ORO-5682-8

DEVELOPMENT OF WOOD AS AN ALTERNATIVE FUEL FOR LARGE POWER GENERATING SYSTEMS

Annual Report, January 3—October 31, 1978

By
Joseph T. Hamrick

October 1978

Work Performed Under Contract No. ET-78-C-05-5682

Aerospace Research Corporation
Roanoke, Virginia

U.S. Department of Energy

Solar Energy

NOTICE

Printed in the United States of America
USDOE Technical Information Center, Oak Ridge, Tennessee

ORO-5682-8
Distribution Category UC-61

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PREPARED FOR THE
U.S. DEPARTMENT OF ENERGY
SOLAR ENERGY
UNDER CONTRACT ET-78-C-05-5682

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EXECUTIVE SUMMARY

Background

A survey of wood burning furnaces in the United States revealed that most of the furnace and boiler systems do not exceed a rating capable of 25 megawatts electrical output. One reason for the size limitation is that feed systems such as traveling grates and fluidized beds have not been developed to provide higher wood feed rates. For economical operation a central power station must have a rating much higher than 25 megawatts. Engineering information is not available for design and construction of plants of 200 to 600 megawatts that burn wood and the cost of such plants cannot be accurately predicted. Coal plants of that size, in which coal is reduced to a fine powder and blown into the furnace, are operational in many areas of the country. Coal fractures on impact and can be economically reduced to powder, whereas wood shreds and cannot be economically reduced to powder for burning. Green wood can be economically shredded in a pulverizer to the point where it will pass through a screen with half inch perforations.

Technical Approach

Based upon the general rule that time required for combustion of a particle varies inversely with the ratio of surface area to particle weight, the burn rate for the commonly used 74 micron coal particles is approximately 12.7 times as great as for wood particles passing a half inch screen. One way to make up this difference for wood is to preheat the combustion air for wood to a higher temperature than is customary for coal. The reaction rate between fuel and air varies as the absolute temperature to the 6th to 8th power. By simple projection, it appears that if the combustion air for the wood can be preheated to 1050°F as compared to 650°F for coal, a burning rate for wood equal to that for coal could be achieved. General calculations for wood burning based upon heat transfer to the particle from the surrounding hot air or combustion gases indicate, however, that much smaller wood particle sizes would be required to produce such a high rate of burning.

To evaluate the effectiveness of high temperature preheated air, a small combustion module was constructed for experimental evaluation of pulverized wood burning. The feed rate for the pulverized green wood particles varied from 800 to 1200 lbs per hour. Green wood which had been pulverized to pass through a half inch screen was fed by a four inch diameter screw conveyor into swirling air preheated to 1020°F. The particles ignited and burned in the same manner as natural gas and all evidence points to the fact that all of the green wood particles burned while in suspension inside the 4.3ft x 5.3ft x 9.3ft chamber. Test results show that stable combustion can be maintained with air preheated to as low as 680°F, but a chamber longer than 9.3 feet will be required to achieve complete combustion while the particles are still in suspension. Additional data on trade offs among particle size, particle free path length, preheated air temperature, wood moisture content, air velocity, and swirl rate are needed to provide the most effective economical wood burning system for retrofitting natural gas or oil burning central power station systems. Currently, natural gas, oil, and coal fired systems use preheaters

that heat the combustion air to 550° to 650°F. The overall heat release rate for the small combustion module was 13,445 Btu/ft^3/hr. However, the burning zone was well enough defined to indicate that heat release rates on the order of 60,000 Btu/ft^3/hr, the approximate maximum for gas fired furnaces, can be achieved. The small combustion module was not designed to provide preheated air in excess of 1060°F because most boiler systems do not have the potential to provide higher temperature air, and heat exchanger materials become much more costly for temperatures above 1000°F.

Conclusions

1) Green wood particles pulverized to pass a half inch screen can be burned in the same manner as powdered coal, oil, or natural gas, if the combustion air is preheated to a temperature of 1000°F.

2) Stable combustion of green wood particles pulverized to pass a half inch screen can be achieved with combustion air temperatures as low as 680°F. However, the path length required for complete combustion while the particle is in suspension has not been determined.

3) A successful burner arrangement with high temperature air swirling and mixing with wood feed from a 4 inch diameter screw conveyor has been demonstrated and test results indicate that heat release rates comparable to those for natural gas can be achieved.

Recommendations

1) Tests should be performed to generate data on trade offs among particle size, particle free path length, preheated air temperature, wood moisture content, air velocity, and swirl rate.

2) A combustor with a 10 to 12 inch diameter screw feed should be built and tested to determine effects of scaling up from a 4 inch diameter screw feed.

3) Performance of pulverizers should be evaluated.

4) Plans should be made and implemented to retrofit an existing natural gas or oil burning central station power system to burn wood.

DEVELOPMENT OF WOOD AS AN ALTERNATIVE FUEL FOR LARGE POWER GENERATING SYSTEMS

INTRODUCTION

The objective of the overall project is to develop a system for retrofitting fossil-fuel fired boilers to burn wood. This effort is expected to provide the data for the design and fabrication of a prototype combustion module which will generate the design information for the retrofitting of large scale boiler systems. The specific goals of this phase of the program are to determine if, by increasing primary air and secondary air temperatures, combustion rates for wood slivers comparable to those obtained in boilers when firing powdered coal, oil, or natural gas are achievable and to increase the use of wood biomass as an energy source to produce steam and electric power in retrofit situations.

To achieve this objective, a small combustion module was designed, fabricated, and run as an integral part of this effort. This apparatus was used for parametric studies of wood pyrolysis and combustion with hot air. Tests in the module have shown that green wood, when pulverized to pass a half inch screen, burns in much the same manner as natural gas or oil when the primary and secondary air temperature is 1000°F. Tests have been made with primary and secondary air temperatures up to 1040°F and with air fuel ratios varying from stoichiometric to 92 percent excess air. The maximum green wood feed rate was 1272 lbs per hour with a heat generation of 5.5 million Btu per hour. With heat loss due to the moisture in the wood having been taken into account, the overall heat release rate for the furnace with 1272 lbs of green wood per hour was 13,445 Btu per cubic foot per hour. The burning of the particles while in suspension has been determined to be essentially complete with excess air in the 20 to 36 percent range and nearly so with no excess air when both primary and secondary air enters at 1040°F. Results of an analysis of the burning in the module indicate that a 60,000 Btu/ft^3/hr heat release rate can be achieved.

Power companies in Virginia, North Carolina, Texas, California, and Oregon were contacted with regard to future use of wood in power generation. The City Public Service Board of San Antonio, Texas has shown the greatest interest in retrofitting one of their existing power plants. The plant uses bunker C oil and has a 59 megawatt capacity.

Background information on wood availability and current use practices, information on potential users, factors which affect wood burning, descriptions of apparatus and instrumentation, test procedures, experimental results, discussion of results, analysis of results, and a summary of results are presented in the following pages.

BACKGROUND INFORMATION

Wood has long been used as a fuel in boilers in the form of chips and in log size on grates of many types for systems up to approximately 50 megawatts capacity. Systems using sawdust or pulverized wood blown into the furnace with the primary air are also in service. The highest efficiencies of wood furnaces now in service average approximately 69 percent.

Inquiries among manufacturers revealed that no wood furnaces for electrical power systems above approximately 50 megawatts had been built and none were contemplated. The two main difficulties that were cited were unknowns in the wood gathering process and extrapolation of design data from existing furnaces to the larger sizes. A third factor involved the quantity of wood available for burning.

It quickly became apparent that the huge,unpredictable cost of designing and building a power plant in the 400 to 500 megawatt range fueled by wood would probably preclude such a program and that an alternate approach would be required. The alternate approach that appeared to best fit the capabilities of a moderate size research and development organization and the possible budgetary commitments of the Department of Energy was development of wood burning techniques which would allow retrofitting of existing powdered coal, oil, or gas fired boilers to burn wood. Conversion of gas fired furnaces to powdered coal presents problems in that the combustion space is so small that the combustion of the coal particles is not completed before striking the boiler tubes which results in slag type build up, and there is no provision at the furnace bottom for collection of ashes or slag. There is very little ash from wood if combustion is complete, and any build up on boiler tubes can be easily removed with steam blowers. Therefore, the probability that green wood could be burned in natural gas boilers appeared good with development of suspension burning techniques.

As for the amount of wood available for use as fuel, inventories were being developed, but there were no overall figures available. A study was made in which the total land eligible for forest fire protection together with reported average minimum annual yields per acre were used to reach an annual production figure for wood products. The results of the study are contained in Appendix 1. Briefly the results indicate that with a plant efficiency of 32.5 percent there is enough wood available after needs for lumber and pulpwood as they existed in 1974, are satisfied to supply fuel on an annual basis for generation of 49.5 percent of the power generated in 1974 by fossil fuel fired central electric power stations in the United States. With intensive forest management it may be possible to raise the figure from 49.5 percent to 275 percent. In the state of Texas there are approximately 34 million acres of mesquite infested range land with annual yields estimated at 1.0 to 2.0 tons/acre. Neither waste wood nor this acreage was taken into account in arriving at the foregoing figures.

INFORMATION ON POTENTIAL USERS

Six power companies were initially contacted regarding their interest in possible future retrofitting of boiler systems to burn wood. They were Virginia Electric Power Company (Virginia), Appalachian Power Company (Virginia), Duke Power Company (North Carolina), The City Public Service Board of San Antonio (Texas), Pacific Gas and Electric Company (California), and Eugene Water and Electric Board (Oregon). Companies close to the coal fields in Virginia and North Carolina, while cooperative, do not foresee wood as an economical competitor to coal. Those farthest from the coal fields have a definite interest. The Eugene Water and Electric Board has three interconnected boiler systems with two wood furnaces. The total output of the two wood fired systems is approximately 25 megawatts with boiler efficiencies of about 57 percent. There is a possibility that the gas fired 7 megawatt system would be a candidate for retrofitting. The Pacific Gas and Electric Company purchases power generated from wood and has considered building a wood fired system in the 50 mw class. They have not expressed an interest in retrofitting an existing boiler at this time.

The City Public Service Board of San Antonio, Texas has expressed an interest in the use of wood in its Leon Creek Unit number 3. That boiler, which uses bunker C oil, has a capacity of 59 megawatts and has a maximum oil feed rate through ten burners of 40,300 lbs/hr. The combustion air is preheated to 575°F. The position of the City Public Service Board is that the Leon Creek Unit number 3 is a possible candidate for retrofitting for wood burning, provided that the results of the engineering, economic, and environmental studies are favorable for such conversion.

There are many small wood fired boiler systems in the country operating at efficiencies up to approximately 70 percent. For some applications such as those for paper mills, an increase in efficiency from 70 percent to 80 percent can result in substantial cost savings. While the main objective of the program is to make it possible to retrofit gas and oil fired furnaces to burn wood, the promise of a substantial increase in combustion efficiency has attracted the attention of those now using wood in the conventional manner.

CONSIDERATION OF FACTORS WHICH AFFECT WOOD BURNING

Coal shatters on impact, whereas wood is fibrous and tends to shred. As a result, reduction of wood especially green wood, to a fine powder for burning is not economical. The problems raised by this difference are best illustrated by comparing some factors which affect coal and wood combustion. The following information was compiled for the minimum approximate economical particle sizes for coal and wood:

TABLE 1 COMPARISON OF COAL AND WOOD PARTICLES

	Pulverized Eastern Bituminous Coal 74 microns	Pulverized Wood Particles passing 1/2 inch screen
Particle size, in.	.003 dia	5/16 x 1/16 x 3/64
Density, #/ft.^{3}	84	42
Particles per lb.	1.6 x 10^9	45,000
Volume of air per volume of solid at stoichiometric conditions	12,000	3,500
Particles per cubic inch of air	6,400	.3
Ratio of particle surface area to weight in.^{2}/lb.	42,300	3,342
Higher heat value, BTU/lb.	13,000	8,000 (dry)

Some observations may be made for the particles in question:

1. The number of particles of the coal dust per pound is such that in air they form a mixture that has the characteristics of a vapor and air upon being ignited. This is not the case with a mixture of the wood particles with air.

2. Based upon the general rule that time required for combustion of a particle varies inversely with the ratio of surface area to particle weight (Ref. 1 page 9-18)* the burn rate for the coal particles is approximately 12.7 times as great as for the wood particles, other factors being equal.

3. The volume of wood required is approximately three times that for the eastern bituminous coal. (It drops to two when compared to western subbituminous coal.)

The foregoing comparison indicated that the order of magnitude for the burning rates was such that some mode of burning wood would have to be found to make up for the 12.7 to 1 burning rate advantage for coal. One advantage for wood appeared to be its noncoking qualities as compared to coal upon being mixed with hot air. In pulverized coal fired furnaces the powdered coal is mixed with the primary air for conveyance into the burner and subsequent firing. Therefore, the temperature of the primary air with which the coal is mixed in the pulverizer must be kept low enough so that the coal particles do not coke and agglomerate in the transit duct and burner. Another factor is safety. For coal with a high percentage of moisture temperatures as high as 750^{o}F may be introduced into

* A list of references is provided in Appendix 4 , page 76.

the pulverizer, but with dry powdered coal which can form a more explosive mixture, the maximum is sometimes as low as 300°F. The temperature of coal and air just before ignition is normally 160° to 200°F. The normal practice in firing pulverized coal is to mix the particles with enough primary air to burn the volatile matter which may constitute on the order of 16 to 40 percent of the coal on a dry basis depending upon the source of the coal. The secondary air which supports combustion of the fixed carbon particles and any remaining volatiles is preheated to approximately 650°F. The system is so arranged that the secondary air sweeps in, surrounding the primary combustion zone.

Green wood particles as large as those passing a half inch screen do not constitute an explosion hazard when mixed with air. Therefore, since coking and agglomeration is not a problem, the temperature of the air that may be mixed with wood particles can be much higher. This offers an avenue of approach for offsetting the 12.7 to 1 advantage of the pulverized coal. Some indication of the approximate increase in combustion air temperature that may be required to offset the 12.7 to 1 edge in burning rate for powdered coal can be computed using the Arrhenius equation (Ref. 1, page 4-6). A simple relationship takes the form:

Reaction rate, $r = aT^m$ where m ranges from 6 to 8 and T = absolute temperature.

By this relationship it can be determined that the primary air temperature should be approximately 500°F and the secondary air temperature 1050°F. However, the volatile matter in dry wood constitutes on the order of 80 percent of the wood, approximately two to three times that for coal, making it difficult to assess the meaning of the relationship in specific terms.

Bench tests with green wood particles in hot gas streams showed that the particles would begin to char as soon as they contacted gases in the 1000° to 1200°F range. From these results it was deduced that introduction of the particles into a hot air stream in close proximity to the combustion zone would accomplish the following:

1. The surfaces of the green particles would be dried out and pyrolysis started in a fraction of a second.

2. If the mixing occurred close to the combustion zone, a high temperature secondary air stream could be injected to reheat the particle surface and insure rapid combustion of pyrolysis products at the surface before the surface could be chilled by the cooler core of the particle.

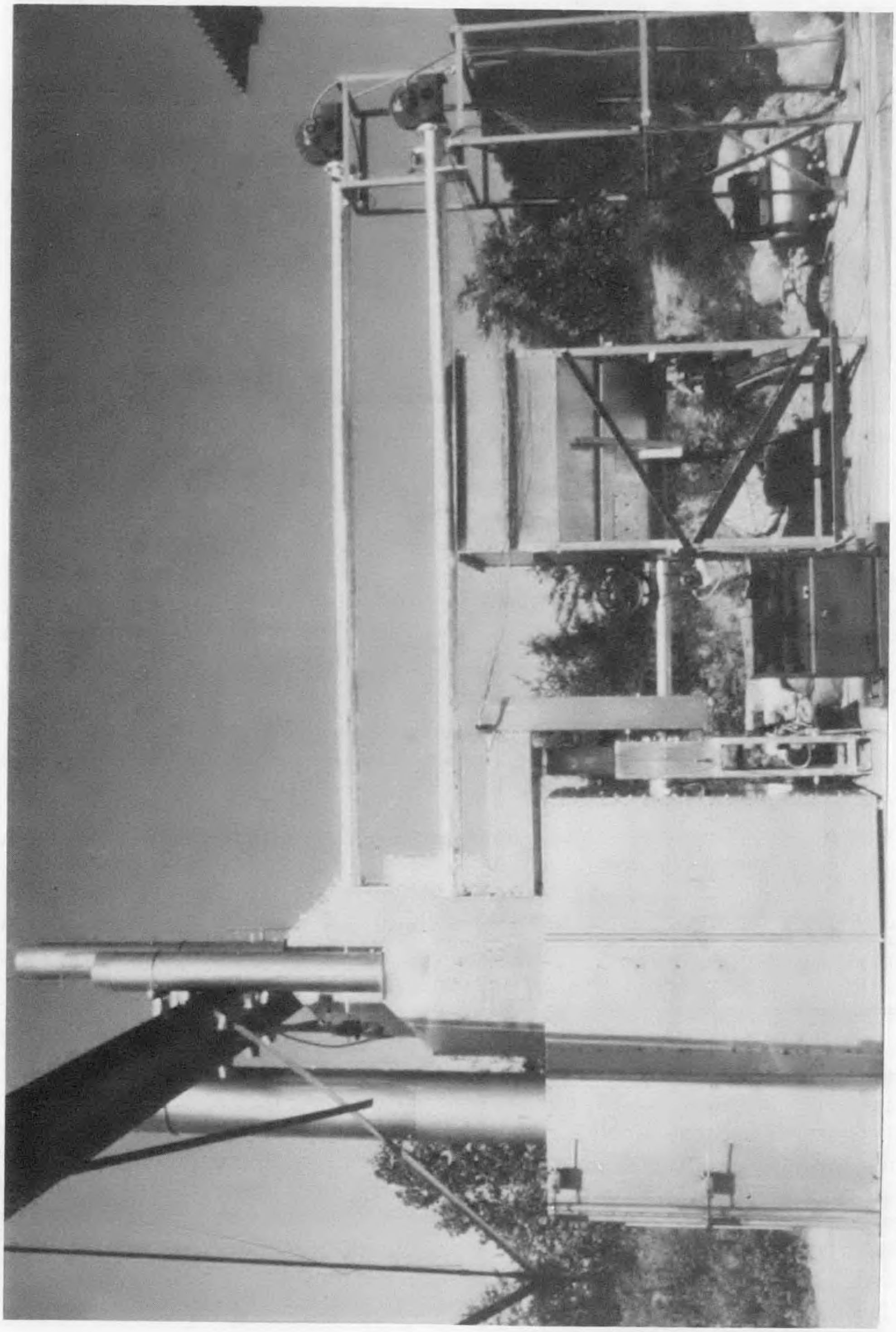
3. Once the particle had moved into the combustion zone, the hot products of combustion would sustain the same process with the sublayers of the particle.

Mixing of the hot air and green wood particles close to the combustion zone is a departure from the normal practice of mixing pulverized coal or dry wood dust with the primary air some distance upstream of the burner. In the case of powdered coal, the mixing takes place in the pulverizer so that the fine particles can be transported by the air. Thus, the differences in the coal and wood burning mechanisms for the particle sizes being considered preclude a detailed comparison of the mechanisms except for approximate rates of burning based on temperature of the combustion air.

In order to arrive at a more fundamentally oriented understanding of the wood burning mechanism, two specialists in combustion were engaged to provide theoretical approaches to the wood burning problem. Dr. Michael E. Leesley, who has made contributions to the literature in the area of powdered coal combustion was given the problem of theoretically determining the ignition times of wood particles. This study concentrated upon the pre-ignition zone of a hypothetical wood-burning furnace. Various mixes of primary and secondary air at various temperatures were used with different sized particles. The results show that the fastest heat up times occur when the bulk of the combustion air is admitted to the furnace as primary air. Dr. Perry L. Blackshear, Jr. who has made numerous investigations into burning of both liquids and cellulosic solids was given the general problem of drying, pyrolyzing, and burning of moist wood particles in suspension. Both studies were carried out simultaneously with the experimental investigations and inputs from both Drs. Leesley and Blackshear were used in setting up the small combustion module and performing the tests. The results of both studies are available to persons interested in reviewing them.

