One 18' long by 14" diameter screw conveyor with 3" hardened steel couplings and 3/16" thick carbon steel flanged U trough to charge raw material bucket elevator from Hollis. Link Belt 14H614.	22 Feb 1978	June 1978	877.20
One shaft mounted conveyor drive for above. Link Belt 203D15 Type C drive. From Hollis.	22 Feb 1978	June 1978	569.50
One 16' long by 12" diameter screw feeder with 1/2 pitch right hand section and 1/2 pitch right hand section with 3" hardened steel couplings. Link Belt 12H614 screw.	22 Feb 1978	June 1978	1,590.00

Item	P. O. Date	Approximate Delivery Date	Cost
One 19' long by 12" diameter screw conveyor from screw feeder to inclined conveyor. 3" hardened steel couplings and 3/16" carbon steel U trough.	22 Feb 1978	June 1978	1,279.80
One shaft mounted conveyor drive with 1.5 hp TEFC electric motor for conveyor immediately above. Link Belt 115 D24 Type C drive.	22 Feb 1978	June 1978	555.00
One 24' long by 12" diameter screw conveyor. This is the inclined screw to vessel.	22 Feb 1978	June 1978	974.70
One Link Belt 203D24 Type C drive for the conveyor immediately above.	22 Feb 1978	June 1978	577.40
One water jacketed charcoal screw conveyor from vessel. 30' long with 25' of this length being water jacketed. 9" diameter screw with 3/8" rod welded to the leading edge of all flights. Clearance between flights and troughs less than 1/4". 1/4" thick carbon steel trough.	23 Feb 1978	May 1978	3,672.00
One Link Belt 203D24 Type C drive complete with 1 hp TEFC electric motor.	23 Feb 1978	May 1978	695.00
Bucket elevator for char. 12" x 35" x 22' with 10 gauge boot and 12 gauge head. Complete with 1 hp motor and drive. Bucket speed approximately 120 fpm.	23 Feb 1978	May 1978	3,150.00
4 yards of 1/8" thick asbestos cloth for making seals.	27 Mar 1978	April 7, 1978	92.53
One 8' x 12' prefabricated building with aluminum siding and roof. Four foot wide door.	30 Jun 1978	Feb. 28, 1978	485.20
One Lovejoy variable speed pulley from Jonesboro Bearing.	Dec. 1977	Dec. 13, 1977	134.11

Item	P. O. Date	Approximate Delivery Date	Cost
7 pieces WRP-X-AQ Wet Felt 2300°F ceramic fiber insulation. Each piece 36" x 48" x ½".	23 Feb 1978	Mar. 11, 1978	219.52
One 25# bag of Fiberfrax insulation for packing around charcoal scoop bolts.	11 Jan 1978	Jan. 19, 1978	41.75
7 pieces WRP-X-AQ Wet Felt 2300°F ceramic fiber insulation. Each piece 36" x 48" x ½".	20 Jan 1978	Feb. 1, 1978	219.52
7 pieces WRP-X-AQ Wet Felt 2300°F ceramic fiber insulation. Each piece 36" x 48" x ½".	6 Jan 1978	Jan. 10, 1978	219.52
10 pieces WRP-X-AQ Wet Felt 2300°F ceramic fiber insulation. Each piece 24" x 36" x ½".	29 Dec 1977	Jan. 27, 1978	159.60
10 pieces WRP-X-AQ Wet Felt 2300°F ceramic fiber insulation. Each piece 24" x 36" x ½".	15 Dec 1977	Dec. 27, 1977	159.60
Drop chute, air pipes for afterburner, and part of partial oxidation air pipe.	30 April 1979	June, 1979	<u>476.00</u>
		PROJECT MONIES	<u><u>\$47,179.03</u></u>

Item	P. O. Date	Approximate Delivery Date	Cost
Surplus gear-motors with approximate listing as below			
2 hp, 43 rpm		Sept. 1978	
5 hp, 38 rpm	Not	Sept. 1978	Estimated
2 hp, 36 rpm	Applicable	Sept. 1978	Total Value of
5 hp, 38 rpm		Aug. 1978	\$2,000.00
½ hp, 78 rpm		Sept. 1978	
14 surplus roller conveyors. Each is 3' wide by 14' long.	Not Applicable	Sept. 1978	Estimated Value of \$1,200.00
Approximately 170 ft ² of Fiberfrax 970-J insulating paper bought for use at University with this much left over.	Not Applicable	June, 1978	\$ 85.00
Approximately 40 gallons of sodium silicate bought for use at University with this much left over.	Not Applicable	Aug. 1978	\$ 55.00
One large (36") micrometer caliper. Government surplus No. MTPM 66651.	Not Applicable	Dec. 13, 1977	Estimated Value of \$ 75.00
	Government Surplus and University Contributions		\$3,415.00
	Grand Total		<u>\$50,594.03</u>

