

**DESIGN AND TESTING OF A SAWDUST DRYER
AND A SUSPENSION SAWDUST BURNER**

by

Arthur R. Egolf

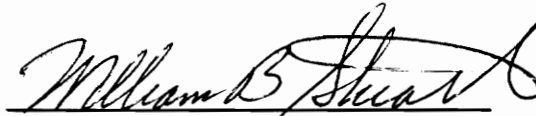
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MASTER OF SCIENCE

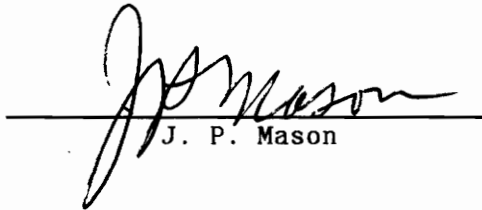
in

Forestry

APPROVED:



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William B. Stuart, Chairman

Forestry

(ABSTRACT)

The objectives of this research were to modify and test a prototype sawdust dryer designed by Arrowhead Forest Products and a sawdust-fueled suspension burner developed at Virginia Tech. The dryer was designed to process green sawdust at small to medium-sized sawmills and pallet mills. The sawdust burner was designed to be the heat source for the dryer and serve more general needs.

A series of trials were conducted to develop the operating parameters of the dryer and measure the dryer's effectiveness at reducing moisture content to 0%. Separate tests were conducted on the burner to determine maximum heat outputs and combustor efficiencies using sawdust fuel of various moisture contents and particle sizes.

The sawdust dryer proved capable of reducing the moisture content to 0% after several passes through the system. The sawdust burner produced close to 400,000 BTU's/HR at calculated efficiencies over 90% and proved relatively insensitive to ranges of fuel moisture contents and particle sizes.

DEDICATION

This thesis is dedicated to Thomas DePew. the initiator of this research project and its most faithful supporter. His interest, support, and vision in the forest products industry will long be remembered. Mr Depew was always a gentleman, upbeat and focusing on the future. We shall all miss him.

ACKNOWLEDGEMENTS

I would like to thank all the members of my advisory committee, Dr. William B. Stuart, Dr. John P. Mason, and Dr. Richard G. Oderwald for their assistance in the completion of my Master's program.

This project would not have been possible without the support of Thomas DePew, of Arrowhead Products, who provided funding for the construction of the burner and dryer.

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INTRODUCTION

In the past, sawdust has been a waste residue from sawmills to be disposed of in the most economical way. These included piling, burning on site, dumping in landfills, or selling. Today, however, increased concerns about air pollution from open air burning, and leaching from waste piles, or restrictions on landfilling, have led to increased research for alternative uses.

Initial utilization involved using green sawdust as bedding or as wet fuel. These uses were not ideal, as wet sawdust promotes the growth of disease organisms when used as livestock bedding (Grace, 1988) and reduces boiler efficiency when used as a fuel. However, recent research has shown that dried sawdust is ideal for animal litter, boiler fuel, and many more specialized uses such as absorbants. These new found uses have increased demand for dry sawdust, which has led to research into more efficient methods of handling and processing sawdust.

Most sawdust dryers currently on the market are large scale, expensive to construct and operate, and designed primarily to dry sawdust for fuel at larger sawmills. The lack of smaller units leaves sawdust from more modest mills underutilized, and prevents these mills from maximizing their revenue by taking advantage of this additional product.

Arrowhead Products conceived the idea for a small-scale sawdust dryer that could be used by sawmills and pallet plants that were producing less than 50 green tons of sawdust per day. The original dryer design attempted to minimize initial capital input and long term operating costs. The design had two basic sections. The first was a 30

foot long, 6 inch diameter, inclined auger and tube heated at the bottom by a home oil burner consuming 1.5 gallons per hour. The water evaporated from the sawdust as the sawdust was augered up the tube. As the sawdust exited the top of the auger tube, the majority of the water in the sawdust flashed off as steam. The second part, the heat siphon, was a 20 foot tall, 20 inch diameter stack with a heated six foot top section. The design hypothesis was that the heated top section coupled with the falling sawdust would induce a "draft" of upward flow of air in the tube. This draft would hold the sawdust momentarily suspended to further the drying process as well as cool the sawdust for safe packaging.

Because of the tolerances between the auger and tube, particles larger than 3/8 inch caused the auger to plug. A vibrating screen was constructed from two overlaid pieces of 3/8 inch expanded metal to screen out these larger particles and solve this problem (Figure 1).

This first dryer prototype proved capable of removing 10 to 60% of the initial moisture content, depending on operating conditions (Grace, 1989). The heat siphon or draft did not develop as expected. The fall served to cool the sawdust but had very little effect on moisture content. This first prototype was promising enough that additional funding was provided by Arrowhead Products for the design and construction of a second prototype (Table 1 shows the differences between the three dryer prototypes discussed). For the rest of this discussion, the first prototype will be called the single tube dryer, the second prototype will

Inclined Screen Constructed
Of 2 Overlaid Sheets Of 3/8
Inch Expanded Metal

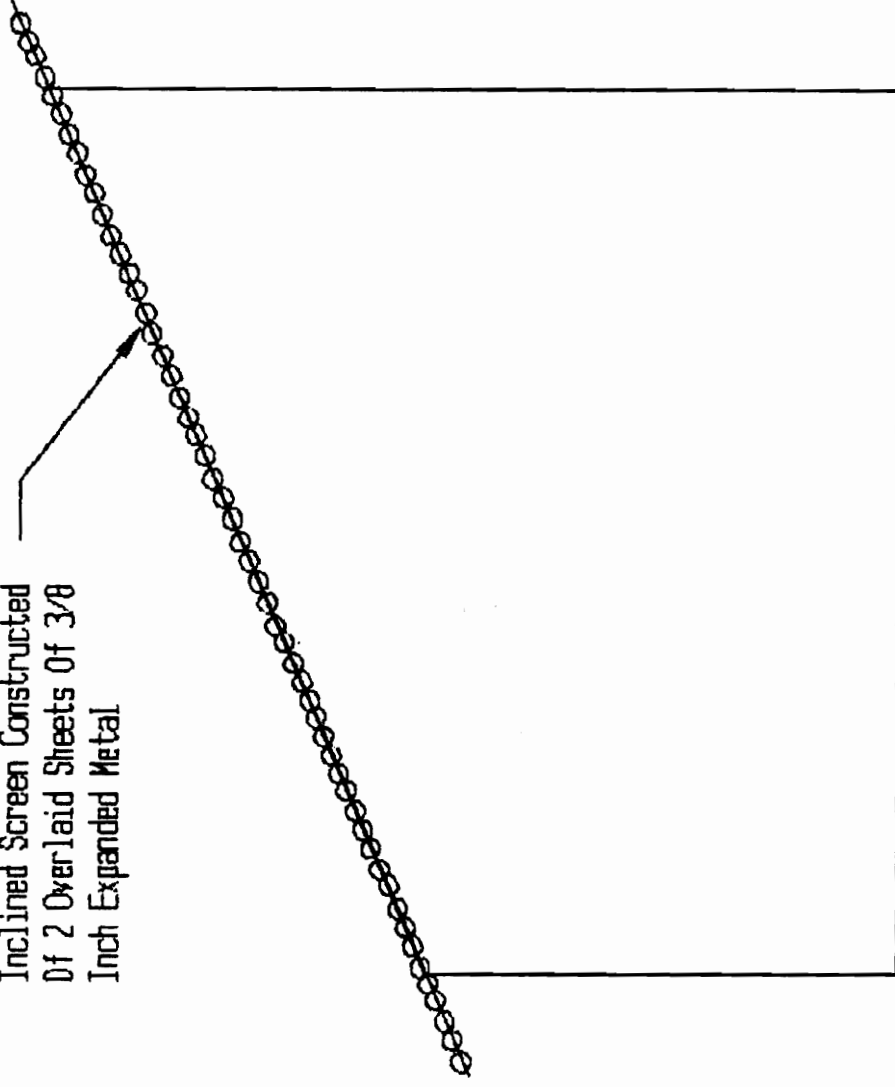


Figure 1: Vibrating Screen Used For Removing Large
Particles And Other Debris From Sawdust

TABLE 1: COMPARISON OF THREE DRYER PROTOTYPES

	Auger Tube Arrangement	Heat Source	Gas Collection System	Sawdust Cooling System	Objectives
Single Tube Dryer	single 30 foot long 6 inch diameter tube set at 30° angle	oil burner rated at 250,000 BTU's/HR input	none	20 foot tall stack, 20 inch diameter	proof of concept
Four-Tube Dryer	4-10 foot long, 6 inch diameter, set in an X-pattern at 50° angle	oil burner rated at 250,000 BTU's/HR input	none	drum screen	drop moisture content of sawdust by 40% in a single pass
Brown Wood Dryer	same as four-tube dryer	sawdust burner rated between 350,000 and 550,000 BTU's/HR	yes	drum screen	produce brown wood in a single pass

be called the four-tube dryer, and the third prototype will be called the brown wood dryer).

The elimination of the heat siphon concept and tower from the four-tube dryer allowed for a much more compact unit. The auger arrangement and firebox were changed. The single-tube dryer used a firebox to supply heat at one end of a long auger tube, while the four-tube dryer used four shorter augers passing through a much larger firebox in an X pattern (Figure 2). This arrangement allowed more even heating of the auger tubes and provided more vents for steam: one at the top of each auger tube. The augers were six inches in diameter and 10 feet in length and they turned inside schedule 40 steel pipes that were placed at an angle approximately 50 degrees from horizontal, to assure that the material was well agitated as it was conveyed through the tubes. Drop tubes connecting the output end of one auger to the input end of the next were constructed from 4 inch by 6 inch box tube. Sawdust conveyed to the top of one auger tube fell by gravity through the drop tube into the bottom of the next auger. The sawdust remained within the firebox while it passed through each of the four auger tubes.

The oil burner was retained as the heat source during the initial testing of the second prototype. It was planned that a grate would be installed in the bottom of the firebox allowing for co-firing with wood and oil, as an intermediate step toward an entirely wood fired unit. As it turned out, the co-firing step was skipped in favor of progressing straight to a sawdust fueled burner.

While the heat siphon of the single-tube dryer was not effective at removing moisture, it was effective at cooling the sawdust to a point