DESCRIPTION OF THE SMALL COMBUSTION MODULE

A photograph of the small combustion module is shown in figure 1. The furnace is 8 ft. high by 6 ft. wide by 10 ft. long. A schematic diagram of the system is shown in figure 2 and another schematic diagram with a more detailed view of the burner section is shown in figure 3. The primary and secondary air supplies are controlled by butterfly valves that may be operated from the control building, which can be seen in figure 4. Synchronous motor driven indicators show the positions of these valves for rough settings. The pulverized wood is fed by a 4 inch diameter screw conveyor driven by a variable speed motor. Preheated air from the primary swirl chamber is accelerated as it moves into the cone surrounding the wood feed exit, mixing with the wood particles, and moving them into the combustion zone. Preheated secondary air swirls in around the mixture. Primary and secondary air preheaters on top of the furnace contain vertical tubes through which the hot combustion gases pass. The combustion air passes across the outside of the tubes, two passes for primary air and four passes for secondary air. Dampers in the



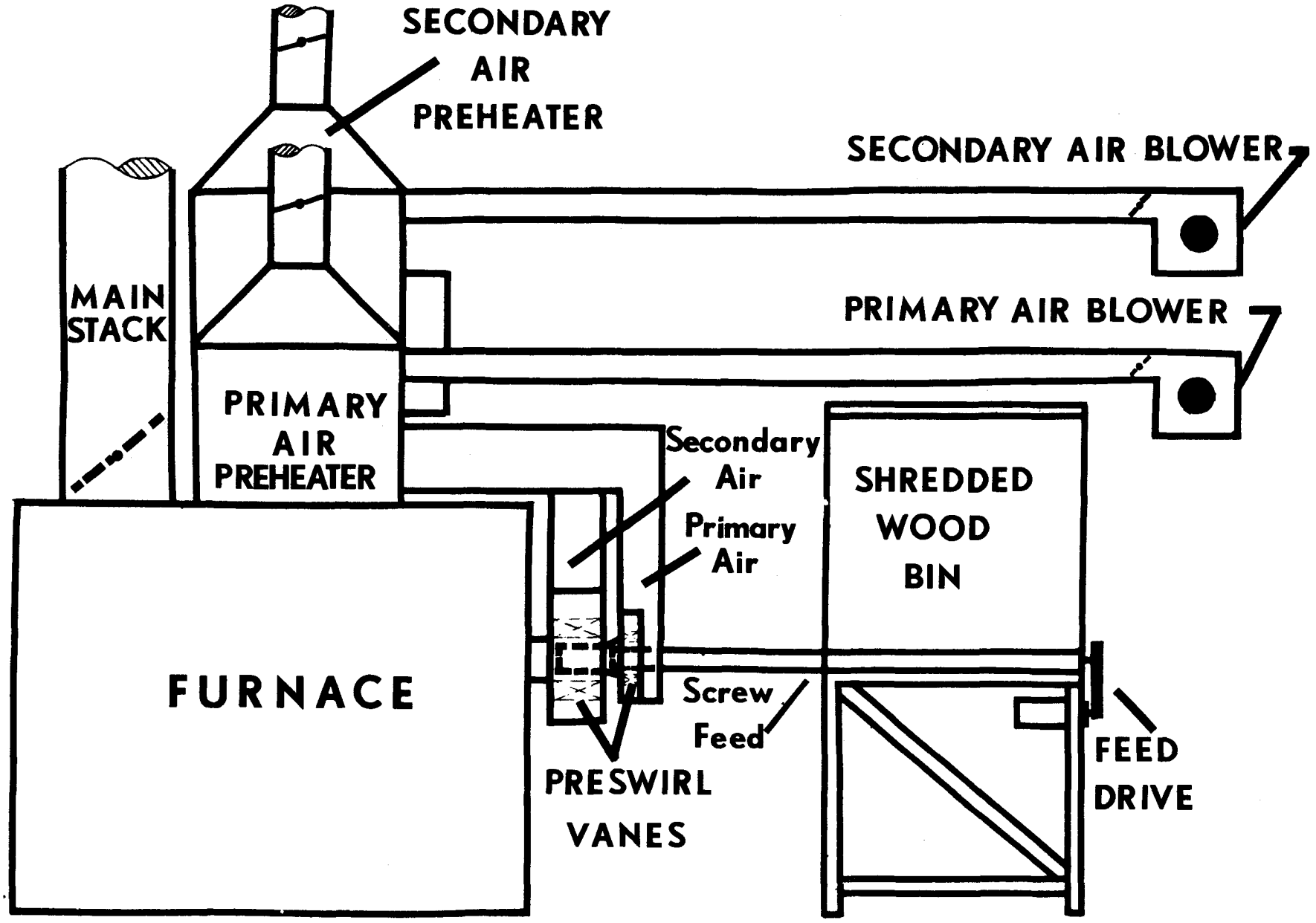


Fig 2 - Schematic - Small Combustion Module

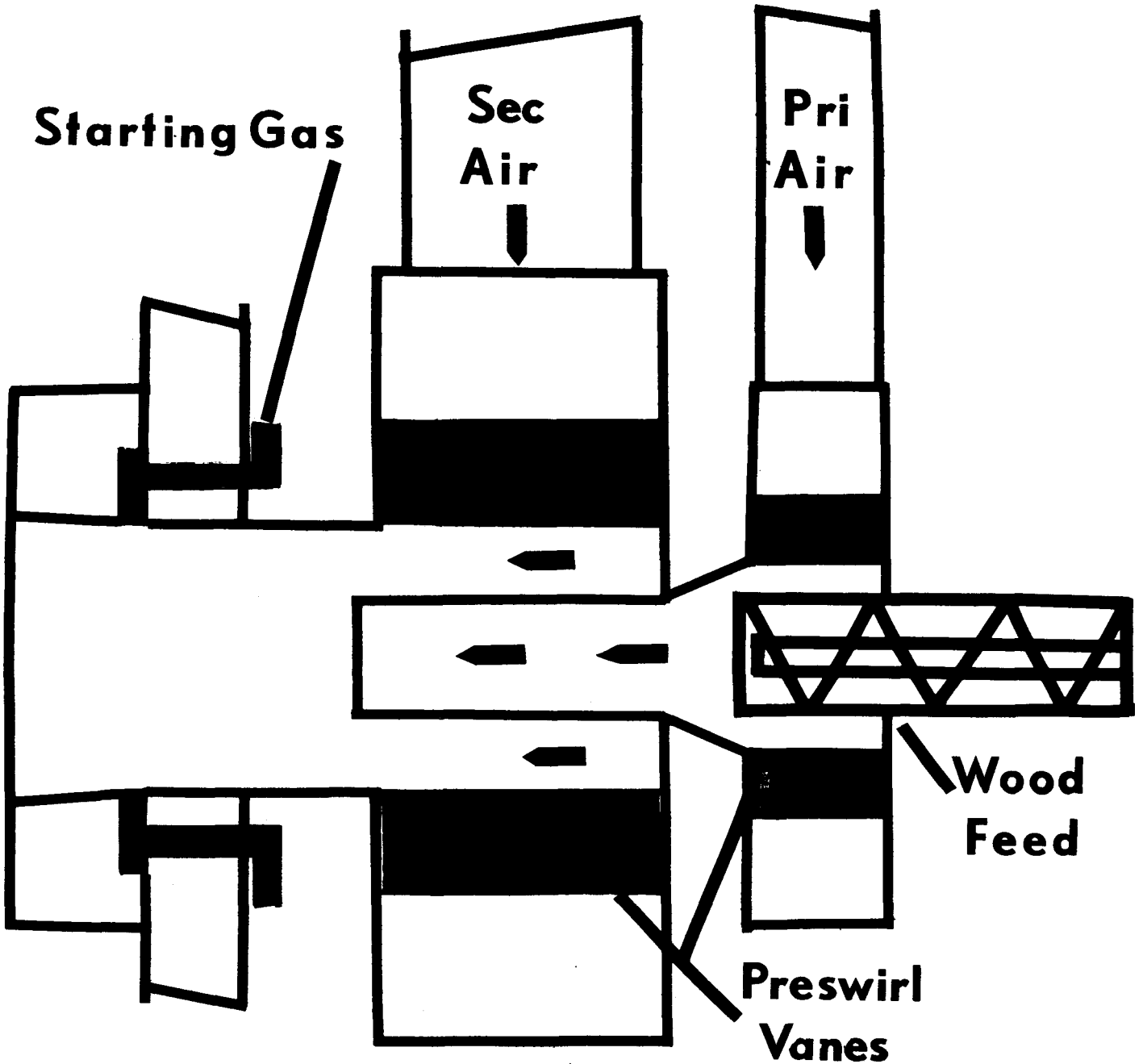


Figure 3-Schematic of wood-air feed

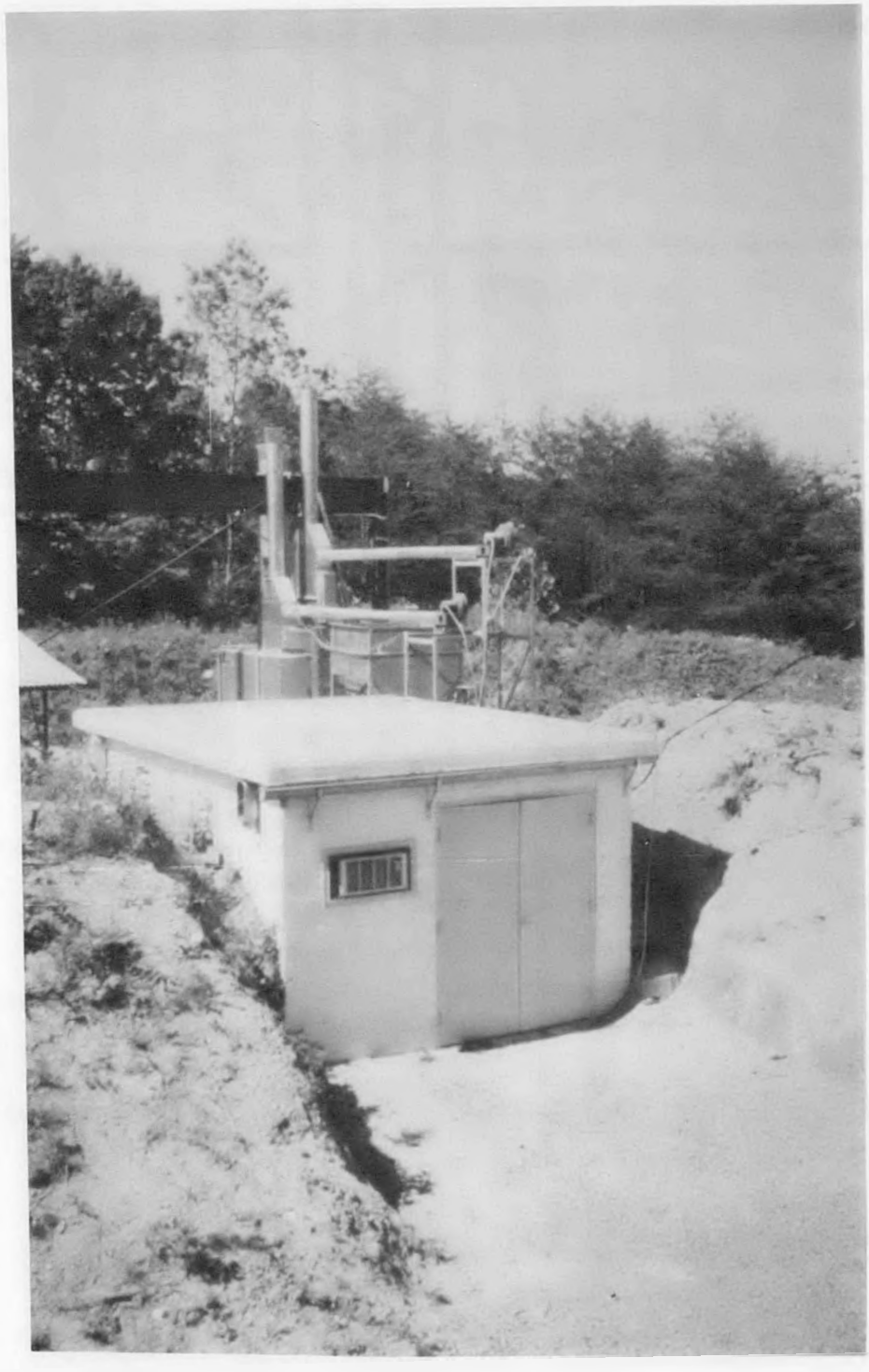


Figure 4 - Overall view of control building and furnace.

preheater exhaust stacks and the main stacks can be moved in steps of one degree, from the control room, to control preheated air temperatures. A propane gas ring around the burner supplies gas for heating the furnace before subsequently switching to wood feed. When the primary air reaches approximately 500°F and the secondary air 1000°F the wood feed is turned on and allowed to run for 15 seconds before turning off the gas. The furnace walls are lined with kaolin based block and wool fiber which can withstand approximately 3000°F. Firebrick was laid over the insulating block on the floor.

INSTRUMENTATION

Thermocouple locations are shown in figure 5. Iron-constantan couples (IC) were used to measure inlet air and wood temperatures. Chromel-alumel couples (CA) were used for all combustion air and combustion gas temperatures except on the furnace ceiling where tungsten 5 percent rhenium-tungsten 25 percent rhenium couples (TR) were used. All thermocouples were read out on a millivolt strip chart recorder using a selector switch except for the tungsten-rhenium thermocouple on the ceiling and one chromel-alumel couple in the primary air swirl chamber. These were read out on separate recorders. A view of the control room instrumentation and controls is shown in figure 6.

Air flow was measured by means of pitot tubes which measured center pipe velocity. Graphs of air flow versus center location pitot tube readings for 10°F steps and for barometric pressures ranging from 28 to 30 inches of mercury were prepared for use in setting air flows. The pitot tube locations are shown in figure 5. Inclined water manometers located in the control room were used to measure pressure differences across the pitot tubes.

The rotative speed of the wood screw conveyor was read by means of a magnetic pick up at the conveyor shaft and a digital read out in the control room. Rough settings of speed were made by means of the drive motor speed control prior to start up. In order to assure a more accurate average of wood feed rate for some tests, the wood was weighed and timed for a constant feed rate into the furnace.

An Orsat type apparatus was used to analyze flue gases. This type analyzer uses selective absorption of the components, except nitrogen, in liquid reagents.

Moisture content of the wood was determined by measurement of weight loss in an oven at 200°F over a 24 hour period. It was determined that no further weight loss was experienced by exposing a sample for an additional two 24 hour periods. A photograph of typical wood particles is shown in figure 7.

The heat value determinations of the wood specimens were made using

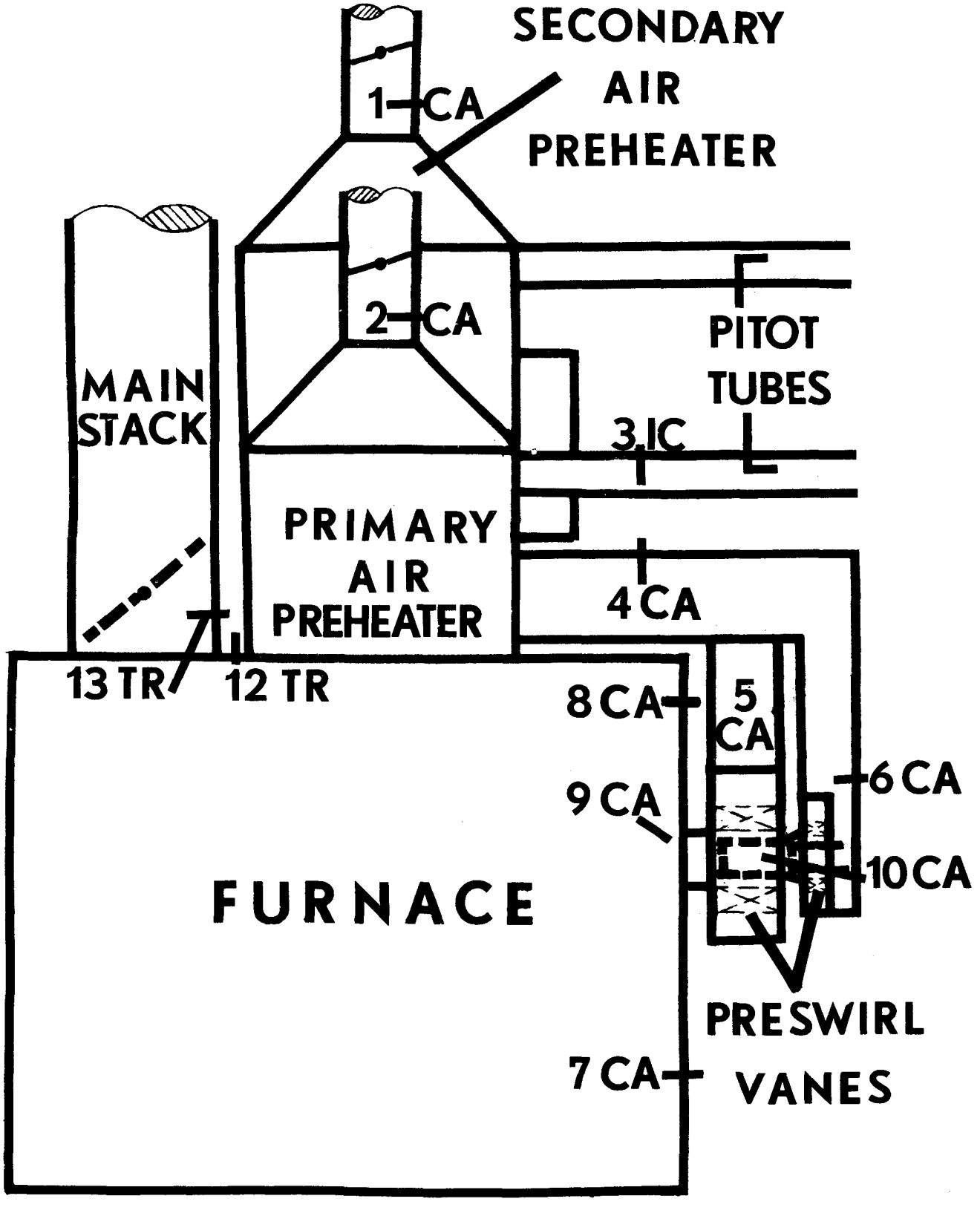


Figure 5-Thermocouple and pitot tube locations

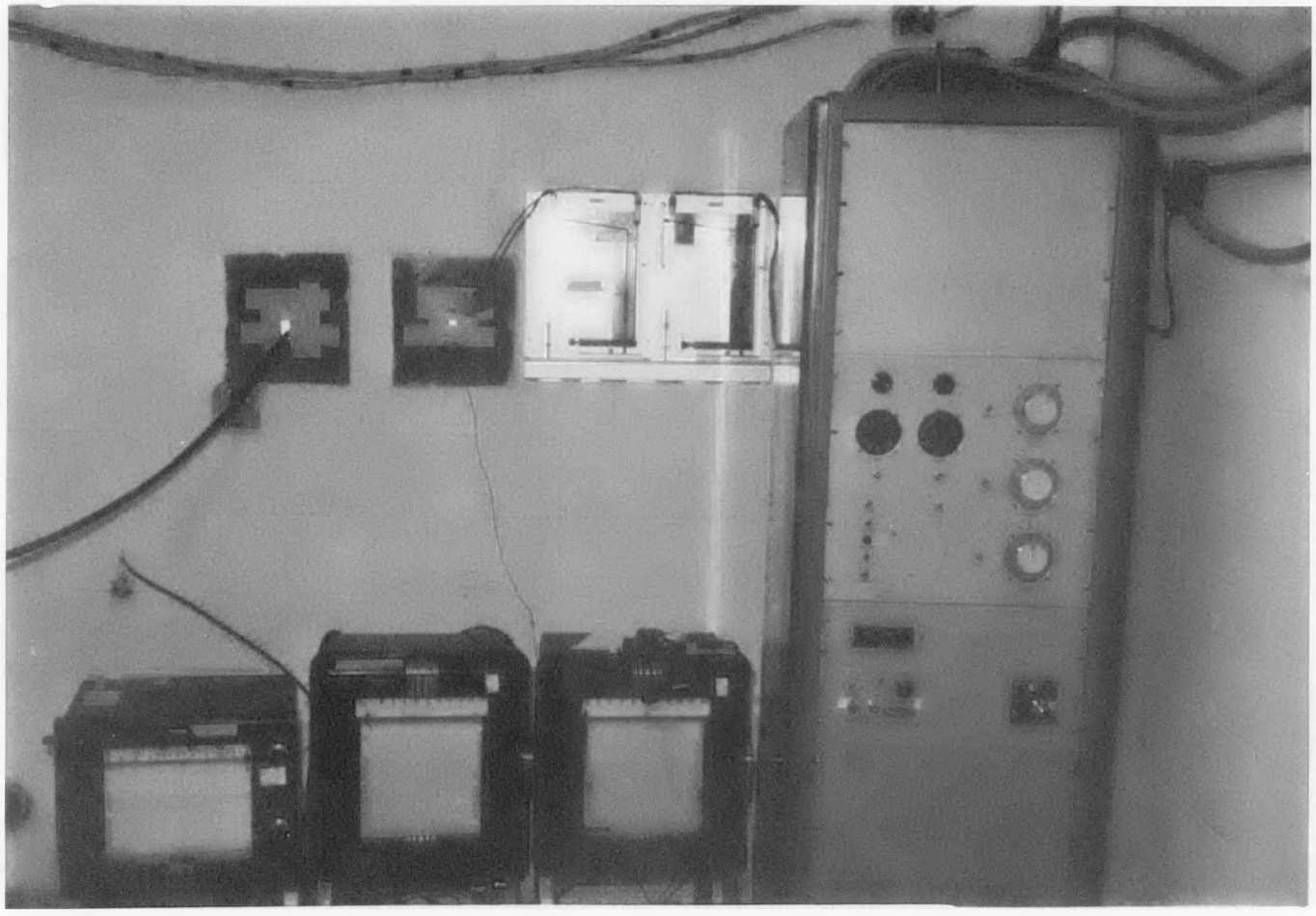


Figure 6 - Photograph of control room instruments and controls.