TABLE F-II. INSTRUMENTATION MATERIALS AND SUPPLIES BOUGHT FOR USE AT A & P COOP COMPANY

31 August 1979

Item	P. O. Date.	Approximate Delivery Date	Cost
Two Modutec 400-8J12 Thermocouples. Standard style protected head, grounded junction, corrosion resistant stainless steel tube. 12" long, 14 gauge iron constantan for measuring temperature of cooled char out.	7 Mar. 1978	May, 1978	\$ 95.22
Same as above except two 400-8K12. Chromel-alumel to measure temperature of hot char out.	7 Mar. 1978	May, 1978	95.22
Four Modutec 1600-J1.5 iron constantan thermocouples for application to pipes. 5/8"-1 1/2" diameter clamp. For measuring cooling water temperature.	7 Mar. 1978	May, 1978	57.96
Six Modutec 1800-K6 thermocouples for application on studs. 3/8" diameter washer. Kiln shell temperatures.	7 Mar. 1978	May, 1978	73.14
Two Modutec 900-8K24 two hole ceramic insulation exposed junction thermocouples. 24" long, 8 gauge chromel-alumel for measuring stack temperatures.	9 Mar. 1978	May, 1978	46.34
Thermocouple extension wire with asbestos insulation	22 Feb. 1978	April 11, 1978	
350' of 16 gauge for use with platinum-rhodium			129.50
160' of 14 gauge for use with iron-constantan			59.20
300' of 14 gauge for use with chromel-alumel			135.00
Thermocouple wire with asbestos insulation	22 Feb. 1978	April 11, 1978	
10' of 14 gauge iron constantan			4.60
10' of 14 gauge chromel-alumel			6.50

Item	P. O. Date	Approximate Delivery Date	Cost
Rotameters for measuring flow rates:			
4 Type 3HCF glass metering tube, type 33J stainless steel float. 11SCFM air at 70°F and 30 psi. Part No. SD211112B112	8 Mar 1978	17 April 1978	612.00
4 Type SHCF glass metering tube, type 53J stainless steel float. 54 SCFM air at 70°F and 30 psi. Part No. SD31112B112	8 Mar 1978	17 April 1978	852.00
Rotameters for measuring flow rates:			
2 Type 1-RB metering tube, type R12 stainless steel float. 5 gph water at 70°F. Part No. SD111112E212.	8 Mar 1978	17 April 1978	270.00
2 Type 3HCF metering tube, type 30J stainless steel float. 2.22 gpm water at 70°F. Part No. SD211112E116.	8 Mar 1978	17 April 1978	306.00
Pyrometers for indicating temperatures. Read directly if cold junction at 77°F. From Modutec.			
One 5S-PYR-J500-H-Z 10 ohm external resistance for use with type J thermocouples (0-500°F). To measure cooled char out temperature.	8 Mar 1978	May 1978	53.59
Three 5S-PYR-J300-H-Z for use with type J thermocouples. (0-300°F). To measure cooling water temperatures. Five ohm external resistance.	8 Mar 1978	May 1978	164.91
Two 5S-PYR-K1000-H-Z 10 ohm external resistance for use with type K thermocouples. (0-1000°F).	8 Mar 1978	May 1978	107.18
Three slide wire contactors for use in Honeywell potentiometric recorders.	8 Nov 1978	November 1978	6.00
Three cables, for use in Honeywell potentiometric recorders.	8 Nov 1978	November 1978	21.00