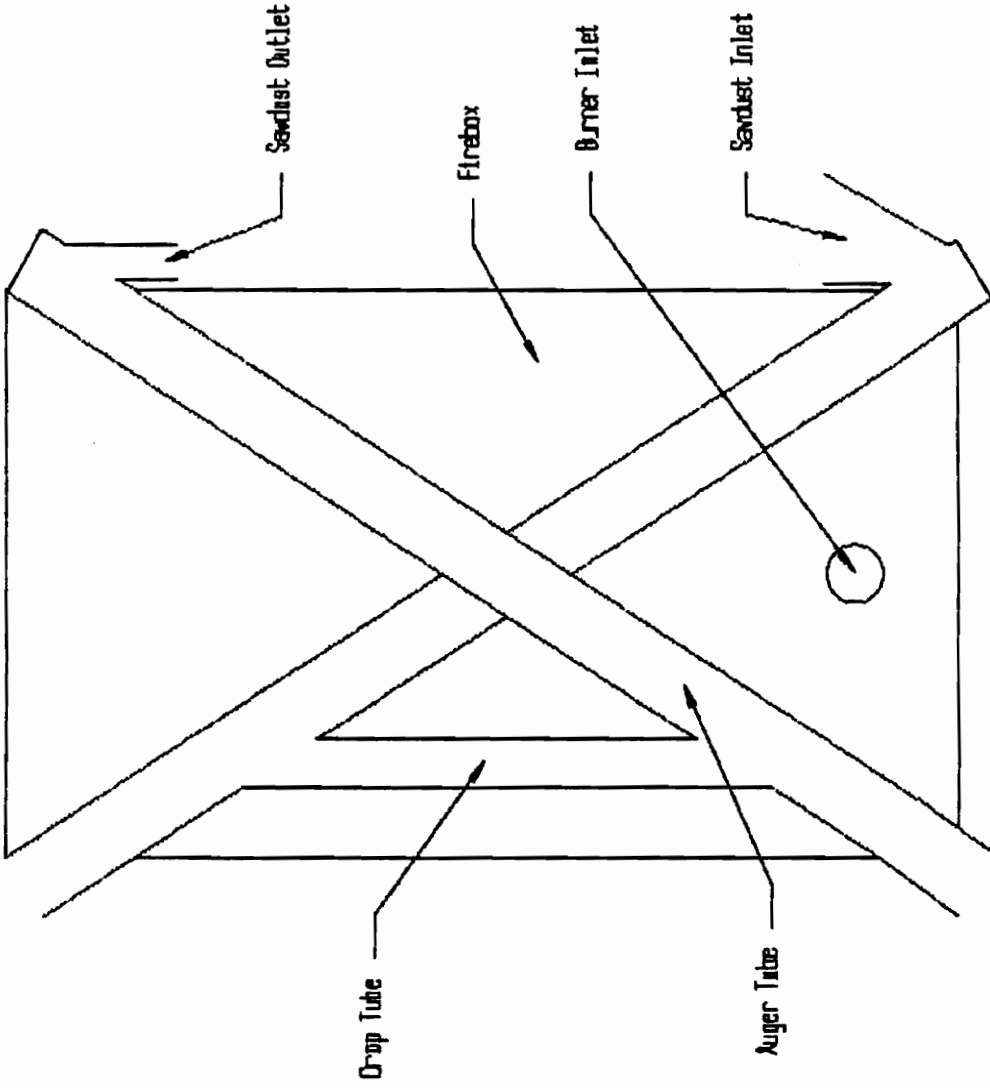


Figure 2: Four-Tube Dryer

where it could be placed directly in storage containers without fear of ignition. Because this heat siphon was left off the four-tube dryer, a means had to be developed to reduce the temperature of the sawdust as it left the dryer. The resulting drum screen served to cool the sawdust as well as further the drying process and separate out particles less than 1/8 inch. A 4-foot diameter, 8-foot long, hexagonal drum was constructed of 1/8 inch hardware cloth and placed at an angle of 12 degrees from horizontal (Figure 3). The drum turned at approximately 8 revolutions per minute as the sawdust entered one end. The sawdust tumbled slowly to the other end with particles less than 1/8 inch falling through the screen where they were collected by an auger and moved out the end nearest the dryer. All larger particles tumbled to the end away from the dryer, where they fell into an auger that carried them out the far end. Ambient air passing through the drum served to carry off the additional steam released, and to cool the sawdust. Figure 4 shows the dryer systems as they were arranged during operation.

This four-tube dryer was more effective at reducing sawdust initial moisture content and was a much more compact unit. As the designs for the dryer prototypes progressed, so did the operating objectives. The original objective, before any prototypes were built, was to reduce the initial sawdust moisture content by 25 to 30% in a single pass. After testing the single-tube and especially the four-tube dryer, it became apparent that the moisture content could be reduced further and faster. It was also discovered that "brown wood" could be produced in multiple passes. Brown wood is formed when sawdust is heated to a point just at the start of pyrolysis.

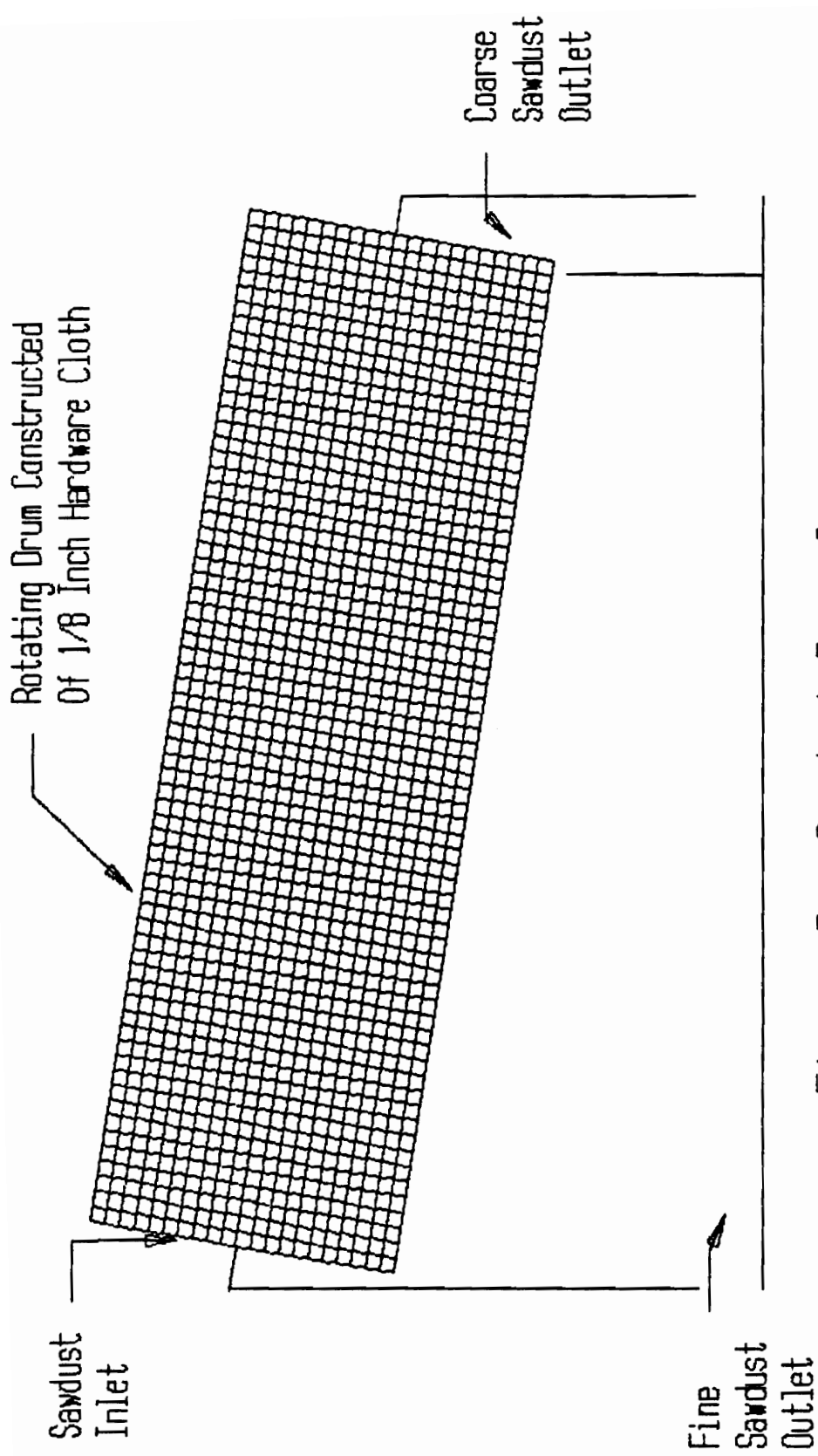


Figure 3: Sawdust Drum Screen

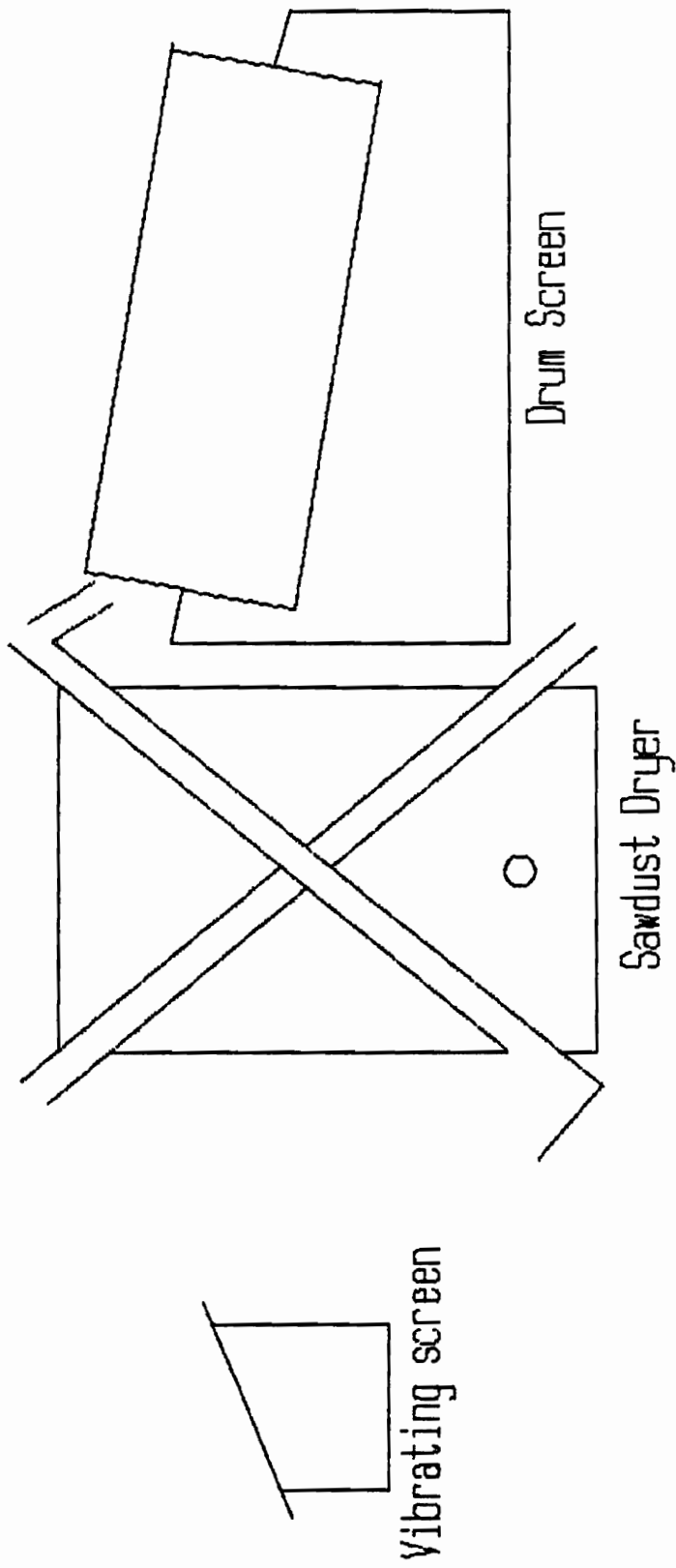


Figure 4: Arrangement Of Dryer Systems During Operation

Brown wood has a much higher market value than the low moisture content fuel that the single-tube and four-tube units were designed to produce. The extremely low moisture content material is a very effective absorbant. With this higher value product now it mind, the sponsor's objective shifted to the production of brown wood in a single pass. Rather than build an entirely new dryer that would contain more auger tubes to increase dwell time, it was decided to try to reach this goal by increasing the heat supplied to the dryer through construction of a second sawdust burner capable of two to three times the heat output of the oil burner.

A sawdust burner was developed to take the place of the oil burner and have roughly the same heat output. A suspension burner was considered the best suited for this application. Suspension burners are the most compact type, work well with the particle sizes found in sawdust, and are the most controllable type.