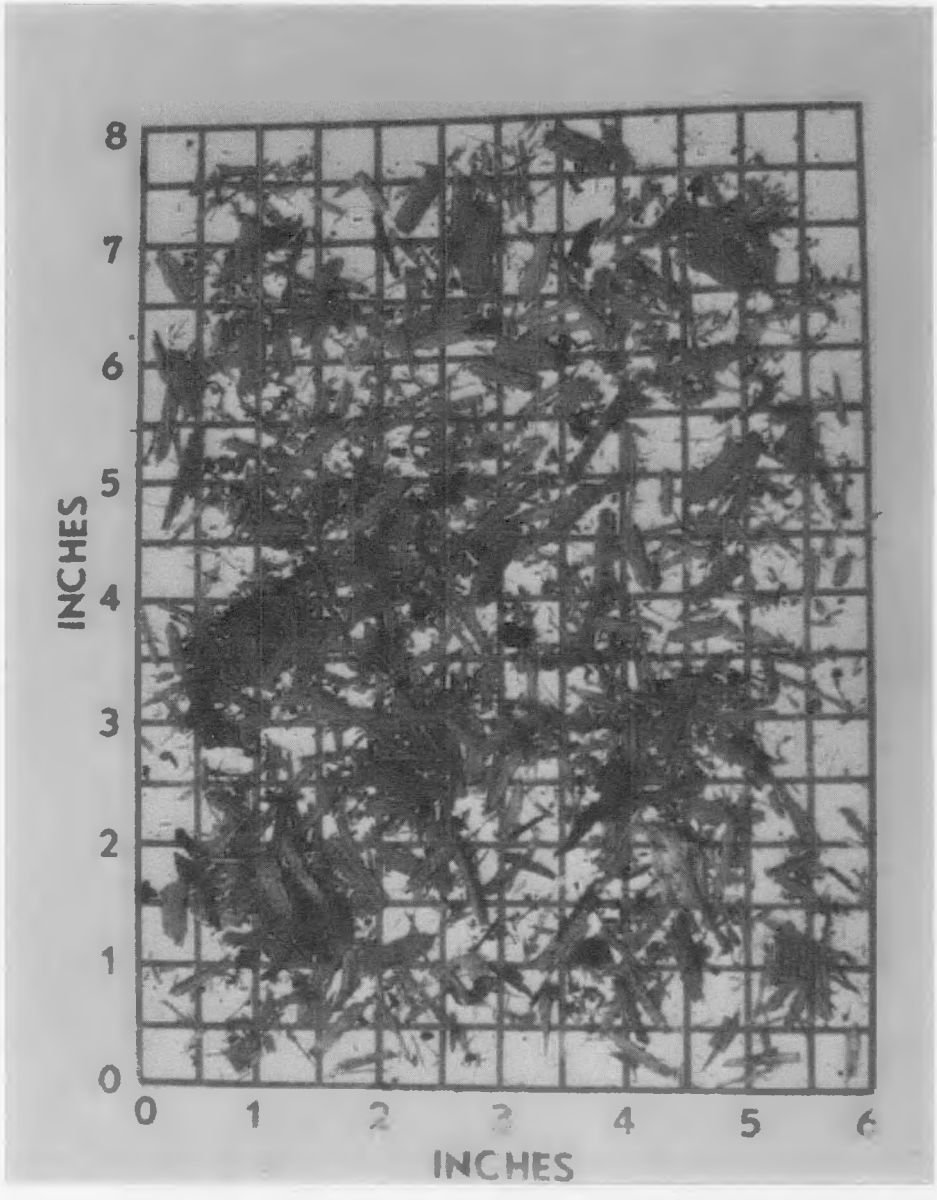


Figure 7 - Wood particles on half inch grid. (Virginia Pine)

a Parr adiabatic bomb calorimeter in accordance with ASTM D20k5-66 by personnel of Froehling & Robertson, Inc. in their Richmond, Virginia laboratory.

AUXILIARY APPARATUS

A study of wood pulverizing equipment resulted in the selection of a Schutte Pulverizer Co., Inc. Wood Grinder Hammer Mill with a half inch screen. Whole tree chips were fed into the pulverizer by belt conveyor and the pulverized wood then loaded into plastic bags for transport to the furnace.

A tank with a capacity of 800 gallons of liquid propane, pressure regulators, and solenoid control valves were used in bringing the system up to temperature before starting the wood feed. A 6000 volt transformer was used to provide the starting spark.

PROCEDURE

All of the tests were started by first heating the system with propane gas. The time required to raise the primary air to 500°F, and to raise the secondary air to 1000°F was approximately two hours. During the heat up period, the furnace walls were brought up to temperatures approximately equal to those for burning wood particles. It was found that for secondary air temperatures below approximately 850°F the wood failed to ignite. Upon reaching 500°F for primary air and 1000°F for secondary air the wood feed preset for the desired feed rate, was turned on and after 15 seconds the gas was turned off. There was no dip in temperature at this point. The temperatures of both primary and secondary air began to rise immediately for a 1000 lb per hour wood feed rate. The flow rates for primary and secondary air were adjusted by means of the butterfly valves. The dampers for the main stack and air preheater exhausts were then manipulated to obtain the desired preheated air temperatures. Readings of temperature were made and manually recorded at frequent intervals. Temperatures were also recorded on strip charts. For most tests a 500 pound charge of wood was adequate to generate the desired data.

The preswirl vanes in the primary air swirl chamber were set so that the blade chord made an angle of 9° with a line running from the center of the swirl chamber to the center of the vane. The preswirl vanes in the secondary air swirl chamber were set at 11°. The direction of swirl for the secondary air was opposite to that for the primary air. Tests were made with wood feed rates from 500 to 1272 pounds per hour and with air feed rates varying from stoichiometric to 66 percent excess air, varying ratios of primary to secondary air, and varying temperatures of primary and secondary air.

Several methods of determining the amount of material burned in

suspension were considered. They included quenching with liquid nitrogen or carbon dioxide to stop the reaction between the air and any wood that had fallen to the floor, the use of light sensitive devices to follow the progress of incandescent particles along their trajectories, and the effects of bombardment by incandescent particles on heat sensitive materials. The latter method proved to be the most effective. Kaowool blanket and Kaowool rigid board, which are manufactured by The Babcock and Wilcox Company, proved to be good materials in the application. The Kaowool board and blanket that were used melt at 3200°F, which is in the range of the wood combustion temperature when the combustion air is heated to approximately 1000°F.

COMPUTATIONS

The theoretical temperatures that should be achieved with burning of wood in air were calculated, taking into account the cooling due to excess air and moisture in the wood. A major consideration in computing the temperatures was the variation in specific heat with the temperature of the gases. For this preliminary investigation, a computer program which could take into account shifting equilibrium was not considered needed. Hand calculations were made using a combination of the specific heat alignment charts of page 3-127 of reference 1 and the formulae of Sweigert and Beardsley page 4-10 of reference 2.

EXPERIMENTAL RESULTS

A total of ten experimental runs were made in which an average of 500 lb lots of wood, pulverized and passed through a half inch screen, were burned in periods varying from 27 to 46 minutes after the system was brought up to starting temperature by propane gas. One run was made in which a 1500 lb lot of wood was burned in 90 minutes. Two of the runs were made with red oak wood with the remaining runs being made with Virginia Pine. Whole tree chips were pulverized and passed through a half inch screen for both oak and pine. The primary and secondary air temperatures varied from an average of 650 to 1020°F. Typical tests will be described for pine and oak and for the 90 minute run with pine in which a range of combustion air temperatures were used.

Thirty Minute Tests With Virginia Pine

For a typical test for which results are shown in table 2, the primary air temperature was brought up to 500°F and the secondary air to 1000°F with propane gas before starting the wood feed. Fifteen seconds after the wood feed was started, the propane gas supply was shut off. Approximately a ten minute period was required to stabilize with a constant wood-air feed. In a 30 minute test using 66 percent excess air with 826°F primary air and 897°F secondary air there was an approximate 36 inch diameter erosion pattern on the refractory opposite the burner ten feet away. The refractory was eroded to an average depth of approximately 1/4 inch. For runs in which the combustion air

Table 2 - Results of tests with green oak and green pine wood particles passing a screen with half inch diameter perforations.

	Oak	Va. Pine
Amount of excess air, %	0	9
Primary preswirl vane setting	11°	11°
Secondary preswirl vane setting	9°	9°
Primary air flow rate, cfm	395	390
Secondary air flow rate, cfm	325	380
Wood feed rate lbs/hr	811	994
Air temperature (3)*, °F	88	74
Wood temperature (11), °F	68	71
Primary preheater stack (2), °F	1686	1660
Secondary preheater stack (1), °F	972	931
Primary swirl chamber (6), °F	965	1020
Secondary swirl chamber (5), °F	1000	1027
Near wall below burner (7), °F	2083	2031
Near wall above burner (8), °F	2205	2132
Primary air-wood mixture (10), °F	628	736
Ceiling of furnace (12), °F	2260	2180
Wood moisture content %	.35	.49
Wood heat value, Btu/lb	8096	8604
Residue, after cool down, lbs.	4	2
CO_2 in exhaust, %**	15.9	15
O_2 in exhaust, %	1.4	3.9
CO in exhaust, %	3	1.5
N_2 in exhaust, %	79.7	79.6

*Numbers in parentheses denote thermocouple location on figure 5.
**Sample taken from primary exhaust stack.

was 900 to 1000°F and there was zero to thirty percent excess air, there was no significant erosion and there was very little ash residue in the furnace. The quantity varied from 2 to 4 pounds depending upon the amount of excess air. The greater the amount of excess air the smaller the amount of residue. Most of the residue was found at the bottom of the door which formed the wall opposite the burner. Determination of burning behavior was difficult because of inability to view the flame. In an attempt to determine if particles had fallen to the floor and burned, liquid carbon dioxide was injected directly into the furnace after shut down at the end of one test. The objective was to quench any particles that may have been in the process of burning and to maintain a blanket of carbon dioxide in the furnace until it was cool enough to remove the end door. The results were that there appeared to have been no wood residue on the floor at the end of the test. The usual amount of ash residue was found at the bottom of the door.

Ninety Minute Test With Virginia Pine

The objective of this test was to start off with high temperature combustion air and reduce the temperature in successive steps to a point where combustion became erratic. The wood particles used in the test had a moisture content of 51.8%. The test was carried out with 10 percent excess air. Because of the high moisture content, starting failed with the primary air temperature at 500°F and secondary air at 1000°F. After the primary air temperature was raised to 700°F and the secondary to 1125°F, the start was made in a routine manner. The primary air was then adjusted to 968°F and the secondary to 956°F. These temperatures were stepped downward at approximately fifteen minute intervals to the temperatures shown in figure 8. In figure 8 the temperatures are plotted versus primary swirl chamber temperature. Starting on the right in figure 8 with the initially adjusted temperatures and moving to the left the final temperature of the primary air was 615°F and the secondary air 679°F. In the tests at these and the higher combustion air temperatures combustion was stable. After the furnace had cooled and the door was opened, there were approximately 2.5 cubic feet of charred wood and insulation debris piled up at the door and a crater approximately 2 feet in diameter had been eroded away in the refractory on the door. A view of the door is shown in figure 9. The center of the crater was approximately 5 inches below the centerline of the burner and to one side of the door as shown in figure 9. In the other runs in which erosion occurred, it was toward the same side as shown in the figure. In the crater, the refractory was eroded away to the sheet metal. The largest portion of the debris accumulated at the door on the side opposite the crater as can be seen in figure 9. Referring again to figure 8, the temperatures on the wall above and below the burner were approximately constant across the range of combustion air temperatures.

Thirty Seven Minute Test With Red Oak

Two tests were made with pulverized red oak. As the oak contained

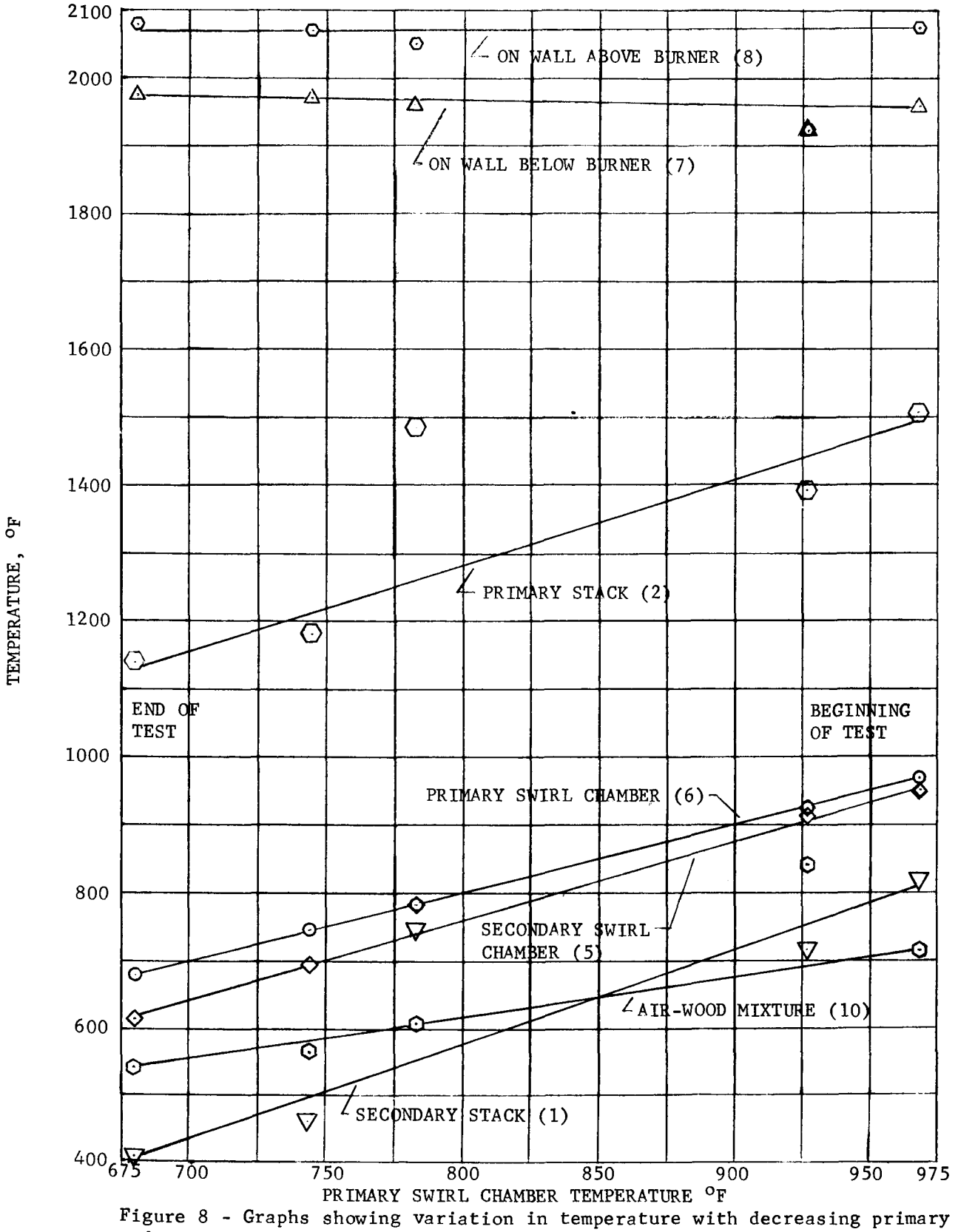


Figure 8 - Graphs showing variation in temperature with decreasing primary and secondary air temperature. Primary air flow rate 1840 lbs/hr., Secondary air flow rate 1749 lbs/hr., Green wood feed rate 1127 lbs/hr.

Figure 9 - Photograph of crater in refractory on door which has been lowered to the ground after 90 minute run with primary air temperature progressively reduced from 956°F to 680°F and secondary air from 968 to 615°F. Wood flow (green) 1127 lbs/hr.

more shredded fines than the pine, it was fluffier and less dense. Therefore, the feed rate was proportionately lower at the top speed of the screw conveyor. However, the minimum primary air flow needed to entrain the particles and move them out into the combustion zone was approximately the same as for the higher weight pine wood feed at the top screw speed. The starting procedure was the same as with the pine. The data for one of the red oak tests with 0 percent excess air is shown in table 2. Test results for the two tests with oak wood were not significantly different from those with pine wood, and the erosion of the refractory material on the door was not measurable.

Overall Results

In all of the tests there appeared to be very little difference in burning characteristics of the propane gas and the green wood particles except for issuance of smoke from the exhaust stacks and erosion of the refractory on the furnace door for combustion air temperatures below approximately 900°F when burning wood. The smoke disappeared within approximately fifty feet of the stacks. A view of smoke emerging from the stacks in a typical test is shown in figure 10.

COMPARISON OF TEST RESULTS WITH THEORETICAL FINDINGS OF LEESLEY AND BLACKSHEAR

The study by Leesley was concerned primarily with heat up and ignition time and by Blackshear, the heat up and burning. It is difficult to correlate reaction times between the experimental results from the small combustion module and the theoretical because particle velocity is initially less than air velocity and computation of terminal velocity is difficult. For the test results with pine wood shown on table 2, the time required to burn the wood particles of the size used in the tests, according to the theoretical analyses, would be greater than 2 seconds. If the air leaving the burner achieved an average temperature of 2000°F and expanded to fill a 2 ft diameter cylindrical boundary it would reach the opposite wall in approximately 1/2 second. It is unlikely that all of the air would follow such a confined path. However, the wood particles with their high momentum leaving the burner apparently do follow a confined path as exhibited by the erosion of the refractory on the door. In the test with pine wood, for which results are shown in table 2, the calculated average velocity of the air leaving the 10 inch diameter burner with an average temperature of 814°F would be 56 ft/sec. Wood particles leaving the burner with the same velocity would fall approximately 5.4 inches by the time they arrived at the refractory on the door 9.3 feet away, if the initial velocity were sustained. The 814°F temperature is the average of the 1000°F secondary air and the 736°F air-wood mixture. The 5.4 inch fall is in general agreement with the approximate 5 inch difference between the center of erosion in the 90

Figure 10 - Photograph of smoke emerging from air preheater stacks. Main stack damper was closed.

minute test and the centerline of the burner. A rough check on wood particle velocity was made by observing wood flow with the furnace door open. The blowers could not supply enough air to simulate the preheated air condition, so particle fall with unheated air at the same weight flow rate was checked. With the air at 74°F the average calculated velocity of the air leaving the burner was 23 feet per second. Wood particles leaving the burner with the same velocity should fall approximately 31 inches in the 9.3 ft distance. Based on observation and the particle distribution on the floor it appeared that the average fall was in the vicinity of 30 inches, signifying that the particles do leave the burner at a velocity approaching that of the air stream.

Assuming that the above reasoning has led to an approximately correct result, the time of suspension of the wood particles after leaving the burner and impacting the refractory on the door would be in the vicinity of .17 seconds. The time of suspension in the primary mixing tube and burner should also be less than .17 seconds. If the premise that very little char impacted the door refractory and combustion was completed between the burner and the door, the calculated times of both the Blackshear and Leesley studies are too long and the assumptions that were made should be reexamined.

DISCUSSION OF RESULTS

The results show that with a four inch diameter screw feed conveyor and high temperature combustion air, the green wood particles can be burned in a manner similar to that for natural gas, and that with combustion air temperatures in the 900°F to 1000°F range, the particles are consumed in a ten foot distance. There was a neglible amount of ash left on the furnace floor. The major problem in evaluating the results lay with determining the completeness of wood particle combustion while the particles were in suspension. The extent of erosion of the refractory provided the best overall indication of completeness of burning. The computed maximum combustion temperature with 25 percent excess air varies from 3000°F with 600°F combustion air to 3170°F with 980°F combustion air. With no excess air the combustion temperatures are approximately 400°F higher. These temperatures bracket the 3200°F melting point of the refractory, and it is conjectured that the flaming char, upon impacting, melts the refractory and is quenched at the same time. The quenched char and melted refractory then fall to the floor.