Item	P. O. Date	Approximate Delivery Date	Cost
Two Honeywell series 152X14-PS-II-III-11, Chart No. 14111, reconditioned potentiometric recorders. For use with platinum-rhodium thermocouples. Twenty-four cycle with 5 second full scale response time. These potentiometers were converted in October 1978, for use with type K thermocouples. 100 day supply of chart paper.	8 Mar 1978	May, 1978	1,000.00
Two Honeywell series 152C23PS-24-11, Chart No. 14008, reconditioned potentiometric recorders. For use with chromel-alumel thermocouples. (0-2000°F). Twenty-four hour cycle with 5 second full scale response time. 100 day supply of chart paper.	8 Mar 1978	May, 1978	1,200.00
One Honeywell K153X84-CS-II-III-71, Chart No. 5458 four point reconditioned potentiometric recorder for use with chromel-alumel thermocouples. (0-2000°F). Chart Speed 2" per hr. One extra roll of chart paper.	8 Mar 1978	May, 1978	1,000.00
One Honeywell-Rubicon reconditioned manual potentiometer, Model No. 2732, 0-80MV, air junction with calibration curves.	8 Mar 1978	April 11, 1978	250.00
One portable stack gas train for sampling gaseous effluents and moisture in stacks complete with pump, flowmeter, dry gas meter, sample case with bubblers/impingers, and 5' sample probe.	8 Mar 1978	June, 1978	
1 Train - Research Appliance Company #20/016			1,414.00
1 Probe - Research Appliance Company #20/007			557.25
One particulate sample collector for Research Appliance Company #996142 & #994542	8 Mar 1978	June, 1978	373.25
One gas stream hygrometer for measurement of water vapor in gas streams. Research Appliance Company #997517.	8 Mar 1978	June 1978 + freight @	135.50 50.00

Item	P. O. Date	Approximate Delivery Date	Cost
Two channel strip chart recorder with multiple span and calibrated zero adjustment for both channels and 10 speed chart speed selection. Antek Model #285MM, Serial No. 31224.	8 Mar 1978	March 31, 1978	895.00
One three chamber portable industrial model flue gas analyzer in carrying case with instruction manual.	16 Mar 1978	April 11, 1978	305.00
One portable beam scale with beam graduated in 8 oz. increments up to 100 lbs. with a total capacity of 1000 lbs.	22 Feb 1978	April 1978	285.00
One balance, counter scale, single beam. Seamless brass scoop with capacity of 50 lbs.	8 Mar 1978	3 May 1978	270.00
Three total immersion mercury filled glass thermometers, -30 to 120°F, 1 division per °F, scale in °F, 305mm long.	21 Feb 1978	February 28, 1978	9.50
Two total immersion mercury filled glass thermometers, 0-300°F, two divisions per °F.	21 Feb 1978	February 28, 1978	10.50
One relay, normally open, 115 volt coil for use with drying oven.	1 Feb 1978	March 9, 1978	123.00
Two glass thermometers (0-350°C) for use with drying oven.	1 Feb 1978	March 9, 1978	42.00
One anemometer, Biram's pattern for measuring air velocities 200-3000 fpm. Four inch diameter with 3 dials. In leather case with correct chart and instructions.	22 Feb 1978	March 16, 1978	250.00
One hand held portable pyrometer. Self-contained complete with furnace type immersion 7" chromel-alumel thermocouple with 43" right angle extension. Eastern Process Instruments No. FD-25.	21 Feb 1978	March 16, 1978	130.00

Item	P. O. Date	Approximate Delivery Date	Cost
Two Eastern Process replacement thermocouples for use with FD-25. 501-T-12-43.	21 Feb 1978	March 16, 1978	32.00
Two Eastern Process replacement thermocouples for use with FD-25. 501-T-24-43.	21 Feb 1978	April 11, 1978	50.00
One triple beam balance and weight set Ohaus model 710. Capacity 610 grams without weight set. Weight set extends capacity to 2610 grams.		January 3, 1978	84.86
Two Dwyer Durablock inclined vertical manometer, Series 424, Model No. 421-5 with 2 vent valves, No. A-310 brass. 1/8" N.P.T. to 1/4" tubing.	21 Dec 1978	April, 1979	157.80
One Plenum venturi tube with 24" diameter inlet and 5.5" diameter throat, 9" diameter outlet.	21 Dec 1978	June, 1979	585.00
One air velocity measuring kit. Dwyer No. 125-AV air meter. 0-1" H ₂ O and 300-4000 fpm. 24" pitot tube and accessories.	10 Jan 1978	March 29, 1978	133.00
Tools for working on instrumentation.		November 1978	<u>20.00</u>
		PROJECT MONIES	<u>\$12,484.02</u>