The first burner prototype consisted of a firebox 34 inches long by 33 inches high by 18 inches wide (Table 2 compares the two sawdust burner prototypes. For the remainder of this discussion, the first prototype will be called the original burner and the second burner will be called the project burner). A metering system supplied the fuel and air to the firebox. The firebox was split into 3 horizontal chambers, one on top of the other, and connected at the ends (Figure 5). This design allowed the sawdust to burn completely within the firebox. The larger particles settled out of the airstream at the bends and remained there, burning, until they were light enough to be carried out by the airstream. Although basically a suspension burner, this settling out of the heavier

TABLE 2: COMPARISON OF TWO BURNER PROTOTYPES

	Firebox Size	Firebox Material	Heat Output	Objectives
Original Burner	34 inches long 33 inches high 18 inches wide	mild steel firebrick stainless steel	approximately 250,000 BTU's/HR	proof of concept
Project Burner	47 inches long 37 inches high 24 inches wide	MorcoCast refractory	350,000 to 550,000 BTU's/HR in present configuration	provide reliable, high volume of heat for sawdust dryer,

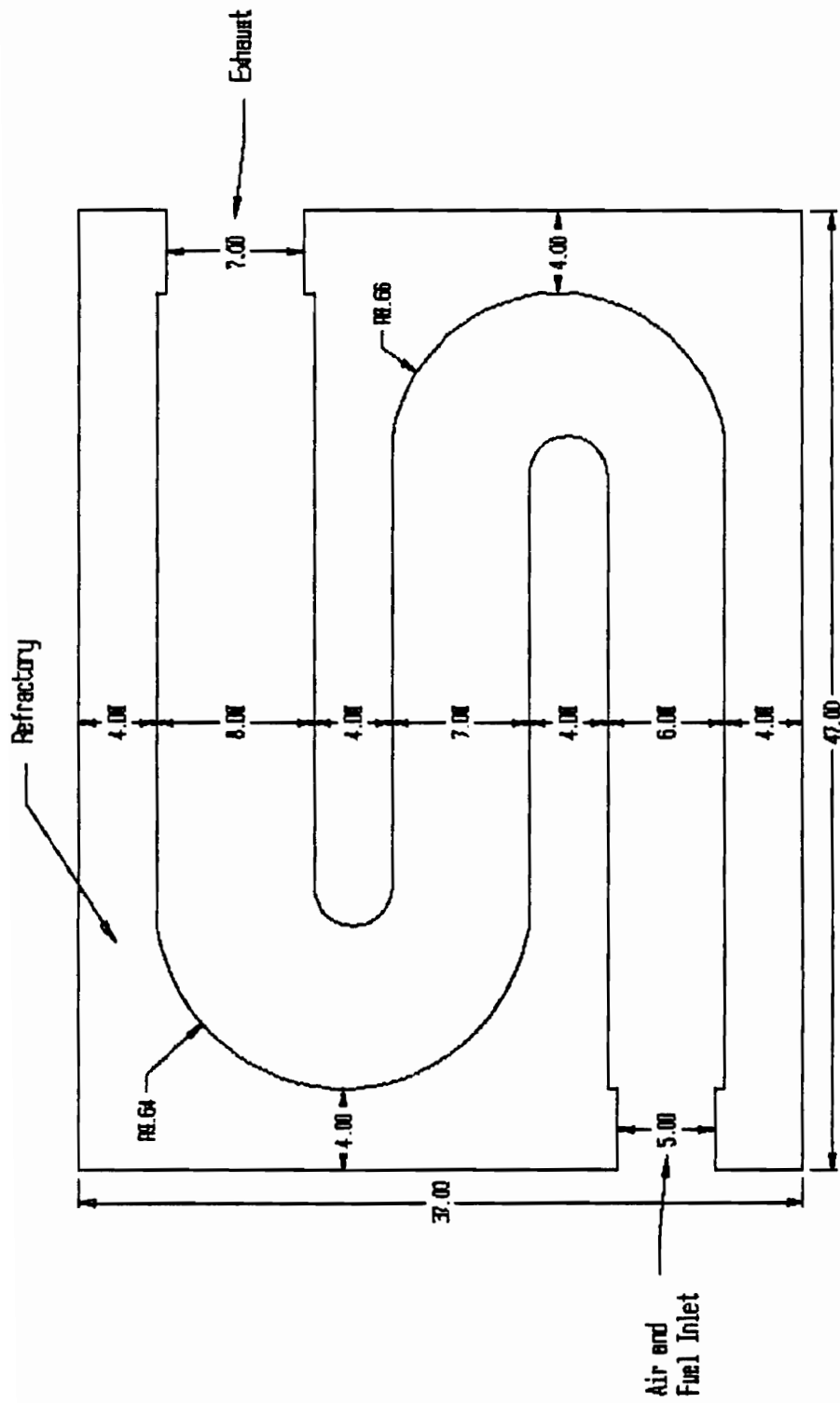


Figure 5: Side View Of Firebox

particles was similar to the operating principle of a pile or grate burner.

When building the original burner, the maximum operating temperatures were not known, and so the unit was built out of mild steel, lined with firebrick, and fitted with internal dividers of stainless steel. Mild steel has a maximum service limit of 900^oF (Reed and Das, 1988), and begins to change form at roughly 1750^oF (Oberg and Jones, 1974). As a result of the 2000+^o F temperatures, the burner essentially melted down, but it had served well in demonstrating the validity of the design concept.

As planned, the original burner was very close in heat output to the oil burner used for previous tests. Dryer tests using this sawdust burner produced results similar to those when the oil burner was used. The project burner retained the metering system from the first, but the firebox was scaled up and made out of refractory to withstand the heat.

When the project burner was coupled to the dryer, operating temperatures of the dryer increased 200 to 300^oF and produced unexpected problems. When first constructed, the tops of the auger tubes were open to the atmosphere to allow steam and/or pyrolytic gases to escape. During the low temperature tests, there were no problems venting the tubes straight to the atmosphere as long as the sawdust was not dried below 5% MC and the firebox was not heated above 600^oF. The higher temperatures achieved with the project burner, coupled with attempting to dry sawdust below 5% MC, greatly increased the emissions of pyrolytic gases.

A duct system was developed to collect these gases to reduce emissions and recover some of the energy in these gases. A blower pulled the gases and steam from the top of each auger and either vented them to the atmosphere when the exhaust was only steam, or injected them into the firebox to be burned when pyrolytic gases were being produced. It was also hoped that the suction of the fan would pull off more steam and further the drying process. The rate of exhaust was controlled by a variable speed motor on the blower and a damper at the top of each auger tube which allowed the vacuum applied to each auger tube to be varied. The duct system worked well at removing the exhaust when it was just steam but attempting to capture the pyrolytic gases resulted in fires which led to damage of the system.

Design work and testing had been conducted on the sawdust dryer and the sawdust burner that proved both systems capable of attaining their original objectives. The attempt of this project was to test these systems and provide data that would result in the development of a commercially operable dryer and burner. The project objectives resulting from this goal were:

1. To modify the Arrowhead Forest Products sawdust dryer to produce brown wood at low emission levels.
2. To modify the sawdust-fueled suspension burner, increasing heat output and burner durability.
3. To test the operation of the dryer to determine throughput rates and time required to produce 0% moisture content sawdust.
4. To test the operation of the burner to determine BTU's/hour output

and overall thermal efficiency.

5. To determine design changes that would increase capacity and improve efficiency of the sawdust burner and sawdust dryer.

LITERATURE REVIEW

Roughly one-eighth of a log's volume is converted to sawdust during the process of sawing lumber (Cheremisinoff, 1980). An estimated 16 million dry tons of sawdust were produced in 1976 and of these, 10 million tons were unused (Haygreen and Bowyer, 1982). Although advancements in sawing technology are decreasing the amount of sawdust produced per log and new uses are resulting in increased demand, there still remains a large unused volume, especially at smaller sized sawmills. The high moisture content of green sawdust interferes with screening characteristics, increases weight and therefore transportation costs, and lowers fuel value (Grace, 1988).

DRYING

The primary use of sawdust is for fuel, and most research on drying has been done in this area. Dry wood is more easily burned, producing flame temperatures in the 2300-2500^o F range versus the 1800^o F possible with green wood. Burning dry sawdust can increase overall thermal efficiency of a boiler by 5-15% (GIT, 1984). Research by Johnson (1975) showed that steam output increased 70% in a boiler when the fuel moisture content was decreased from 63 to 28%. Depending on the drying technique used, the energy required to dry sawdust with moisture contents above 100% is 15 to 20% of the heating value of that same dry sawdust (Bliss and Blake, 1977).

Wet fuel generally refers to a moisture content (MC) of 15-65% (dry weight basis) and dry fuel generally refers to a moisture content of 15%

or less (Rupert, 1978). Fuel with a moisture content above 65% will lead to furnace blackout. Sawdust, as it comes from a sawmill, will often have moisture contents of 100% or more. This is especially true for high production sawing operations using water cooled saw guides. Most sawdust must go through some kind of drying just to be considered wet or green fuel. Research has shown that outside storage in large piles can result in significant drying. In one study of a mixed pine-hardwood sawdust pile, the outer 1-2 feet of the pile remained saturated while the core dried to about 65% in 90 days (White, 1978). Piles with higher angles of repose and large volumes exhibited the most drying. However, further research showed that the net heating value of the entire pile decreased by as much as 40%, due to saturation of the outer portion of the pile and evaporation of some of the volatiles (White, 1983).

AGRICULTURAL CROP DRYERS

Many agricultural crops such as grains and hay must be held in storage for part of the year, and must be dried to prevent deterioration. The initial moisture contents of grains range from 19-33% (dry weight basis) and the final moisture contents range from 12-20% depending on the crop. Since the required moisture content drop is only 10-15%, the usual methods involve moving air through stationary grain, either in a batch dryer or in a storage bin. Batch dryers commonly use large air flow rates of high temperature air (from 20^o F above ambient temperature to 180^o F) moving through a 4-24 inch deep layer of grain. Drying time is anywhere from a few minutes to a few hours. Other types of drying are low temperature drying, natural air drying, and aeration.

Low temperature drying involves pushing or pulling air that is less than 20° F above ambient temperature through a storage bin for a period of several weeks. Natural air drying uses the same principle as low temperature drying except that the air is at ambient temperature. This type of drying is not capable of drying a "wet" crop before deterioration takes place, so it is only used to finish drying crops that are already partially dry.

Aeration is not actually a drying process, but it results in some drying. Small amounts of ambient air are moved through a storage bin to equalize and control temperature, remove excess moisture, remove storage odors, and to apply fumigants.

A more detailed discussion of agricultural dryers is contained in Hall and Dacis (1979).

INDUSTRIAL PROCESS DRYERS

There are many different classifications used in the literature to describe industrial process dryers. For the brief overview provided here, a simplified classification system was developed. More detailed classification systems can be found in GIT (1984) and McDermott (1981).

The three most common types of industrial process dryers are rotary dryers, cascade dryers, and flash tube dryers. While a few have been designed specifically for sawdust and wood chips, many of the dryers used to dry sawdust have been adapted from other industrial or agricultural processes. Most dryers in agriculture and industrial processes use fossil fuels as their heat source while many in the forest products industry use waste heat from flue gases of existing wood-fired boilers.

Rotary Dryers

Rotary dryers are of two types, single-pass or triple-pass. The typical single-pass dryer consists of a rotating horizontal drum (Figure 6). Hot gases and the product to be dried are fed into one end and the product is tumbled through the gases to the output at the opposite end of the drum. The amount of drying is dependent on the surface area of the fuel, the velocity of the drying gases, and the dispersion of the product through all quadrants of the cylinder. Larger particles remain in the cylinder longer, as they are not moved as far each time they fall through the gases.

Triple-pass dryers consist of three horizontal, concentric cylinders rotating one inside the other (Figure 7). The design is similar to the one-pass in that hot gases and the product to be dried enter one end of the first cylinder and are tumbled to the other end. The product then passes through the second and third cylinders to the final output. The gas temperature and velocity are lower in each successive cylinder. Due to the longer dwell time and lower initial temperatures, moisture content can be more precisely controlled in the three-pass than in the one-pass dryer.

More detailed descriptions of rotary dryers are contained in Kirk and Wilson (1986), McDermott (1981), Mohr (1981), Reed and Das (1988), Rydin (1979), and Thompson (1976).