For a particle of given size, two factors appear to affect the extent of erosion, the velocity of the combustion air and its temperature. In the test with 90 percent excess air, there was erosion even though the average temperature of the air was 900°F. In addition, the pattern diameter was larger than that for the 90 minute test. This result is attributed to the higher through flow velocity and increased swirl rate due to the higher flow quantity. The higher velocity particles reached

the door sooner, and they were centrifuged to a larger radius.

The extensive erosion of the refractory during the 90 minute test is attributed to the slower burning rate of the particles with the lower combustion air temperature. The large accumulation of particles on the floor next to the door probably resulted, in part, from the partially burned particles being subjected to greater cooling upon striking the sheet metal which became exposed some time during the test. The sheet metal, being cooled by the air on the outside, would have had a greater cooling effect on the particles than the insulating refractory.

The reason for the erosion occurring off center is not clear. It could have been caused by reaction between the swirling stream leaving the burner and the gases in the furnace, a misalignment of the burner, or both. The reason for the pile up of unburned particles on the side opposite that on which the erosion occurred can be attributed to the swirling motion of the particles as they impacted.

ANALYSIS OF RESULTS

The erosion patterns on the refractory indicate that the wood air mixture leaves the 10 inch diameter burner with a vortex motion and expands to approximately a diameter of two feet in the 10 ft length, dropping down only approximately 5 inches in the process. If it is assumed that the burning takes place in a 2 foot diameter cylindrical zone 10 feet long the heat release rate in the zone at the maximum wood flow rate of 1272 pounds per hour would be greater than 150,000 Btu/ft^3/hr. The burner in this furnace appears to subject the wood particles to action similar to that for coal particles in cyclone furnaces which attain heat release rates of 500,000 Btu/ft^3/hr. In view of these similarities and the high heat release rates achieved in the combustion zone, it is expected that even though the maximum heat release rate based upon total chamber volume was only 13,445 Btu/ft^3/hr, the needed 60,000 Btu/ft^3/hr for retrofitting natural gas furnaces can be achieved without great difficulty. The primary and secondary air temperatures with the 1272 lbs/hr wood flow rate were both 820°F and there was only a small amount of erosion of the refractory. Even in the test in which the primary air was 679°F and the secondary air 615°F it is possible that a combustion zone heat release rate of 75,000 Btu/ft^3/hr could have been achieved if the path length had been increased to allow complete burning before the particles struck the refractory. The significance of this result is that it may be possible to burn green wood in suspension in furnaces having a twenty foot distance for wood particle travel with air heated to a temperature of only 680°F. Most central power station furnaces have widths of twenty feet or greater. If the use of 680°F air should prove possible, the problem of raising the preheated air temperature in existing furnaces would

be significantly less troublesome as most furnaces already have air preheaters that heat combustion air to 550° to 650°F. Results of exhaust gas analyses given in table 2 show that with 9 percent excess air the CO content of the exhaust gases approaches 1.5 percent. In most furnaces, the height of the furnace above the primary combustion zone is considerably greater than that in the small combustion module. The greater height would allow more travel time before the gases reach the exhaust stack and, therefore, more complete combustion of the CO. Combustion efficiencies within 5 percent of those for natural gas should be attainable for pulverized green wood.

The results shown are for one wood particle size range. The economics of wood pulverization have not been fully investigated except to determine from wood pulverizer manufacturers that pulverization of green wood to pass screens with perforations of less than approximately one half inch in diameter is economically impractical. Tests to provide trade off information between combustion air temperature and particle size are needed. The tests should be performed in a furnace which would allow particles to travel 20 feet before impacting. The tests were performed with a 4 inch diameter screw conveyor. Conveyors for large furnaces will have diameters on the order of 12 inches. Performance data for conveyors of that size are needed.

SUMMARY OF RESULTS

1. Tests have shown that by using 1000°F primary and secondary air, pulverized green wood particles which have passed a half inch screen can be burned in suspension in the same manner as natural gas.

2. For green wood delivered by a 4 inch diameter screw conveyor at a rate of 994 lbs/hr into 1020°F combustion air with 27 percent excess air, combustion was completed in suspension within a distance of 10 feet.

3. With a 20 ft. path length it may be possible to completely burn green wood particles in suspension in 680°F air.

4. The overall heat release rate in the small combustion module was 13,445 Btu/ft^3/hr. Results of an analysis of the burning in the module indicate that a 60,000 Btu/ft^3/hr heat release rate can be achieved.

5. It appears feasible to retrofit natural gas and oil fired boilers to burn green wood. However, test results with wood feed screws in the 12 inch diameter range are needed.

APPENDIX 1

ESTIMATED WOOD PRODUCTS AVAILABLE FOR POWER GENERATION

Statistics contained in various annual publications as well as publications by the U. S. Forest Service and some of the states support the thesis that adequate forest product resources are currently available to supply large blocks of electric power, and can be developed to more than double current biomass productivity. Approximate biomass yields per acre, and estimated forest land available for fuel use are discussed.

Estimated Forested Areas - In the contiguous 48 states the National Forest System covers 163,532,660 acres according to the U. S. Department of Agriculture. There is a total area including some non-forested water shed land, private forests, and the National Forest System of 751,220,195 acres that is eligible for forest fire protection under the combined federal-state cooperative Forest Fire Control Program. This area constitutes 40 percent of the land surface area in the contiguous 48 states. The status of the watershed areas is not clear, but it is assumed that it is not being cultivated and is available for forest growth since it needs forest fire protection. It is the function of the Forest Service to manage the National Forest System to make each area yield the combination of uses best suited to public needs. Telephone and letter contact with Forest Service personnel in the Appalachian Forest area has substantiated the interest of these personnel in studying the use of the National Forest System to provide energy. A great deal of information has been supplied by them for a first effort at estimating the annual biomass yield in appalachian forests. The method of arriving at a yield estimate is provided in the next subsection.

Approximate Forest Biomass Yields - While substantial biomass yield information has been and is being generated, the average annual yield that can be anticipated for a large area such as, for example, the Jefferson National Forest in western Virginia is not available. Telephone conversations and letter correspondence with Forest Service personnel in Washington, D. C., Athens, Georgia, and Asheville, North Carolina, and Professor Harold E. Young of the University of Maine has confirmed the nonexistence of such information.

Results have been obtained on small plots for sycamore and poplar and are provided in references 1 and 2*. The sycamore trees were planted in varied spacings in different plots to determine maximum yields over 1 to 5 year cycles. The lowest ovendry yield of wood and bark from seedlings 4 years of age spaced on 6 x 4 ft. intervals was 1.72 tons per year. The highest yield was 3.8 oven dry tons per year for seedlings spaced on 1 x 4 ft. intervals. Reference 2 presents the results of a study of a forest model dominated by yellow poplar and located in the Appalachians of East Tennessee. The estimated annual yield was 5.36 tons per acre of dry biomass including all vegetation. Reference 3 which lists reference 4 and 5 in its bibliography provides an estimated yield of 2 tons per acre per year of net biomass for the forests of the state of Vermont.

* A list of references is supplied at the end of this appendix.

In the appalachians of the state of Virginia the average spacings of trees based on a cursory inspection of areas around Roanoke, Virginia is equal to or less than the 4 x 6 foot intervals for which the production of sycamore was 1.72 tons per year It appears that the use of this figure would be conservative in estimating energy yields for most of the National Forests.

U. S. Forest Service Research - In a letter from the Chief Forest Ecologist Stephen G. Boyce of the Southeastern Forest Experiment Station, Asheville, North Carolina it was confirmed that in 1976 the Station personnel were doing research for estimating biomass from the Appalachian Forests. One of the goals of the Station's studies is to generate energy tables for Appalachian Hardwood Forests. Background knowledge which would be helpful in the task had been generated over the years dating back to at least 1912. Reports which provide above ground yields for a wide variety of trees are listed in references 6 through 16. Additional yield information is provided in references 17 through 22. Economic and Growth information on short rotation sycamore is provided in references 23 through 25. It appears that the United States Forest Service will be providing adequate information on biomass yields as well as direction on how to maximize yields for successive generations of growth.

Estimate of Forest Land Available for Fuel Production - The economic changes that would result from intensive use of forest products for fuel whether used directly or converted to liquid fuels cannot easily be predicted. In addition to lumber, pulpwood for rayon and paper must be supplied by the forests. As with biomass it is difficult to predict production per acre of each. Lumber production in the U. S. in 1975 was estimated at 31 billion board feet (Britannica yearbook, 1976). If it is assumed that an annual harvest of .5 tons per acre per year of conventional harvest (ref. 3) can be realized and using an average figure of 2866 pounds per 1000 board ft. for well seasoned yellow pine, douglas fir, and white pine, the total area required to grow one year's production of 44.42×10^6 tons would be 89×10^6 acres which is approximately 54 percent of the acreage in the National Forests for the contiguous 48 states or 12 percent of the acreage eligible for fire protection.

The total rayon and acetate production (USDA) in the U. S. was 599,400 tons. If it is assumed that wood pulp provided all of the cellulosic raw material, the tons of wood required can be computed on the basis of 4.25 tons of green wood per ton of rayon fibers or 2.5 million tons of green wood. The total weight for paper production in 1974 was 61 million tons (1976 Britannica yearbook). Based on a figure of 3.4 tons of green wood per ton of paper the total wood requirement for paper was 705 million tons. Summing the requirements for rayon and paper gives a total of 707.5 million tons of green wood. The average moisture content for red oak, white oak, yellow pine and white pine is 42 percent. With 12% moisture the total weight would be 495 million tons. It can be assumed that production per acre per year will equal at least 1.4 tons of wood with 12 percent moisture per year. Thus, a total of 354 million acres will be required to supply wood for paper and rayon. This is 217 percent of the National Forest acreage or 47 percent of the total acreage eligible for fire protection. The total acreage required for lumber and pulp production is 229 percent of the

National Forest acreage or 59 percent of the total acreage eligible for forest fire protection. In the foregoing, the current practice of using sawdust and slabs from the lumbering operation in papermaking was not taken into account.

Of the land eligible for forest fire protection the area left for fuel use would be 308 million acres. On a basis of 1.72 tons of dry matter per acre per year the total fuel that could be produced is 5.30 million tons or with more intense maintenance and a production rate of 5.36 tons per year the fuel that could be produced is 1651 million tons. Upgrading of forests for pulp production to 4.56 tons per year could make available an additional 245 million acres and 1315 million tons of biomass per year for fuel.

The foregoing projections which are based upon gross statistics are obviously subject to error, but they place the overall picture in perspective. Since the nineteen thirties much of the marginal farm land has been allowed to revert to woodland growth, increasing the forest area. The current projection by some that there will be a severe shortage of saw timber by 1999 may or may not be correct in view of the recent advances in plywood manufacturing techniques, particle board developments, and use of glued segments. However, the concept of 4 to 10 years growth before cutting for fuel rather than 30 to 40 years as is required for saw timber can place much of the forest land in a much more attractive position for investment. There is much to be settled nationally regarding clear cutting of forests. Regardless of the arguments pro and con, however, forest biomass represents a very large source of renewable energy which should be utilized more heavily with the depletion of fossil fuels.

Energy Plantations and projected programs for extraction of energy from biomass are discussed in references 26 and 27. Included in reference 27 is projection of conversion technology programs to at least 1985. It is possible that the natural forests can be developed rapidly as a biomass source and in view of that possibility it is believed that conversion technology research and development should proceed as rapidly as possible. If the end use of forest products is to be fuel, the most efficient manner of conversion to sensible heat is through direct combustion. It was the purpose of this study to make some projections as to the electric power needs that can be met with forest products, to relate their use to existing modes of power generation, and to formulate an approach toward turning them to practical use.

Projections as to Needs That Can Be Met - According to the 1976 World Almanac, which in turn quotes the Federal Power Commission, the electric power other than hydroelectric that was generated in 1974 amounted to 1,564,513,909,000 kilowatt hours. The 1976 Britannica Yearbook which quotes United Nations Statistics shows an approximate 90 billion kw-hr. higher figure than the World Almanac for 1973 the latest year given by the Year Book. This appears to be a difference approximately equal to the amount generated by nuclear power. It is not considered significant for the following comparison so the above figure will be used. As noted in preceeding pages,

only approximately 41 percent of the forest land or 308 million acres would be available for fuel use because of ongoing needs for lumber and pulpwood. For this comparison the following was used:

Average higher heating value of wood, Btu/lb.	7680
Average power plant thermal efficiency, %	32.5
Average biomass yield per acre, tons	1.72

From the above it can be determined that the average electrical energy yield per acre of rough forest is 2516 kw-hrs. The total yield from the 41 percent of the forest land (308 million acres) would be 774,928 million kw-hrs. or 49.5 percent of the power generated by other than hydroelectric plants. With intense forest management for the 308 million acres the potential of 5.36 tons of biomass per acre might be reached in which case the potential yield would reach 154 percent. The foregoing was based upon improving only the land available after lumbering and pulpwood needs are satisfied. With an increase to 4.56 tons per acre for pulpwood production 245 million additional acres would become available for growing biomass for fuel. With the increase of 1315 million tons of biomass another 123% of current power production other than hydroelectric would be possible.

Relation of Forest Biomass to Existing Modes of Power Generation - It appears that the amount of power that can be generated in the 48 contiguous states with forest biomass without disrupting supply for lumber and pulpwood will range between 50 and 275 percent of the current power generation other than hydroelectric depending upon the degree of forest improvement. Fossil fueled power needs in 1974 were met by use of gas (29%), oil (15%), and coal (56%). The above percentages were derived from ref. 30. Intensive efforts have been made to improve methods of burning coal. As a result, boilers have been developed that can use coal, gas, or oil interchangeably. Wood has received very little attention as a fuel for interchange with fossil fuels. The cost, for example, of shredding wood is regarded as excessive by some, whereas pulverization of coal is an accepted economical practice. If forest biomass is to become a viable source of fuel it is important that an attempt be made to devise methods of using wood as a fuel in existing boilers of 500 megawatts and above because of the large amount of development work that has been accomplished on boilers of that size. This area appears to be the one most vital to wood use. Although the efficient collection of biomass must be developed, it is clear from at least one paper plant operation that economical collection of wood for fuel is possible. The Westvaco paper mill in Covington, Virginia purchased and used 1,679,728 tons of green wood at approximately $10.00 per ton delivered to the mill in 1975. Based on data from U.S. Department of Agriculture Bulletin 753 that amount of wood dried to 12% moisture is equivalent to 837,590 tons of coal. The average amount of coal required for the TVA boilers is 9.02 tons per megawatt output each 24 hours (references 29 and 30.) The amount of power that could be generated by the pulpwood consumed by the Westvaco mill is 2,228,621 megawatts. Thus, a 424 megawatt generating plant operating at the approximate

industry average of 60 percent capacity could be fueled by the wood consumed at the Westvaco plant. The cost of fuel in this example would be 0.754 cents per kw-hr. The foregoing is based upon the assumption that wood can be burned as efficiently as coal. Paper mills will not accept bark coated wood less than approximately 4 inches in diameter nor will they accept dead wood. For fuel use a significantly greater quantity of biomass could have been supplied at lower unit cost. It is reasonable to assume that for an experimental wood fired boiler system an adequate supply of wood for an extended period could be assured at economical prices.

The results of the foregoing study do not include biomass from sources such as the estimated 56 million acres of mesquite infested range land in Texas. According to reference 31, approximately 34 million acres of the mesquite infestations in 1971 were estimated to be dense enough to produce 10 to 40 tons per acre of raw wood. The annual regrowth is variously estimated at between one and two oven dry tons per acre.

Waste wood, which was not considered in the study constitutes a large wood source according to information in reference 32 by the Battelle, Columbus Laboratories. The following table which was prepared from that information shows the percent power generated by oil or gas in various geographical areas in 1976 and the estimated percent of the oil or gas that could be replaced by waste wood:

	Power Generated By Oil Or Gas %	Oil Or Gas That Could Be Replaced By Waste Wood %
New England - ME, NH, VT, MA, CT, RI	79	29
Middle Atlantic - NY, NJ, PA	43	8
West North Central - ND, SD, NE, KS	38	18
East North Central - MN, IL, MI	0	-
South Atlantic - WV, MD, VA, NC, SC, GA, FL	32	77
East South Central - KY, TN, MS, AL	0	-
West South Central - OK, AR, TX, LA	100	19
Mountain - MT, WY, ID, CO, NV, UT, NM, AZ	30	118
Pacific - WA, OR, CA	83	103

It is probable that the amount of waste wood now available has greatly decreased since the above figures were compiled due to an upsurge in the use of wood in homes and industrial furnaces.

It is indicated by this brief study that the existing forested areas in the contiguous 48 states are a significant potential source of renewable energy even without a change in forestry practices, and that with changes in practices a tremendous increase in that potential can be realized.

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APPENDIX 2

IGNITION TIMES OF WOOD PARTICLES

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INTRODUCTION

The possibilities of using wood as a fuel have led to this study of the pre-ignition zone of a wood-fired utility boiler. A short description of the modelled system is relevant here.

Preheated air is split into "primary" and "secondary" air. The primary air is used to carry the fuel, small wood particles, to the furnace. It is assumed that the secondary air mixes instantaneously with the primary air and wood stream at the burner mouth. The temperatures of primary and secondary air may or may not be the same. For the purposes of this model work, two particle sizes were chosen: small: 0.00521" X 0.00391" X 0.0260"

large: 0.01042" X 0.00781" X 0.05208"

The equations for heat transfer to and from the wood were developed and solved.

MODEL BASIS

It is appropriate to begin with some warnings about the value of the results of this study. In order to model the system, it is essential to be able to write equations for the heat tranfer to and from the particle. By considering each of these in turn, we shall see that an inflexible heat transfer equation cannot possibly be applied in an exact manner.

Firstly, the radiative heat transfer to and from the particle can only be calculated with a knowledge of the temperature of the walls, the gases, the flame and the particle itself. The "flame temperature" is, of course, not just one temperature at all but rather should be the integrated effect of the temperature distribution throughout the flame. A particle "looking" downstream can "see" the flame front, but radiation comes through the flame front from the rest of the flame. Similarly, the gas radiation (primarily

from carbon dioxide and water vapor will be the integrated effect of the wide temperature distribution of the furnace atmosphere. Next, the particle surface temperature is critical in the radiative heat transfer equation (as are all temperatures: a consequence of the fourth power which they carry). It is unfortunate that the particle surface temperature is difficult to estimate accurately because of inconsistencies in the wood structure.

After these considerations, an approach had to be determined and the first one was to develop a step-wise model of the pre-ignition zone. The zone was divided into a number (capable of being increased for accuracy) of small but finite slices. The primary air and wood mixture were admitted to the first one as was the secondary air and instantaneous mixing was assumed. In addition, back-radiation from the flame front was calculated and the convective heat flux between air and fuel estimated from empirical equations. Thus, a heat balance could be carried out giving the air and wood temperatures at the exit to slice #1, which, of course, then became the entry condition for slice #2. This was repeated along the pre-ignition zone and used to calculate the length of time for the particles to reach an arbitrarily-chosen ignition temperature of 600°F. This was found to be around 0.07 seconds. I felt this was low and so I rejected this approach since I felt that a smaller slice was necessary and, if so, a better approach would be to develop and solve differential equations describing the system.

THEORETICAL DEVELOPMENT

The results given in this report were achieved using a series of differen-

uations. Their development was as follows.

fer by radiation.

sfer by radiation can be predicted by means of the following

$$Q_{12} = \sigma A_1 F_{12} (T_1^4 - T_2^4) \quad (1)$$

where Q = the heat transferred between the two surfaces, BTU/hour.

A = the area affected, ft^2.

F = the view factor between the surfaces,

T_1, T_2 = the temperature of the surfaces, ^oR.

and σ = the Stefan-Boltzman constant. $[0.1713 \times 10^{-8}$ BTU/ft^2.hr. $(deg.R)^4.]$

In the system studied, heat transfer by radiation occurs in three different ways: - 1. between the wood chips and the flame front;

2. between the air and the flame front;

3. between the air and the wood chips.

A radiative heat transfer equation must be developed for each of them.

The view factor between the wood chips and the flame front is given by (McCabe and Smith - Unit Operations of Chemical Engineering): -

$$F_{12} = \left(\frac{1}{e_w} + \frac{1}{e_f} - 1 \right)^{-1} \quad (2)$$

where e_w = the emissivity of the wood

e_f = the emissivity of the flame

and F_{12} = the view factor.

It was assumed that the emissivities remain constant.

The view factor between the air and the flame front is given by:

$$F_{gf} = \left[\frac{1}{e_f} + 0.8 \left(\frac{1}{e_g} - 1 \right) \right]^{-1} \quad (3)$$

where e_f = the emissivity of the flame

e_g = the emissivity of the air

and F_{gf} = the view factor.

Again, it was assumed that the emissivities remain constant. The is the area of the flame front as "seen" by upstream air.

The view factor between the air and the wood chips is given by:

$$F_{gw} = \left[\frac{1}{e_g} + \frac{A_g}{A_w} * \left(\frac{1}{e_w} - 1\right)\right]^{-1} \quad (4)$$

where e_g = the emissivity of air,
e_w = the emissivity of wood,
A_g = the area of air,
A_w = the area of wood
and F_{gw} = the view factor.

Again it was assumed that the emissivities remain constant. The area term is the surface area of the wood chips.

Heat Transfer by Convection

Heat is also tranferred between the air and wood chips by convection. The heat flux may be calculated by use of the following equations:

$$Q_c = h_c A (T_g - T_w) \quad (5)$$

where Q_c = the heat transferred by convection, BTU/hr.
h_c = the heat-transfer coefficient, BTU/ft^2.hr(deg.R)
A = the heat transfer area, ft^2.
and T_g, T_w = the air and wood temperatures, ^oR.

Total Heat Transer

The total heat transfer to the wood in this system is given by the following equation:

$$Q_T = \sigma A_f F_{fw}(T_f^4 - T_w^4) + \sigma A_w F_{gw}(T_g^4 - T_w^4) \quad (6)$$

where A_f = the area of the flame front, ft^2.
F_{fw} = the view factor between the flame and the wood,
F_{gw} = the view factor between the air and the wood,
h_c = the convective heat transfer area, BTU/ft^2. hr.(deg.R),

A_w = the surface area of the wood chips, ft^2.,

T_f = the flame temperature, ^oR.,

T_g = the gas temperature, ^oR.,

T_w = the wood temperature, ^oR.

the heat received by the wood is given by:

$$Q = m_w C_{pw} \, dT \tag{7}$$

where m_w = the mass of the wood, lbs.,

C_{pw} = the heat capacity of the wood, BTU/lb.,

and dT = the temperature change, (deg.R)/hr.

The heat flux to the air is given by:

$$Q = \sigma A_f \, F_{gf} \, (T_f^4 - T_g^4) \tag{8}$$

where A_f = the flame area, ft^2.

and F_{gf} = the view factor.

The temperature change of the air is given by:

$$Q = m_a \, C_{pa} \, dT \tag{9}$$

Where m_a = the mass of the air, lb.,

C_{pa} = the heat capacity of the air, BTU/lb.,

and dT = temperature change, (^oR)/hr.

In order to determine the temperature profiles of the wood and air, one must take the first derivative of equations 6 and 8 with respect to time. This leads to a system of differential equations which can be solved by numerical methods:

$$dQ_a = 4\sigma A_f \, F_{fg} \, (T_f^3 - T_g^3) \, dT_a \tag{10}$$

$$dT_a = Q_a/m_a\ C_{pa}$$

$$dQ_w = 4\ A_f\ F_{fw}\ (T_f^3 - T_w^3)\ dT_w + 4\ A_w\ F_{wg}\ (T_g^3 - T_w^3)\ dT_w + h_c\ A_w\ dT_w$$

$$dT_w = Q_w/m_w\ C_{pw} \qquad (13)$$

MODELLING

The temperature profiles of the wood chips in the pre-ignition zone were determined by computer simulation. The differential equations listed above were solved using the Runge-Kutta fourth order method. This method can be viewed as an extension of Simpson's quadrature rule to differential equations and is designed to approximate Taylor series methods. A more complete description of the method used in this project may be found in the literature.(1) The Runge-Kutta algorithms are available in a subroutine in the University of Texas Computation Center Library. The subroutine can be "called" by user programs.

The computer code used in this project at the Center is UT2D, 6600 11.59. It is in FORTRAN and includes a main program with two primary subroutines, RKF45 and INITIAL, and five secondary subroutines, SPLINE, AIRMIX, VIEWF, AREAS and CONVCT. Subroutine RKF45 contains the Runge-Kutta method and it solves the system of the discrete points supplied by the user. A list of assumptions is provided in the Appendix.

(1) Computer Methods for Mathematical Computations. Forsythe, Malcolm and Moler, Prentice-Hall 1977, pg. 121.

RESULTS AND CONCLUSIONS

Table 1 shows the ignition times for the smallest possible wood chips, which had an average length of 0.02604 inch, an average width of 0.005208 inch, and an average thickness of 0.003906 inch. Table 2 shows the ignition times for the largest wood chips studied which had an average length of 0.05208 inch, an average width of 0.01042 inch, and an average thickness of 0.007812 inch.

Figure 1 presents the information of both tables in graphical form. The air feed split ("duty split") is in terms of percent of total mass of feed over percent of total mass of make-up air.

Some of the results shown here lead to rather surprising conclusions. First, Figure 1 shows that the shortest ignition times are produced when relatively small amounts of make-up air are used. Also it is surprising that the temperature of the feed stream and air stream appears to have no effect upon the ignition time when small amounts of make-up air are used. Of the cases tested here, the optimum operating condition, with respect to ignition time, would be a 70/30 duty split with a primary air feed temperature of 550°F and a secondary air temperature of 800°F.

Table 2 shows similar results for the largest chip sizes.

Conclusions

This heat transfer study has resulted in a system of differential equations describing the pre-ignition zone in a wood burning furnace, and a computer program to solve those equations.

Some preliminary results are presented in order to generate feedback from the concurrent experimental work. The computer program can be run again in the future with different data as required.

APPENDIX

LIST OF ASSUMPTIONS

1. All emissivities were assumed to be constant.
2. All heat capacities were assumed to be constant.
3. All wood chips were assumed to be one (average) size.
4. Feed and secondary air were assumed to be completely mixed as they entered the furnace.
5. All back radiation from the flame was absorbed by the wood or by the air.
6. The heat transfer coefficient (air/wood) was assumed to be constant.
7. The projected area of the flame front was assumed to be a disk.
8. The wood chips were assumed to be bone dry.

Table 1

Ignition Times For Smallest Chip Size

Duty Split	Feed Temp. (°F)	Air Temp. (°F)	Time (Sec.)
50/50	650	1000	0.6
60/40	650	1000	0.6
70/30	650	1000	0.6
40/60	650	1000	0.7
30/70	650	1000	0.8
50/50	650	800	0.7
60/40	650	800	0.6
70/30	650	800	0.6
40/60	650	800	0.8
30/70	650	800	0.9
50/50	550	1000	0.7
60/40	550	1000	0.6
70/30	550	1000	0.6
40/60	550	1000	0.7
30/70	550	1000	0.8
50/50	550	800	0.7
60/40	550	800	0.7
70/30	550	800	0.6
40/60	550	800	0.8
30/70	550	800	0.9

Table 2

Ignition Times For Largest Chip Size

Duty Split	Feed Temp. (°F)	Air Temp. (°F)	Time (Sec.)
50/50	650	1000	1.70
60/40	650	1000	1.80
70/30	650	1000	1.60
40/60	650	1000	2.70
30/70	650	1000	3.50
50/50	650	800	2.20
60/40	650	800	1.90
70/30	650	800	1.60
40/60	650	800	2.70
30/70	650	800	3.40

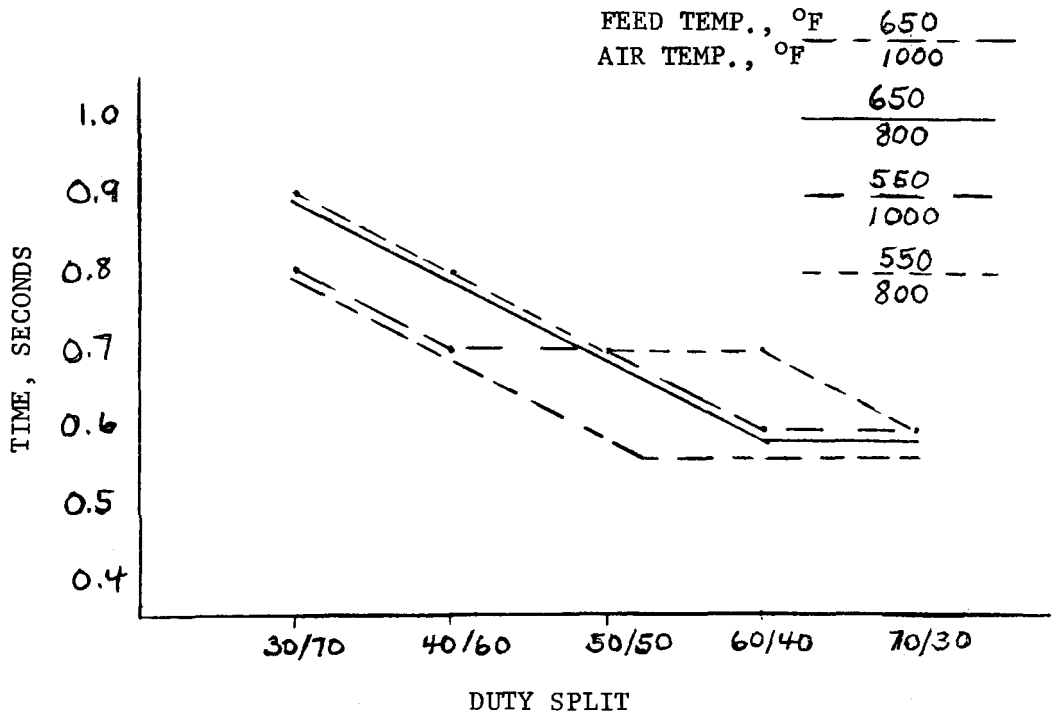

FIGURE 1 - IGNITION TIMES FOR SMALLEST CHIP SIZE

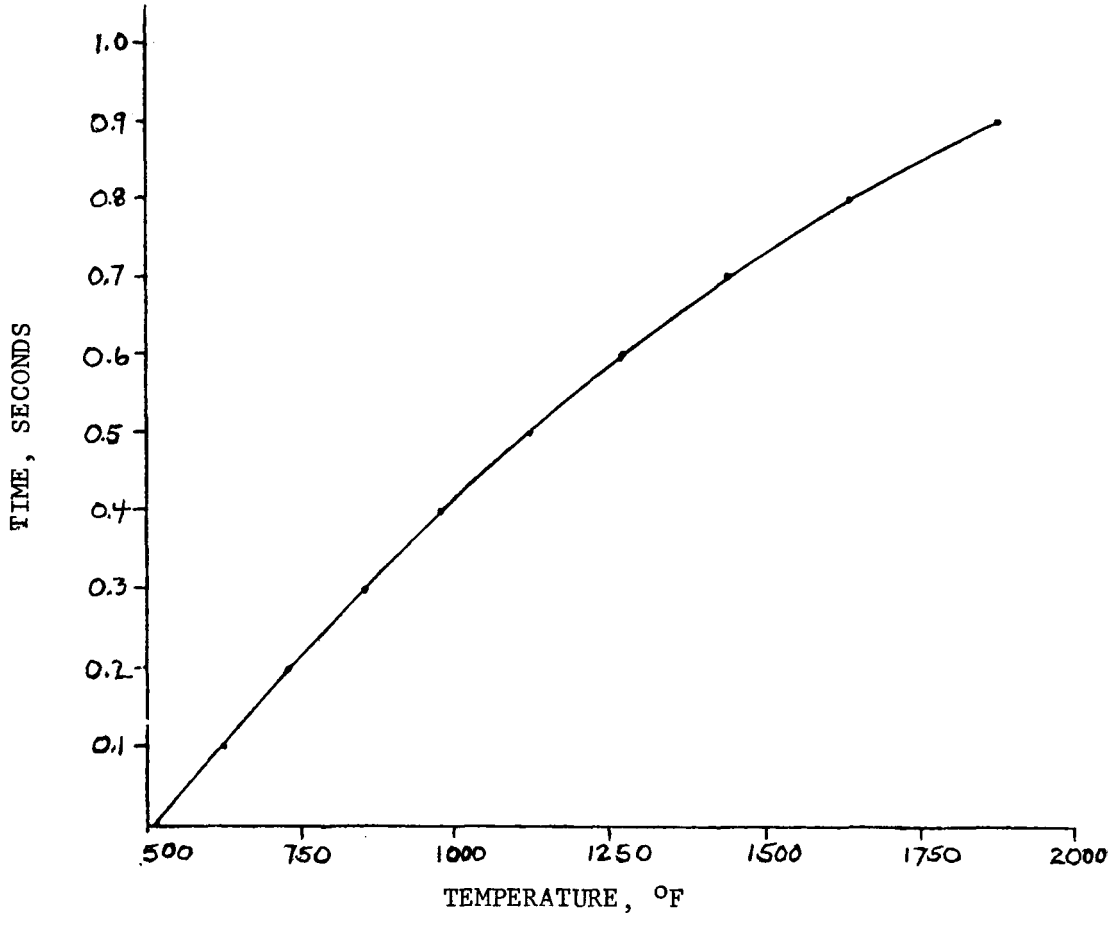

FIGURE 2 - TYPICAL WOOD CHIP IGNITION TEMPERATURE

APPENDIX 3

THE DRYING, PYROLYSIS, AND CHAR BURNING OF INITIALLY MOIST WOOD CHIPS IN A SUSPENSION BURNER

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THE DRYING, PYROLYSIS, AND CHAR BURNING OF INITIALLY MOIST WOOD CHIPS IN A SUSPENSION BURNER

INTRODUCTION

A suspension burner, using either gravity or swirl, or both, to ensure that the particle residence time in the combustion chamber is longer than the gas residence time, allows almost complete combustion of wet wood in a reasonably-sized combustion chamber without predrying or significant air preheating. A sample design (Ref. 1)* is shown in Fig. 1. Other designs that achieve long particle dwell times through the use of swirl offer potential retrofit incorporation into existing furnaces. The system shown in Fig. 1 is designed for handling wet bark and has a thermal output of 1000 kilowatts per cubic meter of combustion chamber. Briefly, the particles are fed by the screw feeder to the bottom of the reaction chamber where they are entrained with incoming air that is introduced in a high-speed annulus. The jet velocity is high enough so that it overcomes the fuel particle fall velocity until a height, shown in Fig. 1 as h_f, is reached. At this height the reduction in jet velocity due to mixing with the recirculated gases allows the particles to fall along side of the jet and be reentrained and recirculated until their weight reduction permits them to rise higher in the jet. After complete dehydration, when pyrolysis commences, the particles will achieve a height shown as h_p, and after complete reduction to char by pyrolysis, they will reach a height shown by h_c. Near the top of the burner the outer wall flares, increasing the cross-sectional area and reducing the gas velocity. If the burner is well designed, this velocity leaving the top will be uniform, and the particles leaving the top of the burner will be those left over from the incomplete combustion of the char at a particle size determined by gas velocity exceeding the fall velocity.

*References for this appendix are provided on page 64.

The gas leaving the top of the burner will be at a temperature and composition that may be estimated from the adiabatic combustion of the incoming wet wood, taking into account the unburned carbon particles entrained.

In the following sections there will be presented: (1) a method for predicting the adiabatic flame temperature, (2) a relationship between the total processing time of the chips and the volume requirements for the desired thermal power, (3) a calculation of the drying time of a chip, (4) the pyrolysis time of a dehydrated chip, and (5) the burning time of the char resulting from the pyrolysis of a chip. When these calculations are examined, it is seen that the total processing time (= drying + pyrolysis + char burning time) is sufficiently large to require a larger combustion chamber than an optimum (derived from consideration of a theoretical minimum combustion chamber volume estimated from chemical kinetics). The char burning time is found to be the longest of the three times such that chip predrying alone would have little effect on the overall processing time. It is recommended that an optimum system would have total processing times of two seconds and that a volume reduction of the proposed chip size of tenfold would accomplish this.

RESULTS AND DISCUSSION

Thermodynamics

In Ref. 2 the use of formaldehyde CH_2O (ℓ) as an analogue for wood in estimating thermodynamic processes is discussed by Forman Williams. The accompanying calculations were made assuming the enthalpy of wood is the same as that for liquid formaldehyde. When the wood is moist, the enthalpy of formation is taken as that of the appropriate mixture of water and formaldehyde. The properties of exhaust products at thermodynamic equilibrium are obtained for a variety of inlet conditions, making use of a combustion

equilibrium calculation procedure originated at NASA Lewis Laboratory (3) and presently in use at the University of Minnesota. The results of these calculations are displayed in the form of enthalpy composition diagrams, figs. 2-5. The enthalpy of the mixture is shown on the ordinate, the mole fraction is the abscissa, and the lines of constant temperature at thermodynamic equilibrium are plotted. These calculations have been made for dry wood and for 25, 50, and 75 percent water in wood on a mole basis.

The enthalpy of the incoming air is easily found by tracing the appropriate isotherm to the left ordinate. The enthalpy of the incoming moist wood is found by multiplying the temperature difference above $0^{o}C$ by the specific heat of the moist fuel and reading off the resulting enthalpy rise above the zero enthalpy line, marking the position on the right-hand side of the diagram where mole fraction of fuel is unity. (NOTE: The isotherms are plotted for conditions of thermodynamic equilibrium. Wood is metastable; thus, the isotherms shown do not represent wood at the initial, metastable state but after reaching thermodynamic equilibrium). In order to determine the adiabatic flame conditions, connect the inlet air point with the inlet fuel point [found by measuring off $C_{p_{wood}}$ (T [K] - 273 [K])]; then read off the combustion chamber conditions at the appropriate mole fraction of fuel. For example, with air at $0^{o}C$ and wood initially at $0^{o}C$ and a mole fraction of fuel of .5, the intersection of the adiabatic mixing line and the f = 0.5 line falls on the $1400^{o}K$ isotherm. On the other hand, if the wood remains at $0^{o}C$ and the inlet air is heated to $1000^{o}K$, the value of the 50 percent fuel line would yield an equilibrium flame temperature of approximately $1600^{o}K$.

The effect of unburned char leaving the combustion zone can be estimated in the following manner: The enthalpy is subtracted from the enthalpy

of the inlet fuel, unavailable because the char is not burned (m_{char}/m_{fuel} x $\Delta H_{c,char}$) to obtain the effective enthalpy of the incoming fuel.

Resident Time in Furnace

If the flow through the combustion chamber shown in Fig. 1 is $\dot{W} = \bar{\rho}\bar{u}A$ and dwell time for a gas particle is $\tau_g = L/\bar{u}$, and reactor volume is $V = LA$, then $\tau_g = V\bar{\rho}/\dot{W}$. The thermal power, P, of the combustion chamber is $P = \dot{W}C_p\Delta T$. Then the volume required per unit of thermal power is $V/P = \tau_g/\bar{\rho}C_p\Delta T$.

A chemical kinetic limit for a well-stirred reactor burning hydrocarbons at one atmosphere pressure is $V/P = 1\ m^3/3 \cdot 10^6$ KW (Ref. 4). We will assume that for pyrolysis products this quantity is $10^{-6}\ m^3/KW$. Combustion chamber designers can hope to reach 1 but not 10 percent of this limit. Then, if $\bar{\rho}C_p\Delta T = 1000\ KJ/m^3$, $10^{-3} < \tau_g < 10^{-2}$ sec. Wet wood chips require longer burning times to dry, pyrolyze, and burn the char than do gaseous fuels. Therefore, it would be good practice if the dwell time τ_f for the fuel is greater than τ_g. Thus, a burner is usually designed so the volume of wood chips per unit volume of mixture in the combustion chamber C_c is greater than that in the incoming mixture, C_i, such that $C_c/C_i = \tau_f/\tau_g$. If C_c is to be kept less than $10^{-2}\ m^3 wood/m^3 mixture$ (in order to behave like a dilute suspension and not have prohibitive particle coagulation) and if $C_i \simeq 5 \cdot 10^{-4}\ m^3 wood/m^3 mixture$, then τ_f must be less than 20 τ_g. Employing this limit we find that the time required for particle burning determines the combustion chamber volume for unit power, as shown below ($V/P = \tau_f/20{,}000$).