Flash or Tube Dryers

Flash dryers or tube dryers are simply long sections of tube through which the product to be dried and hot gases are blown together

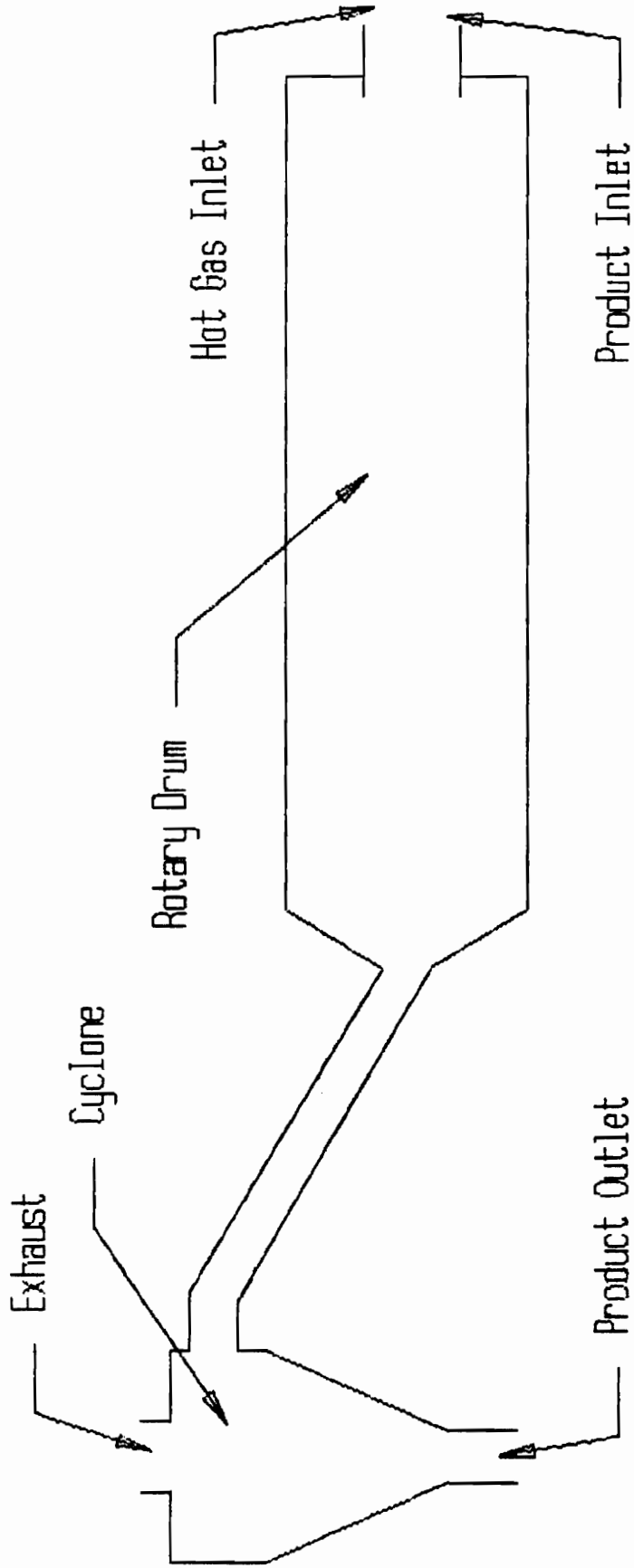


Figure 6: Single-Pass Rotary Drum Dryer

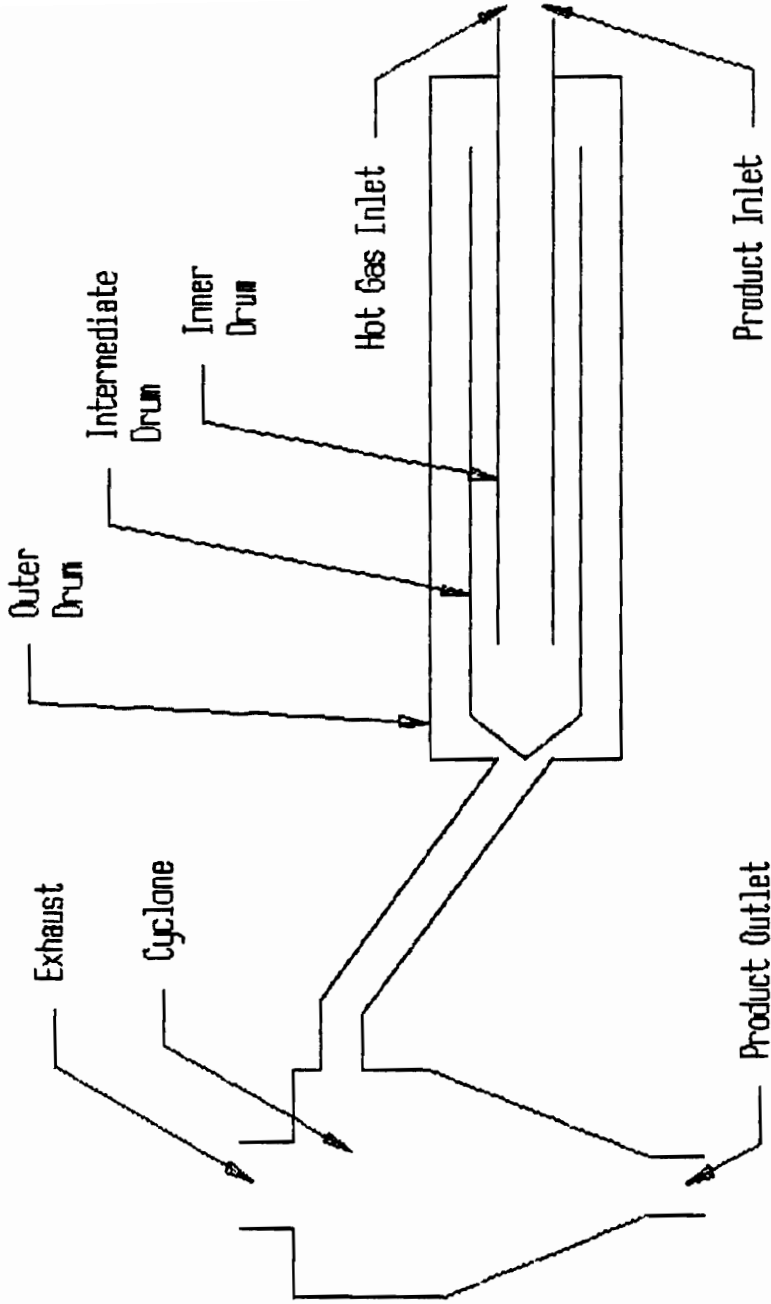


Figure 7: Three-Pass Rotary Drum Dryer

(Figure 8). Because of the large volumes of heated air required, tube dryers are generally less efficient than rotary dryers. Tube dryers require 2200-2400 BTU's to evaporate each pound of water compared to the 1500-1900 BTU's required for rotary dryers, starting with an initial moisture content of 100% (Comstock, 1976). Uneven particle size can lead to uneven drying. Two flashtubes coupled together can produce a more consistent output.

Cascade Dryers

The operating principle of a cascade dryer is to feed material into a high velocity, vertical stream of hot gases within a large chamber (Figure 9). The finer particles are flash-dried and blown out with the exhaust gases, while the larger particles remain suspended for a short time before they fall out of the airstream and are conveyed out the bottom of the chamber. This type of dryer is used primarily for drying bark fuel. Reisinger (1981) provides a more detailed description and drawings.

Compression Dryers

One other technique for drying wood fuels is the use of hydraulic presses to squeeze water out of the cells. Due to the strong cell structure of wood, such presses require a great deal of energy and are usually only capable of drying fuels down to about 65% MC (Rydin, 1979 and Haygreen, 1981).

Screw presses are being used to compression-dry sludge from paper mills to a moisture content where it can be burned in hog fuel boilers