τ_f, sec	$\frac{V}{P}\ m^3/KW$
20	$\frac{1}{1000}$
2	$\frac{1}{10{,}000}$
0.2	$\frac{1}{100{,}000}$

A reasonable target for a combustion chamber is a V/P that is one percent of the chemical limit. This points to a τ_f = 2 sec. On this basis, we conclude that if the particle fed to the burner in Fig. 1 were small enough, it should be able to accept ten times the air flow it is presently designed to take and should be able to put out ten times as much thermal power for the given volume. Particle size reduction to yield a total particle dwell time of two seconds appears worth working for. We will show below that this means reducing the size of particle employed to about one-tenth the presently proposed mass. Further particle size reduction, below that which gives τ_f = 2 sec, should not greatly improve furnace performance because gas phase mixing and chemical kinetic limitations would dominate over limitations introduced by particle performance. On the other hand, if the furnace has a combustion chamber that is over-designed (that is, V/P > 1/10,000) and is to be converted to wood burning, there is little reason to "overgrind" the wood. Briefly, if the combustion chamber allows fuel particle dwell times 20 times τ_g (as in a suspension burner), the optimum size is that which gives a particle process time of τ_f = 20,000 V/P.

When the particle dwell time is forced to follow the gas stream, optimum size is determined by a total process time, τ_f = 1000 V/P. Here τ_f is in seconds, V in m^3, and P in thermal kilowatts.

Drying Time

Experiments with wood (even almost completely dry wood) rapidly heated from the surface show that the water that remains in the wood evaporates and migrates into the cooler core of the wood and thus generates a fairly thick thermostated region within the wood at about the boiling point of water (5). Then, as the outer regions of the wood dry out, this constant temperature region shrinks to the center of the wood being heated. We will take advantage

of this behavior in estimating the drying time for the wood and assume that the wood is introduced at its boiling point and that its surface remains at the boiling point until it is completely dry. After the calculations have been completed, we will show that the resistance offered by the dry wood layer toward the end of the drying process is smaller than the resistance offered by the fluid mechanic boundary layer, and thereby justify its neglect in the drying process. Because heat and mass transfer literature is frequently in CGS units, I will switch to those units at this point. The specimen has the dimensions 0.79 x 0.159 x 0.119 cm and a mass of 0.0127 g, which is half water, half wood. The surface area is .477 cm^2. We make the assumption that the terminal (free fall) velocity that regulates the heat and mass transfer to and from the wood chip will be calculable by assuming that the particle behaves as though it were a sphere with a surface area of the wood chip ($4\pi r^2$ = .477 cm^2); that is to say, of radius R = .195 cm. It has the weight of the original particle. In the calculation it is convenient to account for the weight by employing a fictitious density; we will use the volume of the sphere having the same radius (which has twice the volume of the wood chip), and therefore the chip will behave like a sphere of half its original density ($\rho_{original}$ = 0.6734 g/cm^3); that is, it behaves like a sphere of volume $3.1 \cdot 10^{-2}$ cm^3, of density .337 gm/cm^3, and of total mass 0.0127 gm. A first attempt at calculating thermal velocity by assuming that Stokes flow exists, quickly reveals that the Reynold's number of the resulting particle (Reynold's number $Re = u2R/\nu$) in free fall is outside of the Stoke's flow regime. The free fall velocity u was therefore calculated using the intermediate low friction factor, $f = 18.3/Re^{3/5}$. Thus, the drag is

$$\frac{1}{2} \rho u^2 A f = \frac{4}{3} \pi R^3 g \, (\rho_s - \rho); \; f = 18.5/(u2R/\nu)^{3/5}$$

or

$$u^{7/5} = \frac{8 \times 2^{3/5}}{3 \times 18.5} R^{8/5} \cdot \frac{g(\frac{\rho_s}{\rho} - 1)}{\nu^{3/5}}$$

let

$$R = 0.195,\ g = 981,\ \frac{\rho_s}{\rho} = 337 \times \bar{T}/300 = 1051,\ \nu = 1.16\ cm^2/sec$$

(ν is evaluated at T = 936 K)

u = 962 cm/s, Re = 324 at start of drying

At end of drying ρ_s/ρ = 525, u = 586, Re = 197

Then, using the Nusselt number for sphere in cross flow, we obtain

$$Nu = \frac{h2R}{k} = 2(1 + 0.28\ Re^{1/2}\ Pr^{1/3}) \quad \text{(for Pr = 1)}$$

Say, Nu = 14.54 to 11.74. The temperature in the recirculating gas is assumed to be 1500°K, and the surface temperature is 373°K. Then the mean temperature in the boundary layer will be 936 K and the thermal conductivity (estimated from air values) is $1.1 \cdot 10^{-4}$ cal/cm s K. The heat transfer coefficient is then

$$h = \frac{k}{2R} \cdot 13.11 = 3.7 \cdot 20^{-3}\ cal/cm^2\ s\ K$$

A mean heat transfer rate is $h \cdot A \cdot \Delta T = 3.7 \cdot 10^{-3} \cdot 0.477 \cdot 1127$ = 2 cal/s. If we assume that the barrier to heat flux is the gas boundary layer and the initial particle is 1/2 water (i.e., weight of water is $5 \cdot 10^{-3}$ g), the drying time will be $5 \cdot 10^{-3} \cdot 539 = 1.94$ sec.

It is now of interest to compare the heat transfer coefficient with the barrier to heat flux within the solid when the water has retreated to the core of the wood fragment. We will use the thermal conductivity of the solid (4×10^{-4} cal/cm s K) divided by the half thickness (.06 cm) and obtain

a solid conductance of 6.67×10^{-3} cm^2/deg. Now, if we compare the u value in the following way

$$\frac{1}{U} = \frac{1}{h} + \frac{\delta}{k} = 270 + 150 = 420$$

$\frac{U}{h} = 0.64$; mean value of U is $2.6 \cdot 10^{-3}$, we see that the U would be reduced from the gas value of 3.7×10^{-3} to $2.38 \cdot 10^{-3}$ cal/deg cm^2/sec at the end of drying. These values are of interest in two respects. First of all, there is not enough alteration in the overall heat transfer coefficient to warrant taking the internal resistance into account. The second points out the unresponsiveness to increasing h; should we greatly speed up the relative motion by making the flow excessively turbulent or introducing extremely high values of swirl, the U value would be determined by resistance to heat flux within the solid and would stay quite close to the value presented here. Thus, we feel that the heat transfer calculation as employed represents a good estimate of the drying time, even if our estimate in the film heat transfer coefficient were to turn out to be too low.

The value of the drying time derived above, 1.35 s, will be seen below to be roughly the same as the pyrolysis time of the particle and about one-third the burning time of the char. Thus, an investment in a fuel dryer would reduce combustor volume by less than 25 percent.

If the shapes of particles remain similar but the size changes, drying times vary as

$$\tau_d = \frac{36.4\ (\text{mass}_0)^{2/3}}{k\Delta T(1 + 25.3\ (\text{mass}_0)^{1/3})}$$

Pyrolysis Time

There are numerous basic studies of pyrolysis of dry cellulosic fuels. I have been unable to find studies which would address the potential merit of pyrolyzing wet cellulosic fuels. I will treat the pyrolysis process as though it occurred independently of the drying and char burning processes. There are good reasons to expect that this is not a bad assumption. First, not much pyrolysis can occur in the superficial layers of the fuel particle while the core is dehydrating because the drying time is short compared to the pyrolysis time until the surface exceeds 700°K. I think it is possible to defend the postulate that for the size of particles proposed and smaller, the sequence of events is dry--pause--pyrolyze--no pause--char gasification.

In the next section I estimate a char gasification time as though no char burning occurred during pyrolysis. In larger specimens we have shown that this is not the case (5): char burning accompanies pyrolysis. On the other hand, the amount of char formed depends on the history of the heating rate. The process can produce more char (at low heating rates and high inorganic impurities) or less (high heating rates and low inorganic impurities).

In any event, 20 percent char residue at the end of pyrolysis is a reasonable fraction to be disposed of after pyrolysis ceases, so the time required for char removal may be justified even though the tidy sequence of events, drying--pyrolysis--char burning may not be all that tidy in respect to the overlap of pyrolysis and char burning.

An inspection of the literature shows that the strongly endothermic reaction that occurs in pure α-cellulose at approximately 350°C is not found in wood, and the strong exothermic reaction that occurs at 410°C in lignin also is muted by the presence of cellulose (6) (see Fig. 6). Thus, a reasonable assumption in modeling the pyrolysis of wood as a result of very rapid

heating is that the heat of pyrolysis is nil and that the pyrolysis rate is determined by the rate of heating the wood to the pyrolysis temperature. Maa and Bailie have made sample calculations on different-sized particles and have concluded that for particles of the size less than 1 mm, the heat transfer process is not important and that kinetics dominate (7). I will show that when the gas temperature is $1000^{o}K$ or higher the heating rate remains important for particles 1 mm in radius and that the woody particle behaves as though it were a fuel oil with a boiling point (depending on size) somewhere between 725 and 825 K. Murty and I have shown that the apparent kinetics of large specimens varies with the temperature and history (5). For small specimens heated uniformly throughout, Broido and associates have shown that the time a specimen spends at intermediate temperature can modify its subsequent behavior when it is heated to high temperature, and in particular, modify the amount of char which is produced. At the heating rates that are expected in the suspension burner, however, the time an element of fuel will spend at an intermediate pyrolysis temperature is sufficiently short so that the slow pyrolysis discussed by Broido (8) will have no time to alter the specimen. The two kinetic equations usually used for cellulose pyrolysis are (from 2):

1) $\frac{dm}{dt} = A_a \exp(-\frac{Ea}{RT})$; $A_a = 5 \cdot 10^9$ g/cm^{3}s, Ea = 35 kcal/g mole

2) $\frac{dm}{dt} = mA_b \exp(-\frac{Eb}{RT})$; $A_d = 3 \cdot 10^{17}$ s^{-1}, E_D = 55 kcal/g mole

We will use the second equation, because with rapid heating the specimen will not lose appreciable mass by reaction a. The temperature time history of the particle (since the heats of pyrolysis are assumed to be nil) can be estimated from the detailed calculations of "thick" slabs made by Schneider and

appearing in the Heat Transfer Handbook (9). These are included as Fig. 7-11. Figure 12 is a replot of part of Fig. 11. $T - T_o$ in the early stages of warming at the slab's center is a linear function of time for $T - T_o/T_a - T_o < 0.4$. Then $d/d\theta$ can be written $\frac{d}{dT}\frac{dT}{d\theta}$. b becomes b', and b' is

$$\frac{d \ln m}{dT} = \frac{d\theta/\delta^2}{d\left(\frac{T - T_o}{T_a - T_o}\right)} \cdot \frac{\delta^2}{\alpha(T_a - T_o)} \cdot Ab \exp\left(-\frac{Eb}{RT}\right).$$

This is shown in Fig. 13. It can be seen that the integral $\int_{(complete)} \frac{dm}{dt} dt = 4.61$, where the reaction is 99 percent/ occurs at a value of $\frac{d \ln m}{dT} \simeq 1$ where the dimensionless temperature $0.3 < \frac{T - T_o}{T_a - T_o} < 0.4$. Therefore, the time for pyrolysis to occur to, say, 99 percent completion in the center of the specimen can be determined by finding the time required for the center of the particle to achieve a dimensionless temperature between .3 and .4. The data can be expressed in terms of $\alpha\theta/\delta^2$, and the results are shown in Fig. 14. To facilitate the use of Fig. 14 we may show that $Nu = 2(1 + 80\delta)$, $\frac{h\delta}{k_s} = \frac{Nu \cdot kg}{6.52\ Ks}$ or for the chips proposed = 0.5. Figure 14 shows how the value of $\alpha\theta/\delta^2$ is determined to be 0.85 if $h\delta/k_s = 1$ and 1.45 if $h\delta/ks = 0.5$. Then from a knowledge of α and δ(.003 cm^2/s and 0.06 cm, respectively) we find θ = 1.77 sec = τ_p.

The model employed ignores two effects: (a) the specimen is cylindrical and not planar, and therefore the heat rate would be expected to be faster than recorded here, and (b) there will be outgassing that will act to reduce the heat transfer from the surface when the flow of gas is normal to the direction of heat flux. These two effects will tend to cancel each other out, and their magnitudes are not expected to produce more than a factor of two effect; in ignoring them, therefore, we cannot have altered the predicted pyrolysis rate by a great extent.

Even though the kinetics may vary considerably, as long as the onset of rapid pyrolysis is in the neighborhood of 700-800^{o}K (as it appears to be in virtually all woody materials), the pyrolysis time for a given suspending gas temperature and with rapid heating should be approximately the same order of magnitude. It can be seen in Fig. 14 that contrary to Maa and Bailie's results at slower heating rates (7) the rapid heating of small fuel particles is strongly heat-transfer dependent. Those design modifications that influence the heat transfer coefficient h should strongly influence the pyrolysis time.

The effect of scale can be seen from Fig. 14 and from

$\frac{h\delta}{k_s} = \frac{2(1 + 80\delta)k_g}{6.52k_s}$, $2(1 + 805)$ approaches 2 as $\delta \to 0$. Thus, $\frac{h\delta}{k_s} \to 0.08 =$ const so that in this limit θ varies as δ^{-2}.

Char Burning Time

We assume the char particle has the same size and shape of the initial particle but ten percent of the initial mass. (One-half the initial mass is assumed to be H_2O, 80 percent of the dry wood is pyrolyzed, leaving charcoal at an elevated temperature).

We estimate the suspending gas composition from the stoichiometric equation

$$CH_2O + \frac{30}{18} H_2O + O_2 + 3.74\ N_2 \to CO_2 + \frac{48}{18} H_2O + 3.74\ N_2$$

The mass fractions of O_2, CO_2, and H_2O are 0, 0.22, and 0.24, respectively.

We assume that the carbon particles are sufficiently hot for equilibrium to prevail at the surface, hence the mass fraction of CO_2 and H_2O will be nil there.

Then, using the method of Spalding (10), the value of B for mass transfer from a particle "burning" in exhaust products will be

$$B = \frac{12}{44} m_{CO_2} + \frac{12}{18} m_{H_2O}$$ (evaluated in the well-stirred gas far from the surface of the char)

$$= 0.061 + 0.1622 = 0.2237$$

Because the particle mass is now 1/10 the original value, we will assume the Re number to be small, Nu = 9 initially and approaches 2 as the process goes to completion. Estimating thermal conductivity at $1.3 \cdot 10^{-4}$ cal/cm s K and specific heat $C_p = 0.26$, then ρD, where D is the effective diffusion coefficient for CO_2 and H_2O mixtures ($\rho D \simeq \frac{k}{C_p} = 5 \cdot 10^{-4}$ g/cm^{2}s). Then the initial charring rate is

$$\frac{dm}{dt} = -A \cdot \frac{k}{C_p} \frac{Nu}{2R} \ln (B + 1) = 0.477 \cdot 5 \cdot 10^{-4} \cdot 2.0195 \ln (1.2237)$$

If the area remains fixed until the particle disappears, the burning time, t_c, will be

$$t_c = \frac{1.27 \cdot 10^{-3} \text{ gm}}{5.176 \cdot 10^{-4} \cdot 0.477 \cdot \frac{5.5}{2}} = 5.14 \text{ sec}; \quad t = 1.87$$

If the area shrinks the way a sphere's would, the burning time, t_c' is

$$t_c' = \frac{Ro^2 \, s}{2\frac{k}{C_p} \ln (B + 1)} = 6.35 \text{ sec}$$

The correct model would probably fall between these values; thus, $\tau_c = 4.11$ seems a reasonable estimate. Char burning rates should vary nearly as $1/\delta^2$ for very small particles and as $\simeq 1/\delta$ where Nu > 4 so that these char burning times can be reduced to the values desired by size reduction.

Total Fuel Processing Time

For the size chip proposed we estimate

Drying time, τ_d = 1.35 s

Pyrolysis time, τ_p = 1.77 s

Char burning time, τ_c = 4.11 s

Total fuel processing time, τ = 7.23 s

In the Reynold's number regime in the hot gas a modest change in the linear dimensions will alter the total processing time almost linearly. Thus, to achieve τ = 2 sec,δ must be reduced about threefold or the particle mass tenfold.

SUMMARY OF RESULTS

1. Thermodynamic considerations show that moderately wet, unpreheated wood and unpreheated air should give an exhaust product that replaces that produced by oil or natural gas in existing furnaces with the same air flow.

2. A relationship between fuel particle dwell time and combustion chamber volume requirements for unit power output show that an optimum total particle process time (drying, pyrolysis, and char burning) in the combustion chamber is two seconds. If particle requires less time, it has been over-preprocessed (dried or size-reduced too much) or over-processed (swirled or mixed) in the combustion chamber. Gas phase mixing and chemical kinetic limitations control combustion chamber performance at realizable combustion chamber loadings. If the particle processing times add up to greater than two seconds, their process times limit the combustion chamber loadings and therefore reductions in process times are sought. If the combustion chamber is already overdesigned (i.e., with V/P greater than 1/10,000), particles with longer particle times should be optimum

a) Suspension burners (when fuel dwell time, τ_f = 20 times the gas dwell time, τ_g) should tolerate process times, $\tau_{f1}(s)$ = 20,000 (V/P)

b) burners where fuel dwell time equals gas dwell times $\tau_f = \tau_g$ = 1000 V/P

3. Drying time calculations for wood chips measuring 0.79 x 0.159 x 0.119 cm weighing 0.0127 g and containing 0.006 g H_2O require 1.35 sec to dry at gas temperature, T = 1500^oK, in a suspension burner. Drying time is weakly dependent upon turbulence or swirl, varies as $1/(T - 373^oK)$ and very nearly as $(\text{mass})^{1/3}$.

4. Pyrolysis time of the dehydrated particle (of same dimensions) in a T = 1500°K suspension burner is found to be 1.77 sec. This time was found proportional to $1/(T - 800^{o}K)$ and very nearly to $(\text{mass})^{1/3}$ and was weakly dependent upon swirl and turbulence.

5. Char burning time, t_c, was found to be $1.87 < \tau_c < 6.35$ sec (say $\tau_c = 4.1$ sec) and dependent primarily upon $\text{mass}^{1/3}$ and $T^{-0.7}$.

DISCUSSION

Optimum design for a suspension burner requires $\tau_D + \tau_p + \tau_c = 2$ sec. For the particle size selected, $\tau_D + \tau_p + \tau_c = 7.23$ s. If the mass of the particle were reduced by a factor of 10, the processing time could be reduced to the optimum for a suspension burner, i.e., $\tau_D + \tau_p + \tau_c = 2$ sec. If $\tau_D + \tau_p + \tau_c = \tau_g = 0.1$ sec, optimum size would require roughly a 1000fold reduction in particle mass.

A suspension burner, once it is burning, should be able to maintain itself with cold, wet wood and cold, dry air feeding it. It must be assisted at the start. The large mass of recirculating wet wood and char have to be heated. The starting process, thus, will require a program in which the burner is started with a conventional fuel and gradually weaned from it as the supply rate of wet wood chips is gradually increased to the design value. Needless to say, this overview of a number of interacting processes needs to be followed by much closer look at the several processes. The conclusion that drying time was short compared to char burning time should (and could) be verified by experiment. I think a small facility designed on the lines of Fig. 1 that would permit a measure of the total mass of material in the recirculating zone as moisture, particle size and composition, jet velocity, and overall fuel air ratio were varied would be of first order

of importance. The ratio of particle concentration in the burner to that in the incoming mixture gives the ratio of particle to gas dwell times, and since gas dwell times can be computed, we will have a direct measure of the all important fuel processing time.

$$\tau_f = \tau_d + \tau_p + \tau_c$$

I don't have time here to discuss the important problem of char leaving the top of the burner. Any residual jets or intermittent puffs of gas will carry particles out before their size is reduced to the desired level. It looks like tricks to produce uniform steady efflux velocity profiles would be worth considering.

In any event, it looks like 50-50 water-wood particles about 1/10 the mass proposed would burn satisfactorily without predrying and without preheating the air if the burner were a suspension burner with adequate recirculating hot gas and allowed a particle dwell time 20 times the gas dwell time. Once ignited, it should be no more limited in its power output per unit volume of combustion chamber than a gas-or oil-fired burner would.

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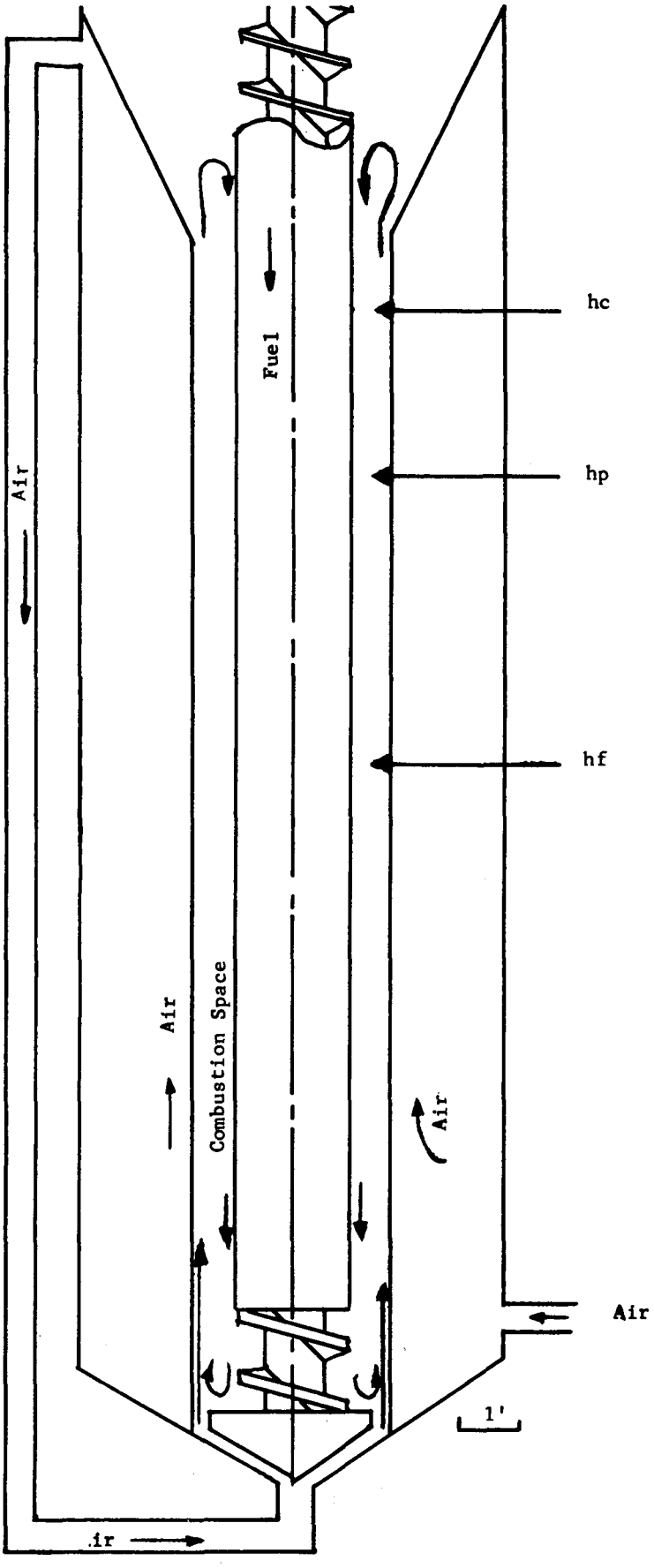


FIGURE 1 - SUSPENSION BURNER

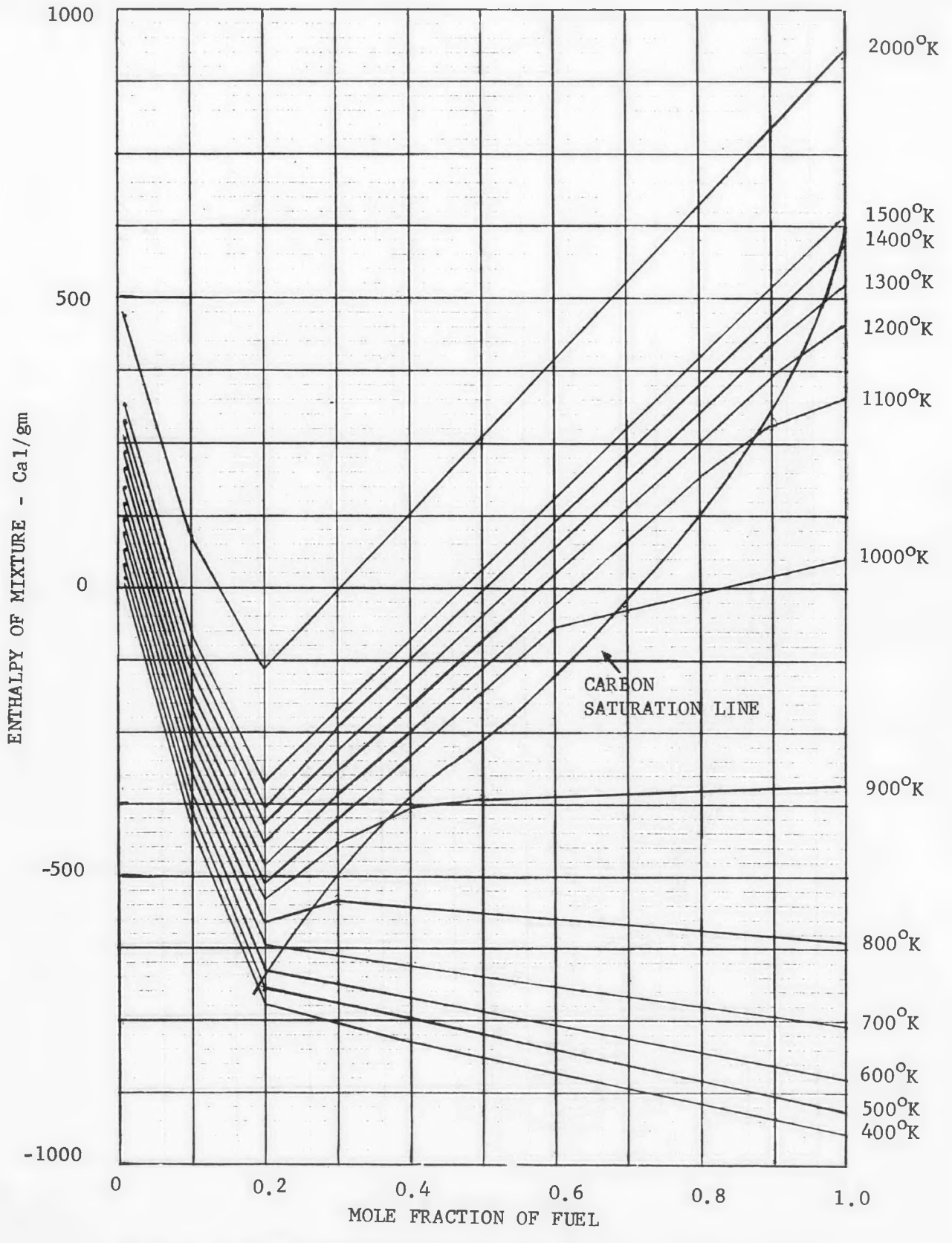


FIGURE 2- ENTHALPY COMPOSITION DIAGRAM WITH INITIAL REACTANTS CH_2O and $(0.21O_2 + 0.79N_2)$, PRESSURE, 1 ATMOSPHERE

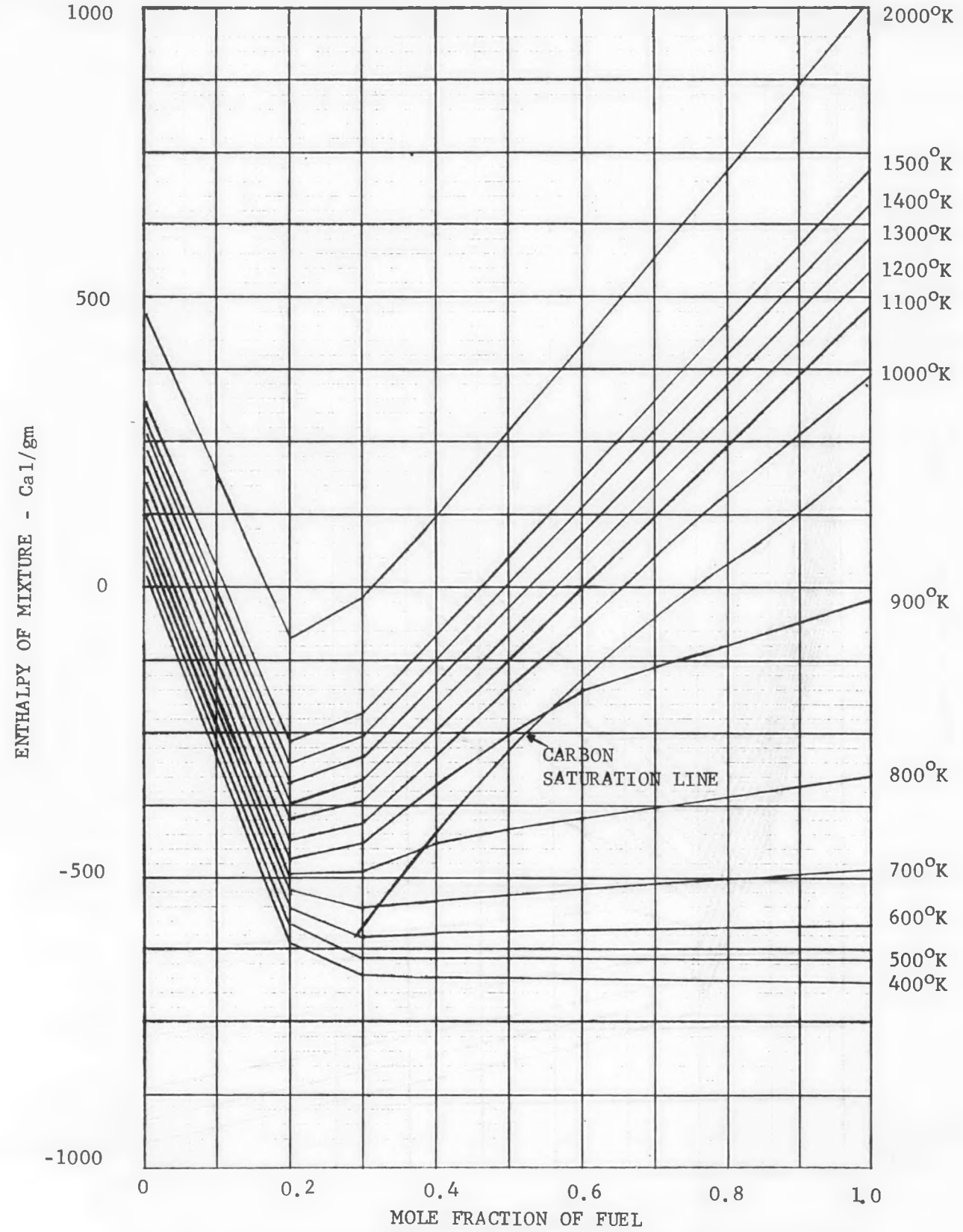


FIGURE 3 - ENTHALPY COMPOSITION DIAGRAM WITH INITIAL REACTANTS $0.75CH_2O + 0.25H_2O$ and $(0.21O_2 + 0.79N_2)$, PRESSURE, 1 ATMOSPHERE

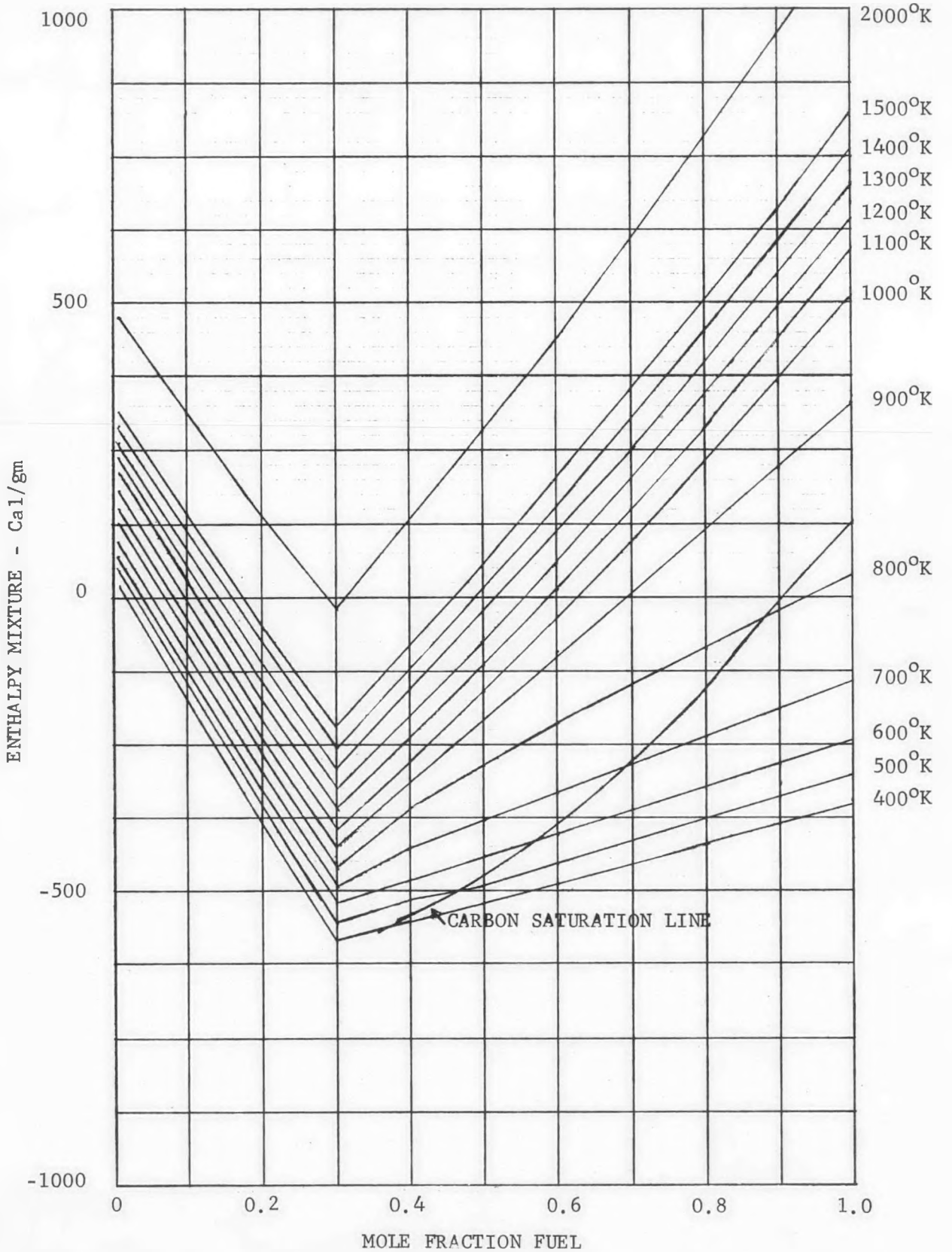


FIGURE 4 - ENTHALPY COMPOSITION DIAGRAM WITH INITIAL REACTANTS $0.5CH_2O + 0.5H_2O$ and $(0.21O_2 + .79N_2)$, PRESSURE, 1 ATMOSPHERE

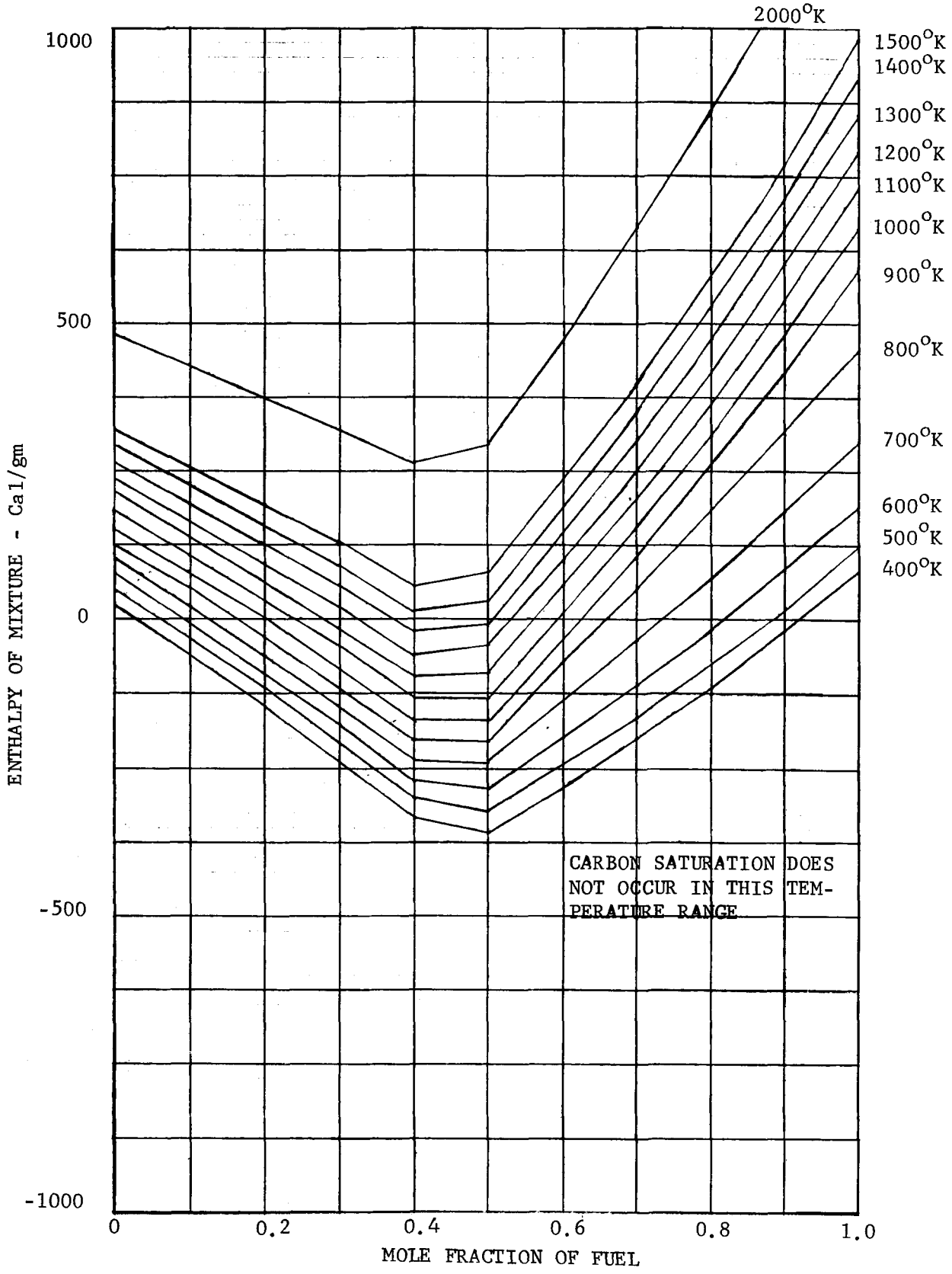


FIGURE 5 - ENTHALPY COMPOSITION DIAGRAM WITH INITIAL REACTANTS $0.25CH_2O + 0.75H_2O$ and $(0.21O_2 + 0.79N_2)$, PRESSURE, 1 ATMOSPHERE