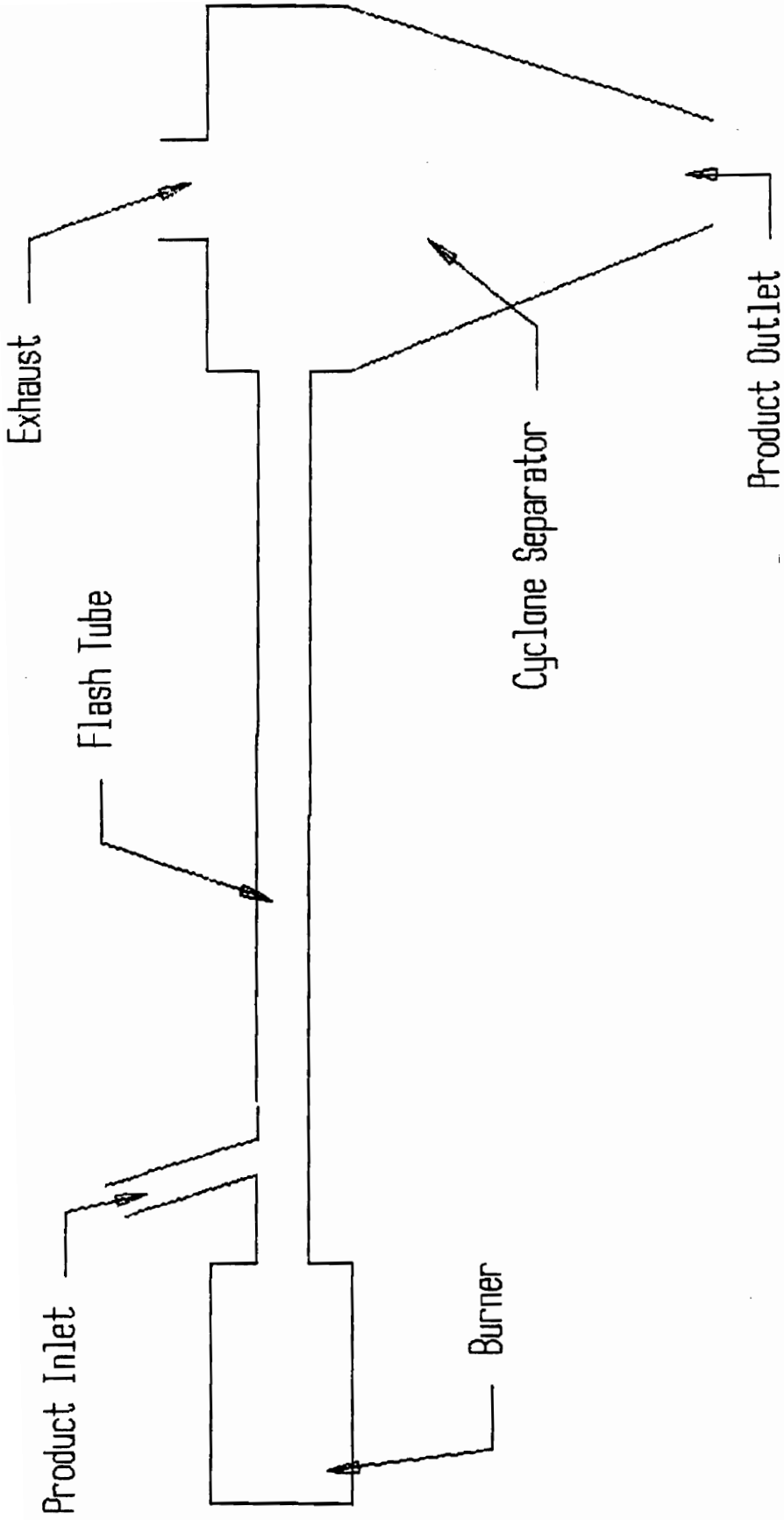


Figure 8: Flash Or Tube Dryer

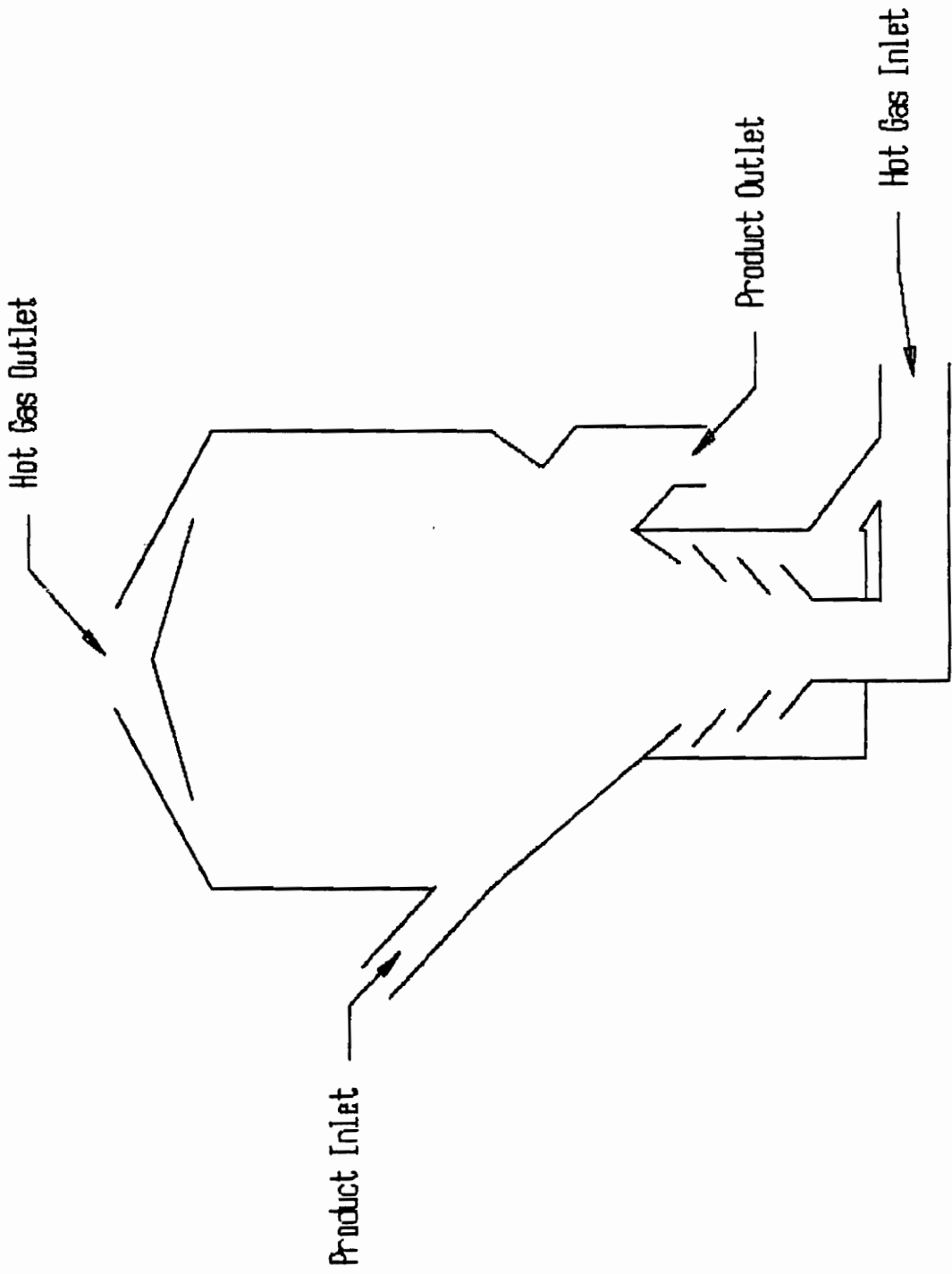


Figure 9: Cascade Dryer

when mixed with other fuels (McCready, 1991). The wood cell structure in sludge is already broken down, much less power is required to wring out the liquid. The press consists of a tube-shaped chamber made of screen which contains a large screw. The sludge enters one end and the liquid portion is forced out through the screen as it is compressed by the auger (Figure 10).

SEPARATING EQUIPMENT

All of the dryers described above, with the exception of the compression dryers, utilize hot gases mixed with the material, and require some type of separating unit at the end. The most common is a cyclone separator (Figure 11). As the dust laden gas enters a cylindrical chamber, it is forced around and loses velocity to a point where the particles fall out of the airstream and into a collection chamber at the bottom of the cylinder. These can be used singly or together as a multicyclone.

Other filtering systems used in industrial processes include bag filters and electrostatic precipitators. In a bag filter system, the air is passed through a cloth or cloth-type filter, leaving the product behind (Figure 12). An electrostatic precipitator removes particles by passing the dust-laden air between a discharge electrode (usually a wire suspended in the airstream) and a collecting electrode (usually the wall of the filter). The fine particles become charged and flow to the collecting electrode, where they form a tight dust layer and fall into a collecting container (Figure 13). Electrostatic precipitators and bag filters can remove even the finest particles (< .1 microns), but they do

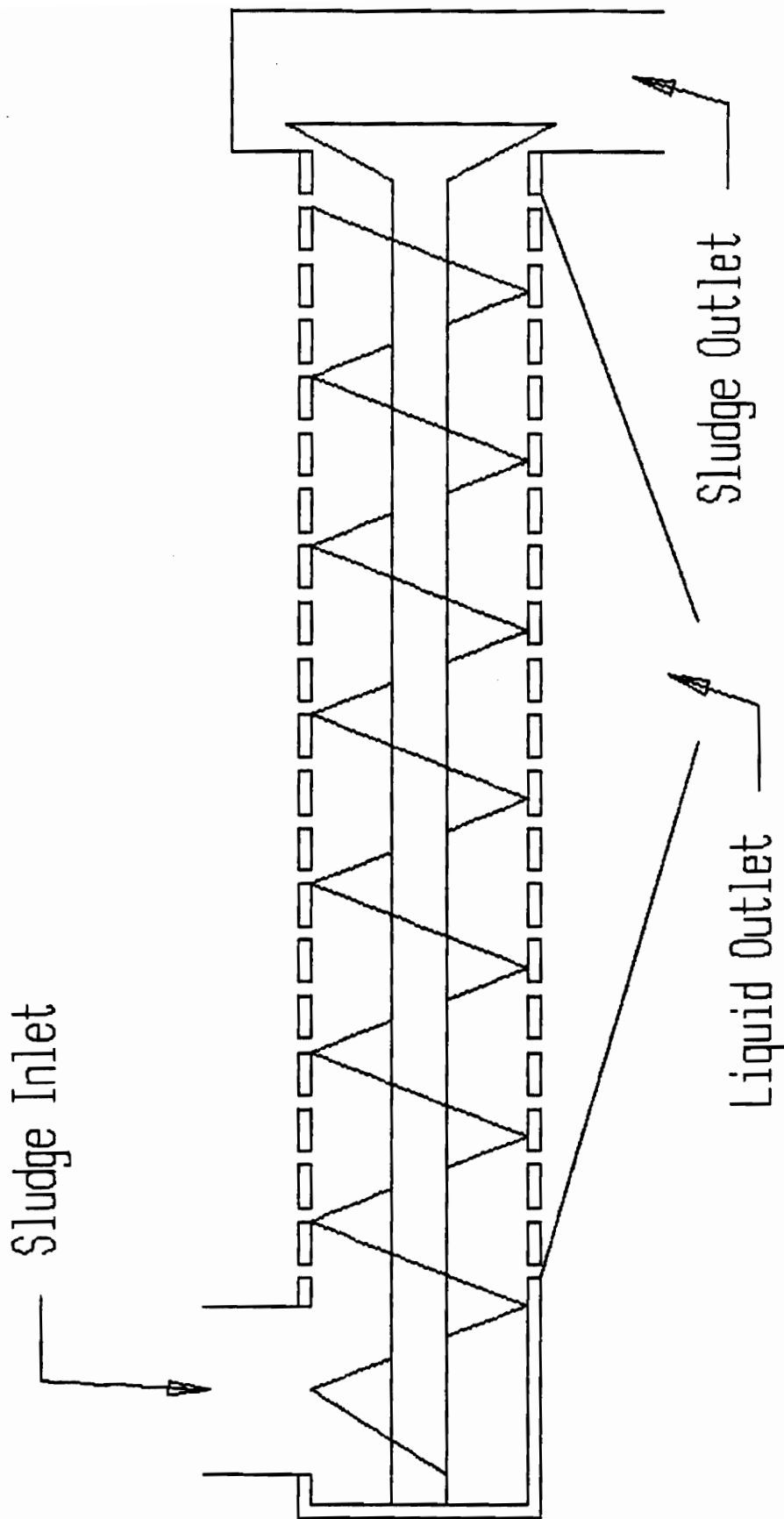


Figure 10: Screw Press

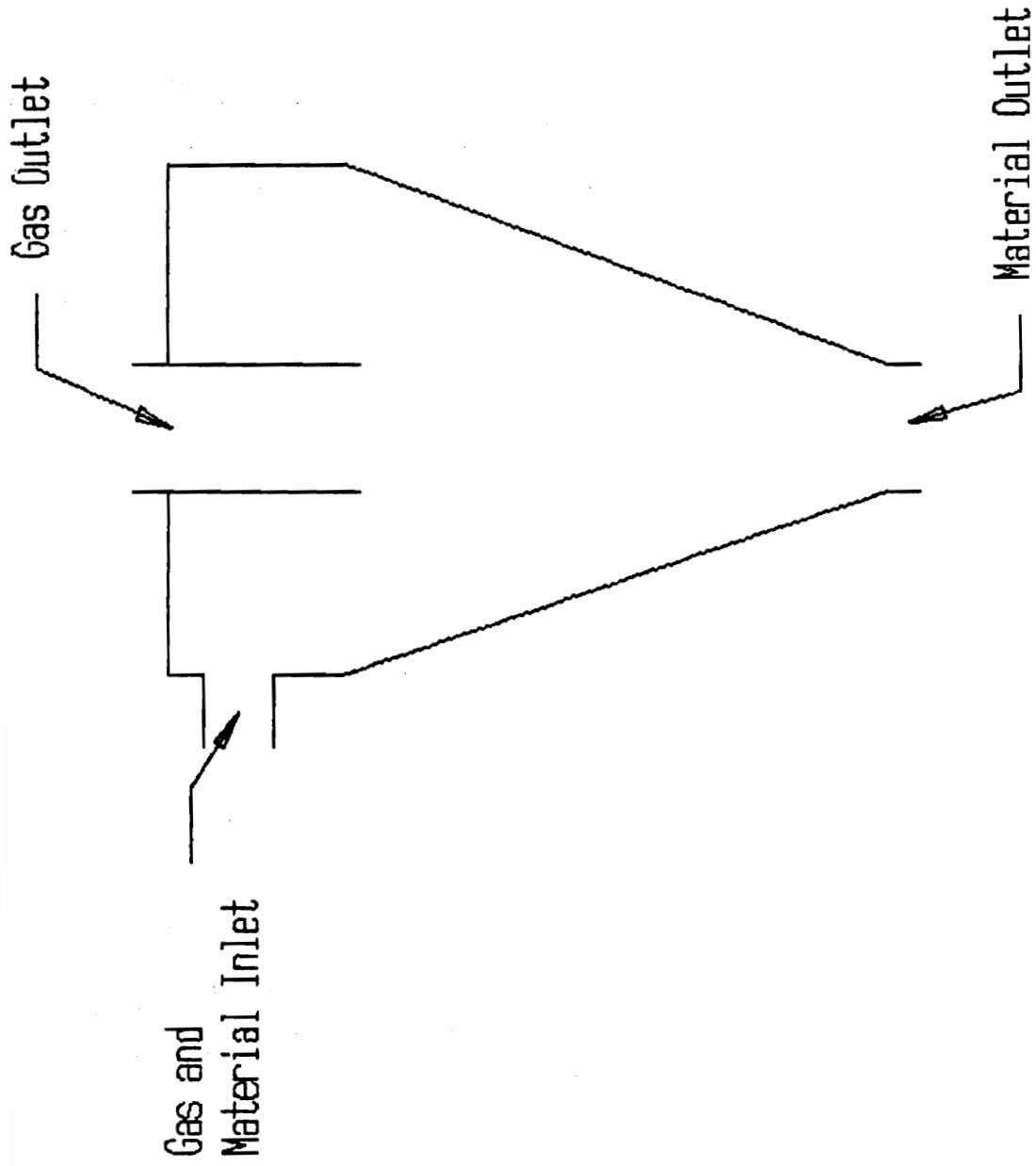


Figure 11: Cyclone Separator

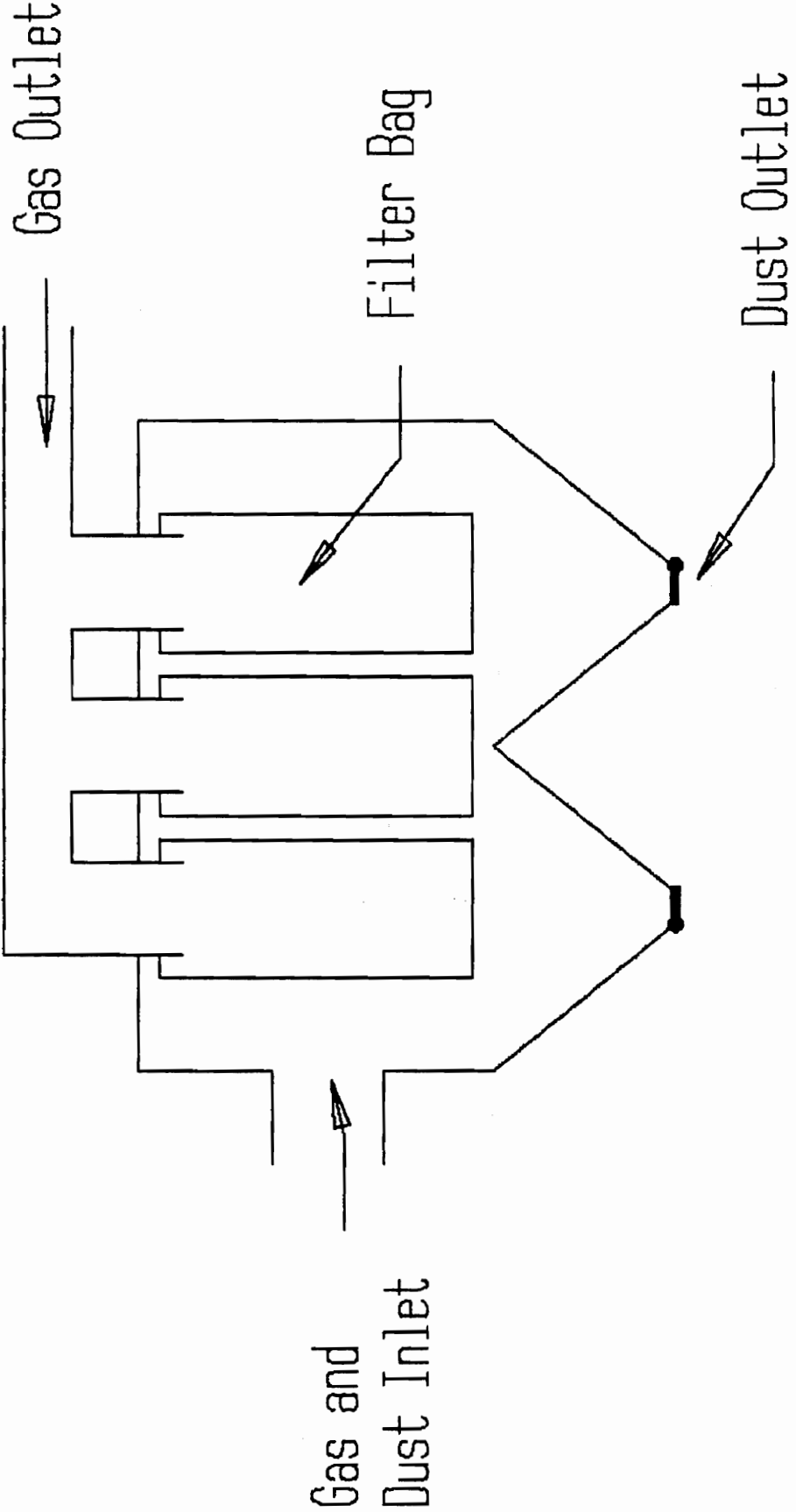


Figure 12: Bag Filter

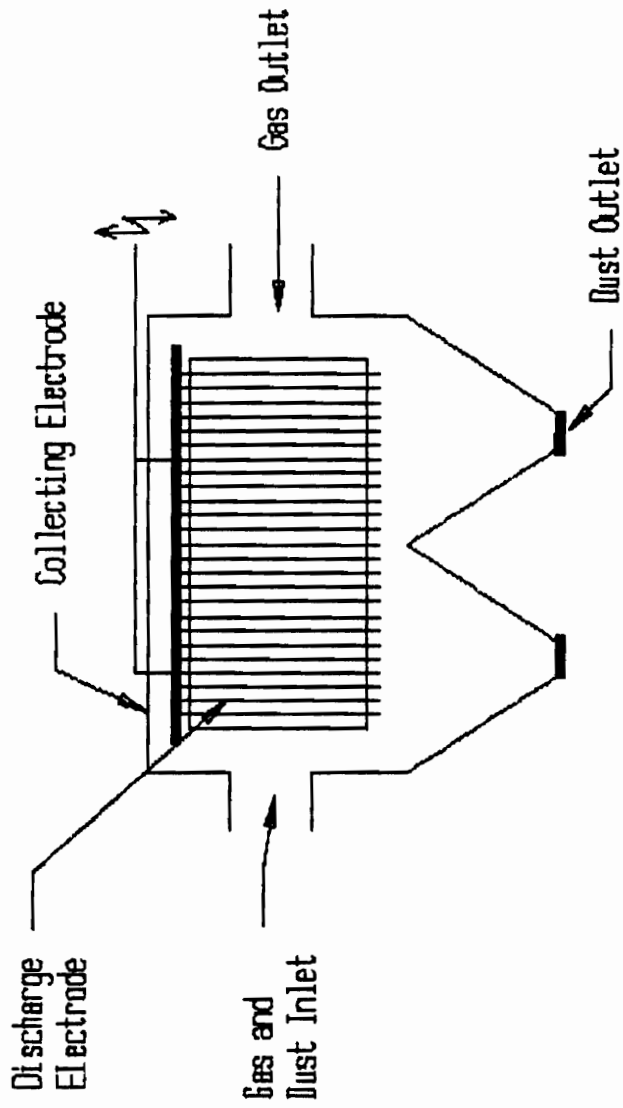


Figure 13: Electrostatic Precipitator

not work well with large particles and cannot be used with high temperature gases.

Ogawa (1984) provides detailed descriptions of each system and the theory behind its operation. Other sources include Grimm (1985).

ENERGY FROM WOOD

Approximately 50% of wood harvested worldwide is for fuel (Cheremisinoff, 1980). Wood has heating values of about 8500 BTU's/pound for oven-dry hardwood and about 8900 BTU's/pound for oven-dry pine, with variations between individual species (Arola, 1978). Dry wood is composed of roughly 85% (by weight) volatiles and approximately 15% fixed carbon with less than 1% ash. Again, there are variations between individual species (Corder, 1976). Energy can be recovered from wood either directly by combustion, or indirectly by thermochemical conversion to gas or solid, which is then burned.

THERMOCHEMICAL CONVERSION

Thermochemical conversion processes allow biomass to be converted into types of fuel which can be substituted for various fossil fuel forms. Solid fuel products can be substituted for other solid fuel types such as coal, and the gaseous forms can be substituted for petroleum fuels.

The result of thermochemical conversion to a solid fuel is charcoal, manufactured by heating wood in the absence of oxygen, driving off the volatile gases and leaving carbon (Tillman, 1978). While varying slightly between tree species, wood decomposes at 750⁰F into 50%

pyroligneous liquor, 17% wood gas, and 34% charcoal. Higher temperatures increase gas yield to 25% and decrease charcoal yield to 25% (Satonaka, 1982).

Unlike combustion, where 100% or more excess air is required, gasification is the partial combustion of a solid fuel in the presence of only about 10% excess air (Discussion, 1981). Gasification processes can be either direct or indirect. Direct gasification uses air or oxygen to generate heat through exothermic reactions. In indirect gasification, heat is transferred to the reactor from the outside. The result is a combustible gas composed of CO, H₂, CH₄, and heavy hydrocarbons. Ideally, gasification converts biomass into combustible gases that contain all the energy originally present in the biomass, but in practice only converts 60-90% (Reed and Das, 1988). Research on wood gas conducted by Johansson (1979), found the composition of combustible gases to be as follows:

Carbon Monoxide	17-22%
Hydrogen	16-20%
Methane	2-3%
Heavy hydrocarbons	.2-.4%

The remaining non combustible portion of the gas contains 45-50% nitrogen and 10-15% carbon dioxide.

Within a gasifier are five distinct regions: the drying zone, the distillation zone, the reduction zone, the hearth zone, and the ash zone. In the drying zone, water vapor is driven off, leading to partial

pyrolysis in the distillation zone as the more volatile gases are driven off. Pure carbon, or charcoal is left as the gases are driven off. A small amount of air, introduced in the hearth zone, reacts with the 1450-1650^o F charcoal to produce carbon monoxide, hydrogen, and methane. McNeel (1981) provides a more in-depth description. Descriptions of different gasifier configurations can be found in Discussion (1981), Flanigan et al (1981), Reed and Levie (1984), and Reed et al (1988).

The resulting gas can be substituted for other gas or liquid fuels. Wood gas has been used successfully in internal combustion engines, although substantial engine power losses and the difficulty of producing a consistent quality gas have limited its use (Discussion, 1981).

DIRECT COMBUSTION

Direct combustion of wood involves several successive and overlapping stages. First, heat must be supplied to drive off moisture in the wood. This drying stage occurs when the wood is heated from 60^o F to 395^o F, and thermal breakdown begins, resulting in water vapor and other nonignitable gases being driven off. The next stage, pyrolysis, occurs when the wood is heated from 395 to 535^o F, generating more gases and releasing some heat although no flames are present. As the gases burn, the temperature increases to 935^oF, leaving only carbon. As the carbon burns, the temperature rises above 935^o F. All four of these stages occur simultaneously, resulting in many secondary reactions that complicate complete description of the combustion process (GIT, 1984).

The wood fuel particle size can range in size from fine sawdust to large bolts of wood. In addition to being burned in the form they are

produced, fine particles can be compressed into densified pellets that provide a more uniform and higher heat output per unit volume than ordinary wood fuels. The pellets are extruded and hold together as a result of the pressure alone or by the addition of wax or other binders (Pursley, 1980 and Resch, 1982).

BURNER TYPES

As mentioned above, combustion is affected by the temperature and the amount of air supplied. Different types of combustors or burners have been developed to achieve desired heat outputs or efficiencies from the various fuel forms. Burning dry wood can easily produce flame temperatures of 2300⁰ F, and flame temperatures as high as 3200⁰ F can be obtained when the combustion air is superheated (Discussion, 1981). The necessary temperatures for efficient pyrolysis are 1300-1400⁰ F, but temperatures in excess of 2200-2300⁰ F cause the ash to melt and build up slag in the burner (Black, 1981).

This paper will discuss systems that burn sawdust or chips for direct heat or steam cogeneration such as pile or grate burners, fluidized-bed burners, or suspension burners. More detailed descriptions than those provided below can be found in Discussion (1980), Koch (1972), Koch (1985), Lovelton (1980), and Tillman et al (1981). These burners vary in the utilization of fuel size, moisture content, and amount of excess air. The grate and fluidized-bed burners operate more efficiently with drier fuel, but it has been estimated that somewhere around 35% fuel MC is best in terms of optimum balance between dryer cost, furnace and

dryer performance, system efficiency, and problems such as dusting and explosions from dry fuels (Schweiger, 1980).

PILE OR GRATE BURNERS

Pile or grate burners generally have a single or multiple chamber firebox with a grate on to which fuel is continuously fed. Air is fed over the top and up through the grate on the bottom, allowing the fuel to burn on the entire outside of the pile. Some of the more common arrangements for the grate and the feed systems are dutch oven burners, travelling grate burners, and inclined grate burners. The dutch oven burner is a simple pile burner where the fuel is piled in the bottom of a firebox (Figure 14). Air is introduced around the pile and most of the burning takes place on the surface of the pile. Fuel is fed continuously, either onto the top or up from the bottom of the pile. This is probably the oldest type of burner and while not the most efficient, does have the benefits of being able to burn large pieces of wood with moisture contents as high as 65%, while producing low stack emissions. Pile burners use fuels that are low value, or even waste material, and as a result, the volume of heat output is of more concern than operating efficiency. One drawback of these type of burners is that they are difficult to regulate, start, or stop. They are usually used in large steam cogeneration setups where only moderate control is required.