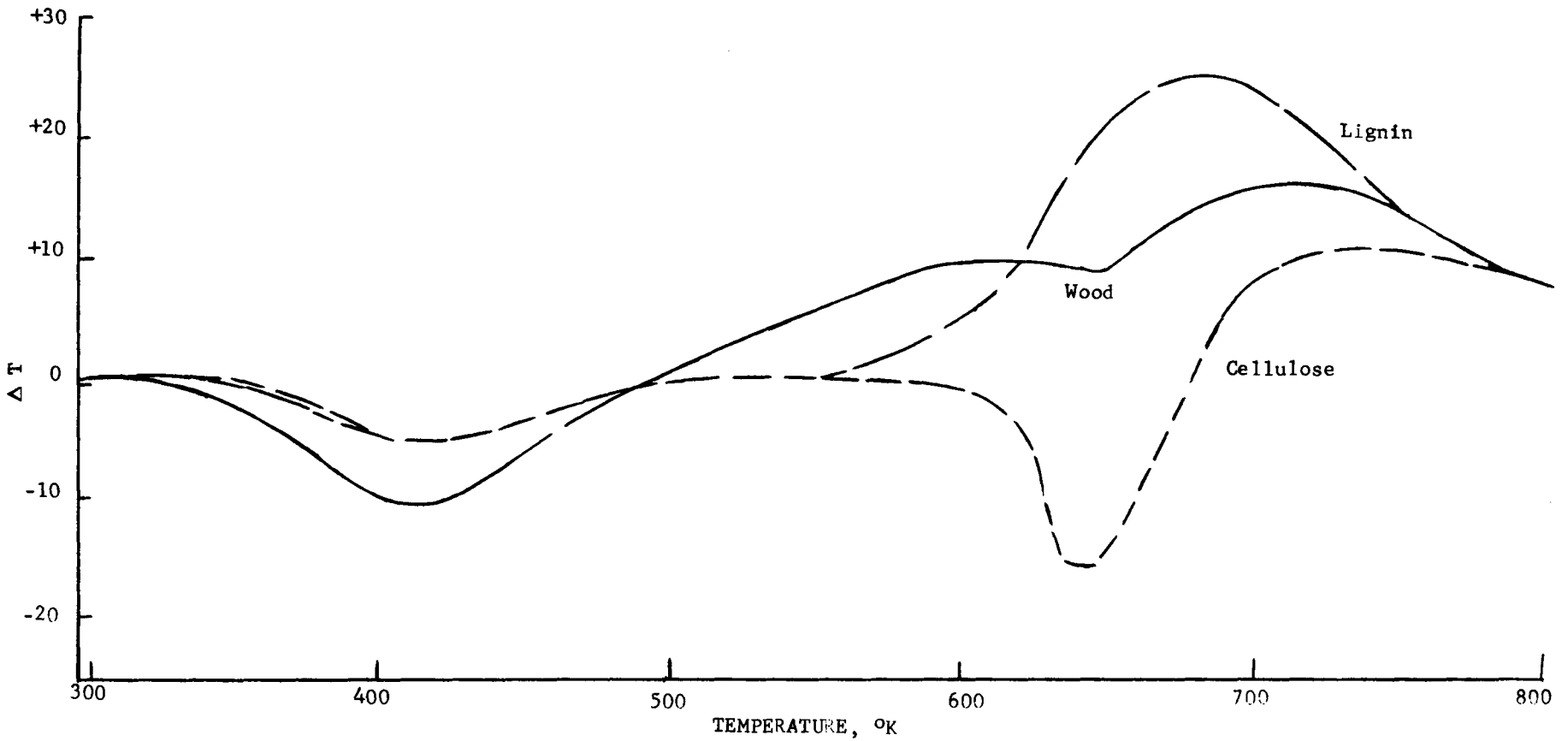
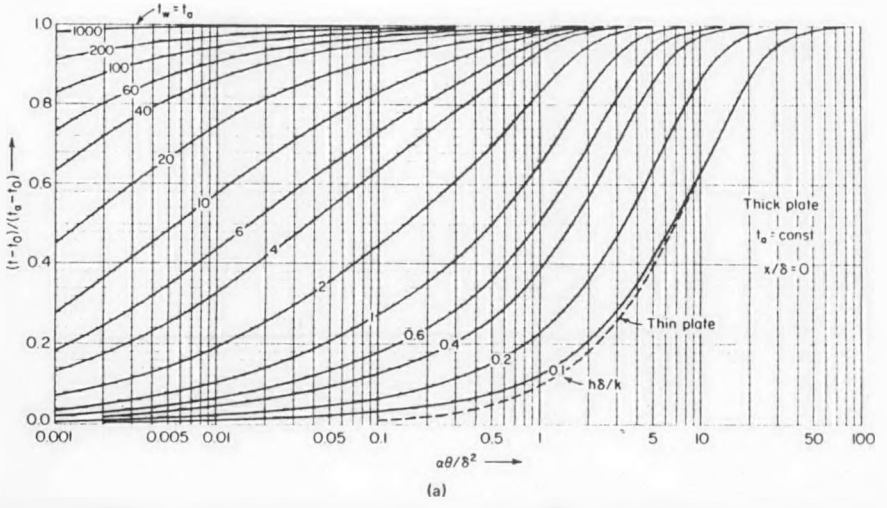


FIGURE 6 - DIFFERENTIAL THERMAL ANALYSIS, FROM REFERENCE 6



(a)

Fig. 7 Temperature response of thick plate ($0 \leq x \leq \delta$) with insulated rear face $x = \delta$ after sudden exposure to uniform convective environment t_a at $x = 0$: $x/\delta = 0$.

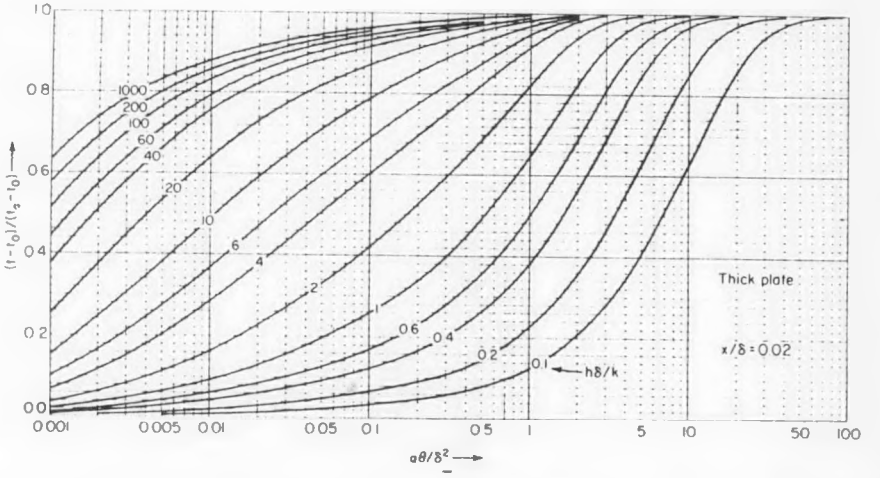
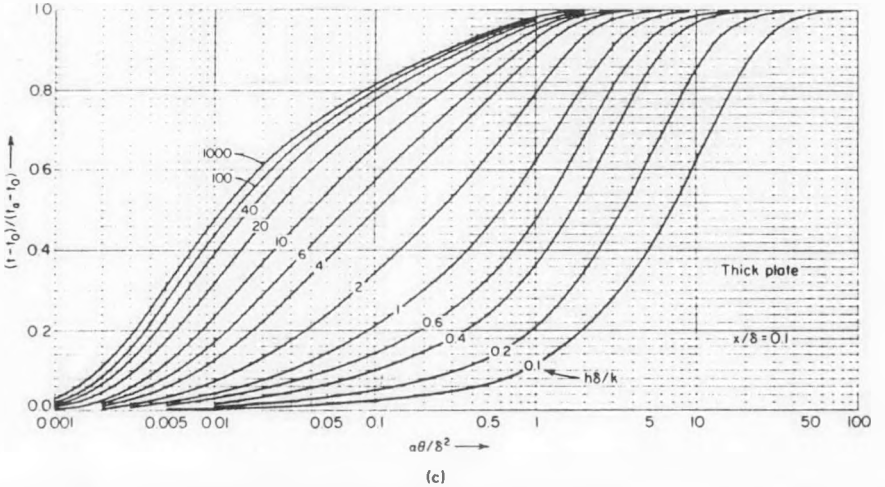
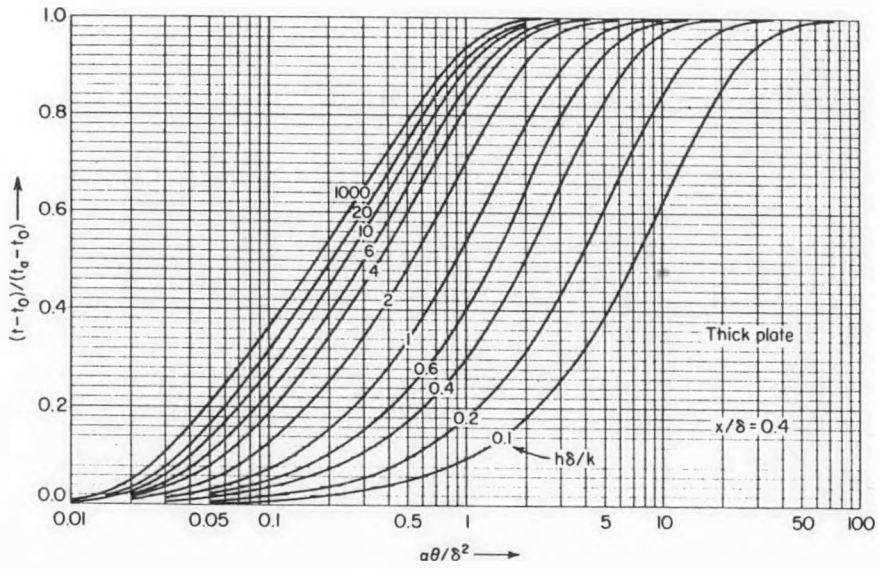


Fig. 8 Temperature response of thick plate ($0 \leq x \leq \delta$) with insulated rear face $x = \delta$ after sudden exposure to uniform convective environment t_a at $x = 0$: $x/\delta = 0.02$



(c)

Fig. 9 Temperature response of thick plate ($0 \leq x \leq \delta$) with insulated rear face $x = \delta$ after sudden exposure to uniform convective environment t_a at $x = 0$ $x/\delta = 0.1$.



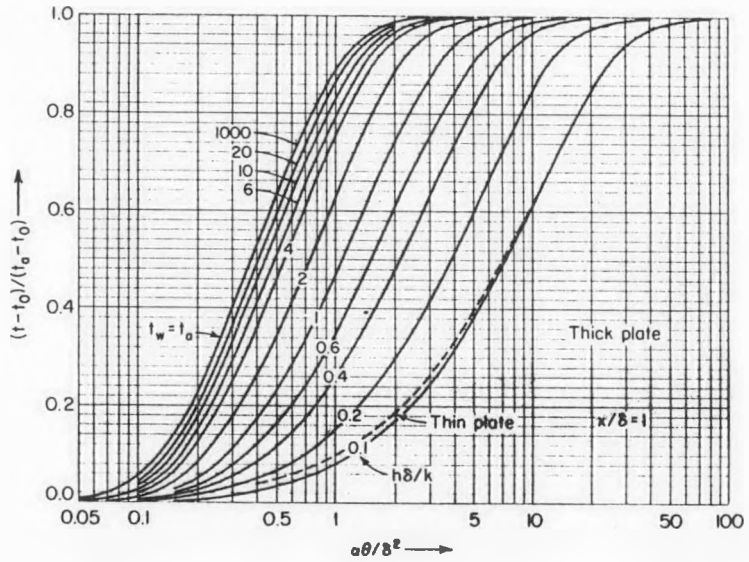


Fig. 10 & 11 Temperature response of thick plate ($0 \leq x \leq \delta$) with insulated rear face $x = \delta$ after sudden exposure to uniform convective environment t_a at $x = 0$: (i) $x/\delta = 0.4$, (ii) $x/\delta = 1$.

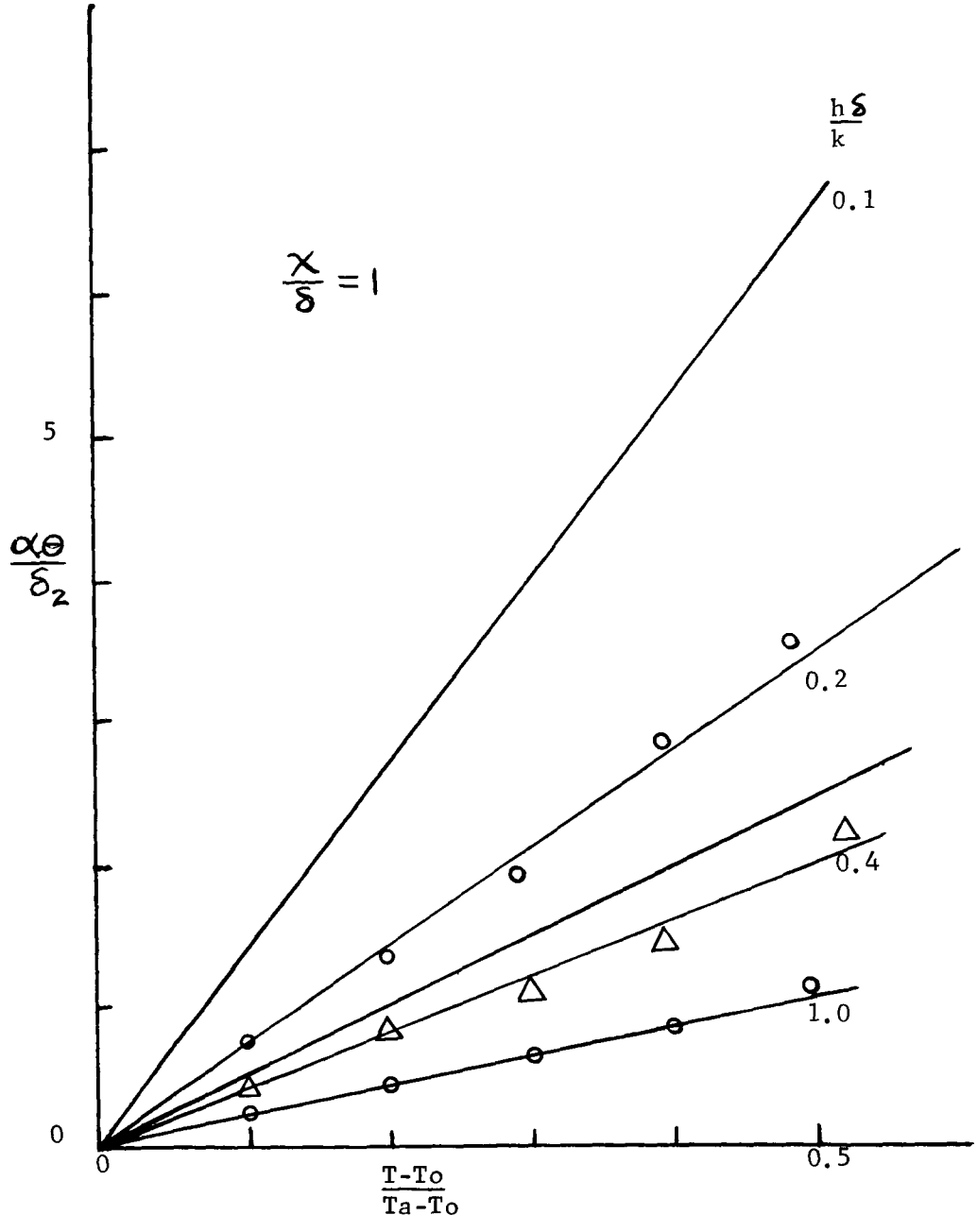


FIGURE 12 - REPLOT OF FIGURE 11, TEMPERATURE RESPONSE OF THICK PLATE

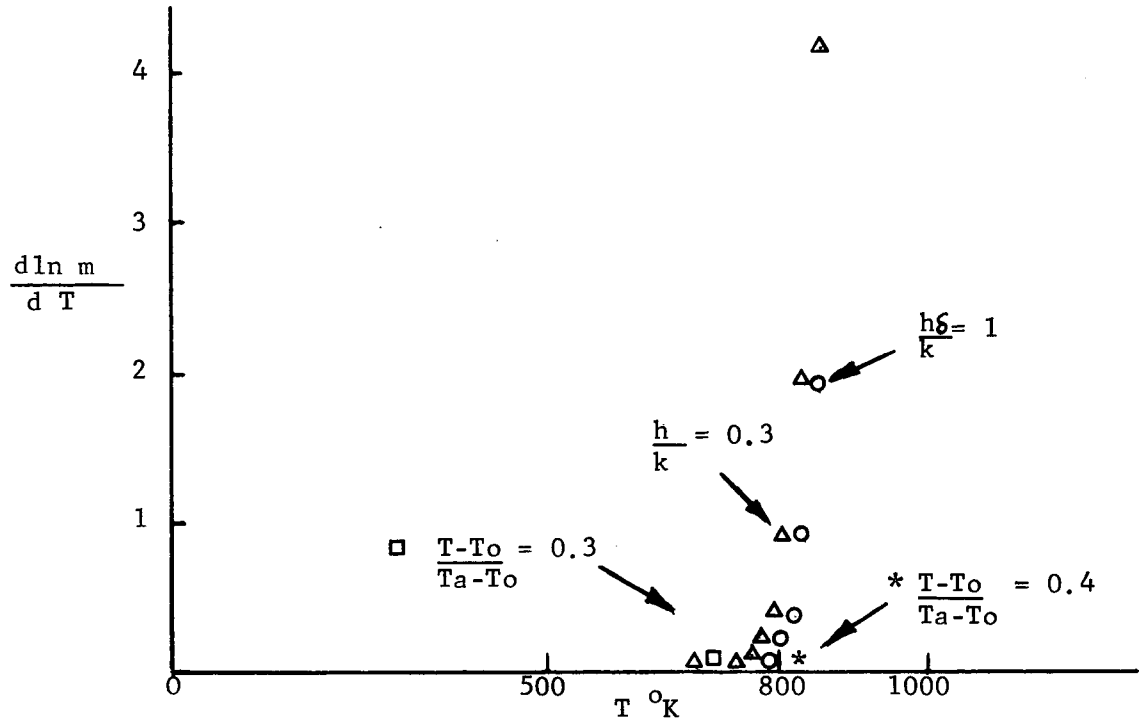


FIGURE 13 - FUNCTIONS USED IN PREDICTING PYROLYSIS RATE

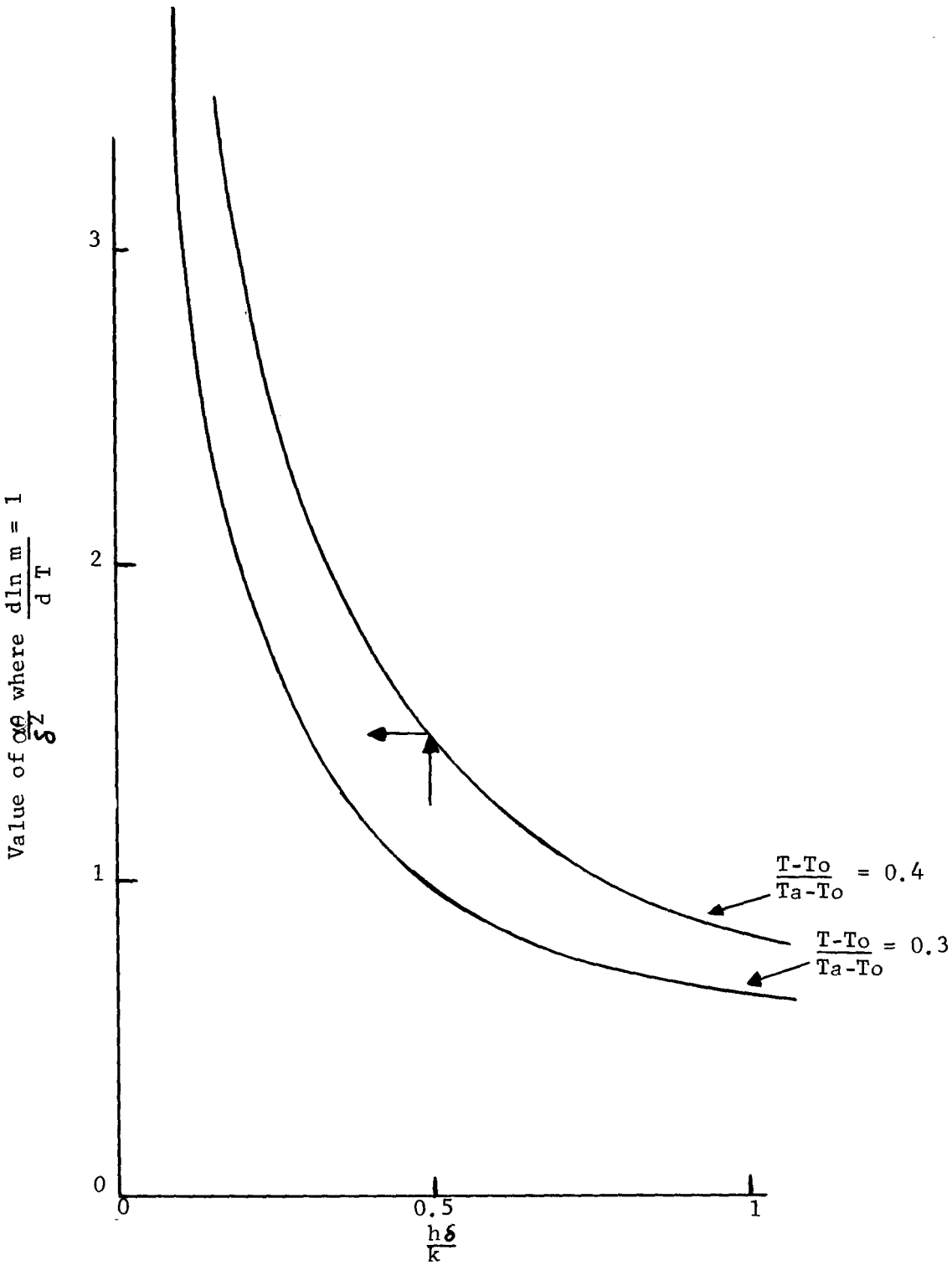


FIGURE 14 - CURVES USED FOR PREDICTING PYROLYSIS RATE

APPENDIX 4

LIST OF REFERENCES

1. Perry's Chemical Engineers' Handbook,4th Edition, 1963, McGraw-Hill Book Co.

2. Marks' Standard Handbook for Mechanical Engineers, Eighth Edition, 1978, McGraw-Hill Book Co.