A traveling grate burner has a slow moving continuous loop grate (Figure 15). The fuel enters the firebox on one side and combusts completely by the time it exits the other side. This design can burn fuel with moisture contents up to 55%, but does not burn pieces larger

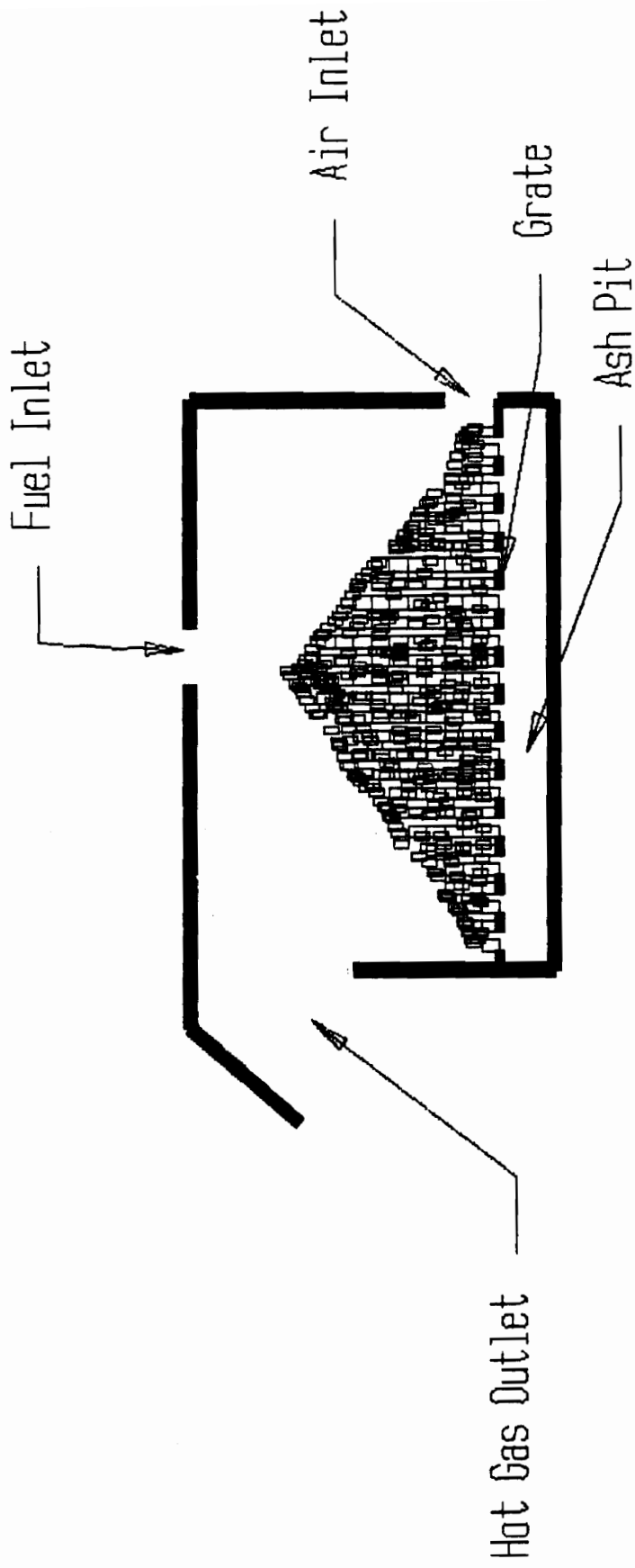


Figure 14: Dutch Oven Burner

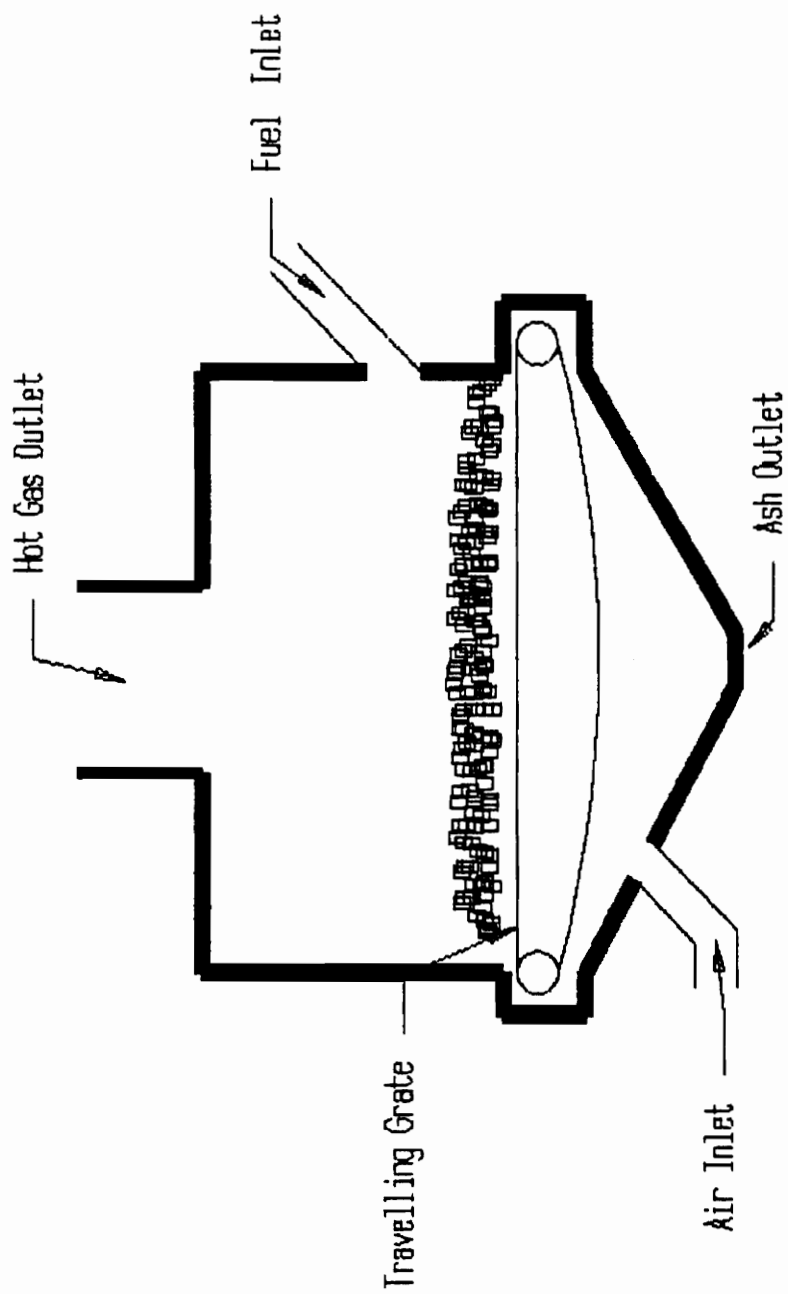


Figure 15: Travelling Grate Burner

than 2 inches very well because combustion time is controlled by grate speed.

An inclined or sloping grate burner has one side of the firebox, as well as the bottom, incorporated into the grate (Figure 16). The sidewall grate is set at an angle of 35-55⁰ from horizontal. The fuel is continuously fed onto the top of the grate in an even layer about 8-10 inches deep, and dries and burns as it slowly slides down to the bottom. Because of this drying action, inclined grate burners can burn wood with moisture contents as high as 65%. A pinhole grate burner is basically a modified inclined grate burner. However, rather than having the fire only on the bottom part of the grate, air is introduced over the entire surface of the grate through small pinholes and the fire covers the whole grate. The angle of the grate is not as steep and the fuel is spread on the grate as deep as 3-6 feet.

FLUIDIZED-BED BURNERS

In a fluidized bed burner, the combustion air is blown up through a layer of heated sand and fuel mixture (Figure 17). This air keeps the sand and fuel suspended slightly above the floor, in a constant boiling action. This action provides air to the entire surface area of the fuel as it dries and burns. Gases given off are burned right above the floor. Wetter particles remain suspended until they dry, allowing fuels up to 55% MC to be burned in a self-sustaining fire at efficiencies comparable to oil or gas-fired equipment while meeting air pollution requirements. Since more air is required to suspend large particles than is required to burn them, this type of burner does not work well with fuel sizes greater

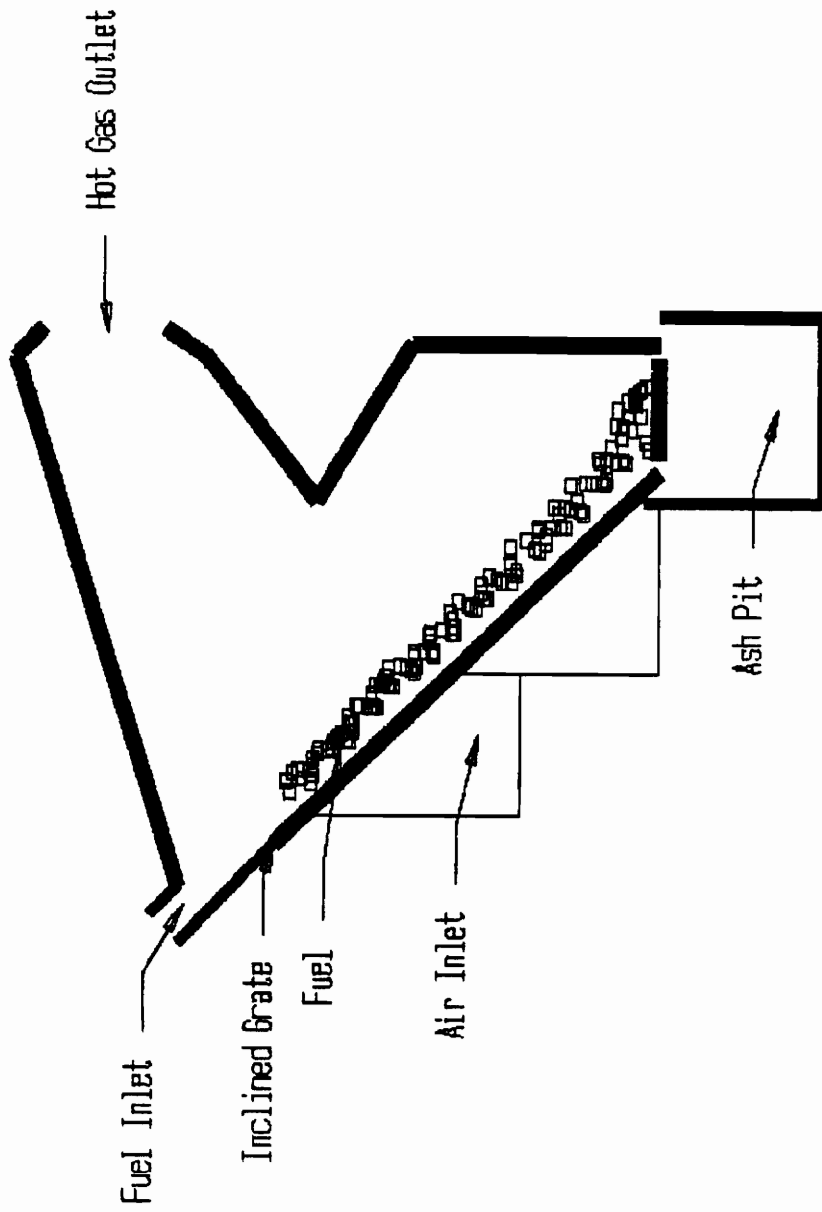


Figure 16: Inclined Grate Burner

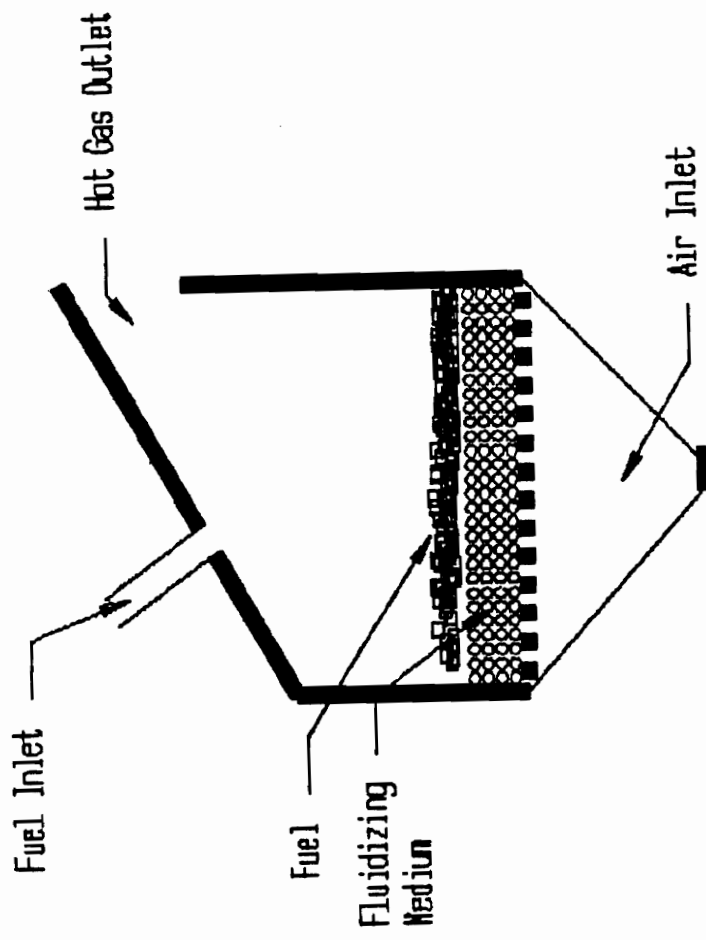


Figure 17: Fluidized-Bed Burner

than 2 inches in the largest dimension. The fluidizing medium is continuously removed to screen out ashes and larger trash, and then recycled back into the system.

SUSPENSION BURNERS

Suspension burners are fueled by fine, dry wood particles (<1/8 inch and <15% MC) which are mixed with air and blown either directly into a firebox, or into a cylindrical chamber to achieve better mixing and air movement within the firebox (Figure 18). The gun type is similar to pulverized coal burners in that a very fine wood flour is injected into a combustion chamber where it instantly ignites as a fireball. Overfire and underfire air are used to keep the fireball suspended in the combustion chamber below the heat exchanger. This type of burner is being developed in Sweden to replace oil or natural gas burners with minor modifications (Schmid, 1985). The flame and burning characteristics for wood powder are very similar to those of oil and natural gas, making the conversions quite simple. The pulverizing process is fairly expensive, but the gain in usable energy over other wood fuels more than makes up for the cost (Marks,1990).

In suspension burners with a mixing chamber, the air enters at several points along the side of the cylindrical combustion chamber. The air is forced around the edge of the combustion chamber resulting in a cyclone. The sawdust is metered in one end where it is mixed with air, ignites, and exits as exhaust gases and ash at the other end. The cyclone action results in uniform mixing of air and sawdust and helps to hold the particles in the burner until they are completely combusted.

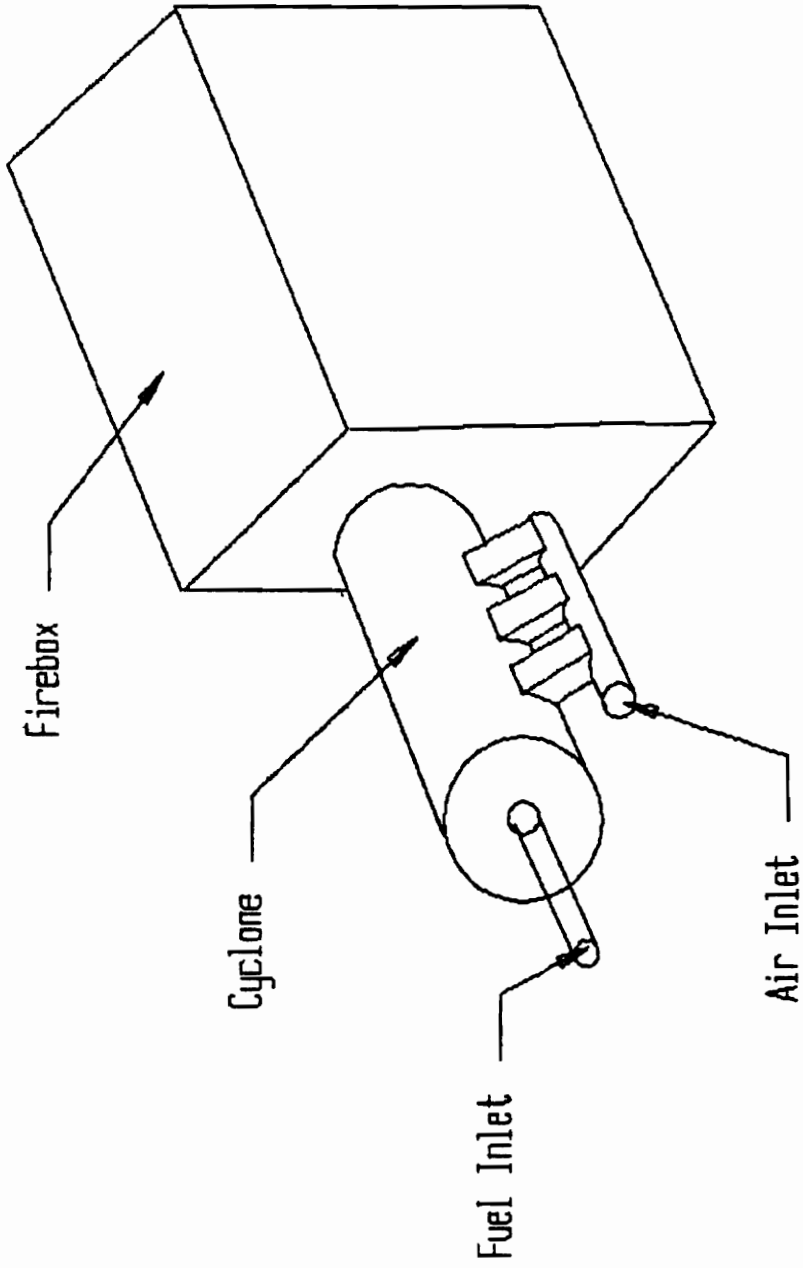


Figure 18: Cyclone Suspension Burner

This type of suspension burner has found wide application in direct-fired dry kilns and is best represented by the McConnell suspension burner. These are the smallest type of industrial burner and range in heat outputs from 1.5 million to 20 million BTU's/HR. An experimental suspension burner of this type was tested using green bark (Jasper and Koch, 1976), but no recent mention of such a burner was found in the literature.

METHODS AND PROCEDURES

Design and testing of the original sawdust burner and the single-tube and four-tube dryers proved that the designs were capable of operating at the levels set forth in the original objectives. For this project, the overall objective was to produce brown wood in a single pass through the dryer, while using a suspension sawdust burner as the heat source. The specific objectives were to modify the four-tube dryer so it could operate at higher temperatures with longer dwell times, build a larger and more durable sawdust burner, determine operating parameters of the dryer and burner, and determine design changes that would increase capacity and improve efficiency of both the dryer and burner.

MODIFICATIONS TO THE FOUR-TUBE DRYER

The sawdust burner used as the heat source for the dryer generated about twice the heat obtained from the oil burner used in all earlier tests of the dryer. The dryer had to be modified to allow it to operate at these much higher temperatures. A gas collection system was constructed to remove gases generated during the drying process. When the sawdust first entered the dryer, the gas generated was mainly steam, but as the sawdust approached 0% MC, the gas contained pyrolytic gases. The gas collection system consisted of a set of ducts connecting the top of each auger tube to a fan. A control valve at the fan output allowed the gases to be vented to the atmosphere when they were composed mainly of steam, or to be injected into the firebox and burned when they contained pyrolytic gases. A variable speed motor on the fan and a

damper in each of the four ducts allowed the amount of vacuum applied to each tube to be varied.

All other modifications to the dryer involved changes in the sawdust feed rate. The higher temperatures generated by the burner led to faster drying of the sawdust, but production of brown wood in a single pass required increasing the dwell time. Increasing dwell time involved changing the gearing on the auger tubes, but different auger speeds produced different feed characteristics for sawdust. The slower the augers turned, the more prone they were to packing, so this project attempted to find the optimum balance between auger speed and sawdust feed characteristics. To provide a consistent flow of sawdust, a variable-speed auger was used to meter sawdust into the dryer.

DRYER TEST PROCEDURE

Testing the dryer involved measuring its effectiveness at reducing the moisture content of sawdust as it came from a sawmill. The sawdust, as obtained from a mill, contained large pieces of wood, bark, and other debris that could not be carried in the augers without jamming them. The first step was to screen the sawdust by passing it through a vibrating screen constructed of two overlaid pieces of 3/8 inch expanded metal placed at a 20 degree angle.

A test of the dryer involved passing a constant flow of sawdust through the unit while taking the following measurements:

1. Dryer surface temperature
2. Firebox internal temperature
3. Firebox exhaust temperature

4. Sawdust feed rate
5. Sawdust input moisture content
6. Sawdust output moisture content

Temperatures were measured at regular intervals with thermocouple probes and a digital thermometer. As a barrel of sawdust was metered into the dryer, input moisture content samples were taken near the top and bottom of the barrel, and output moisture content samples were taken at regular intervals during the test. Measuring moisture contents of the sawdust involved drawing samples of sawdust and weighing them immediately. The samples were then dried to 0% MC in a heated drying shed and re-weighed. Zero % MC was verified using a microwave oven and established drying procedures. Moisture contents (dry weight basis) were then calculated using the following formula:

$$MC = \frac{\text{weight of wet sawdust} - \text{weight of dry sawdust}}{\text{weight of dry sawdust}} * 100\%$$

DESIGN AND CONSTRUCTION OF THE BURNER

The sawdust burner consisted of two parts: a fuel and air metering system, and a firebox. The fuel and air metering system was very similar to that found on most suspension burners; the sawdust was metered from a hopper by a paddlewheel feeder into an airstream (Figure 19). The resulting suspension of air and sawdust was then blown into the combustion chamber. The weight of sawdust fed per unit time was controlled by a variable speed electric motor on the paddlewheel feeder and the volume of air was controlled by a gate valve on the blower

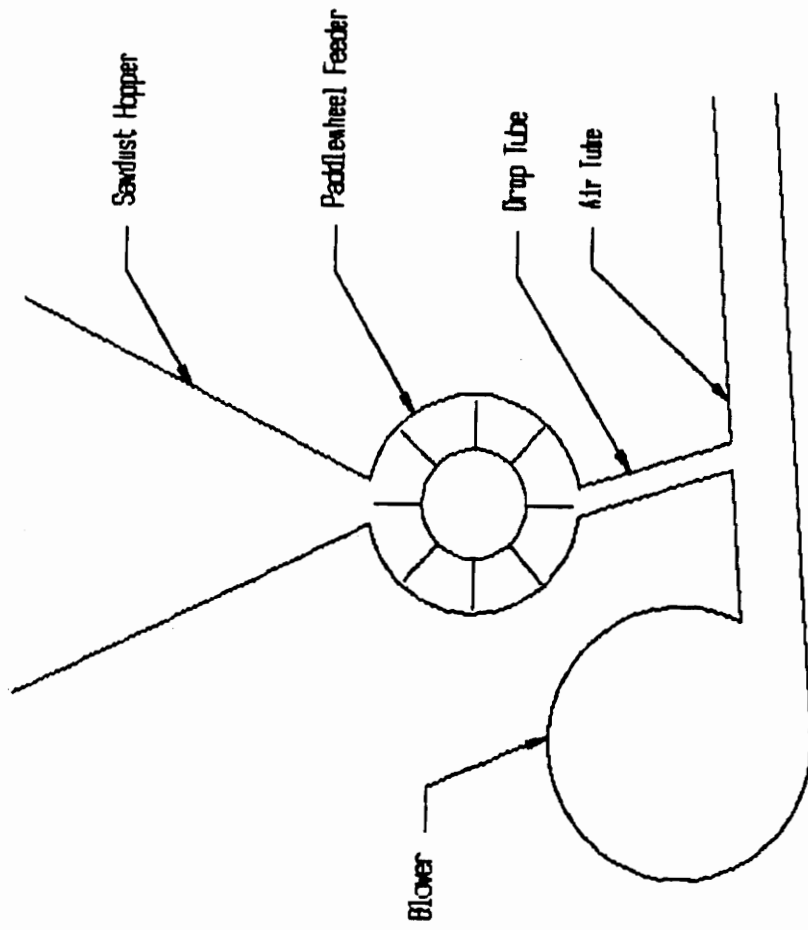


Figure 19: Sawdust And Air Metering System

intake. The metering system used on the project burner was the same as that used on the original burner.

While most suspension burners utilize a cylindrical combustion chamber, this design utilized an S-shaped passageway in the firebox to allow the smaller particles to burn immediately in suspension while the larger particles settled out of the airstream at the bends and burned within the firebox until they were light enough to be picked up and carried out by the airstream.

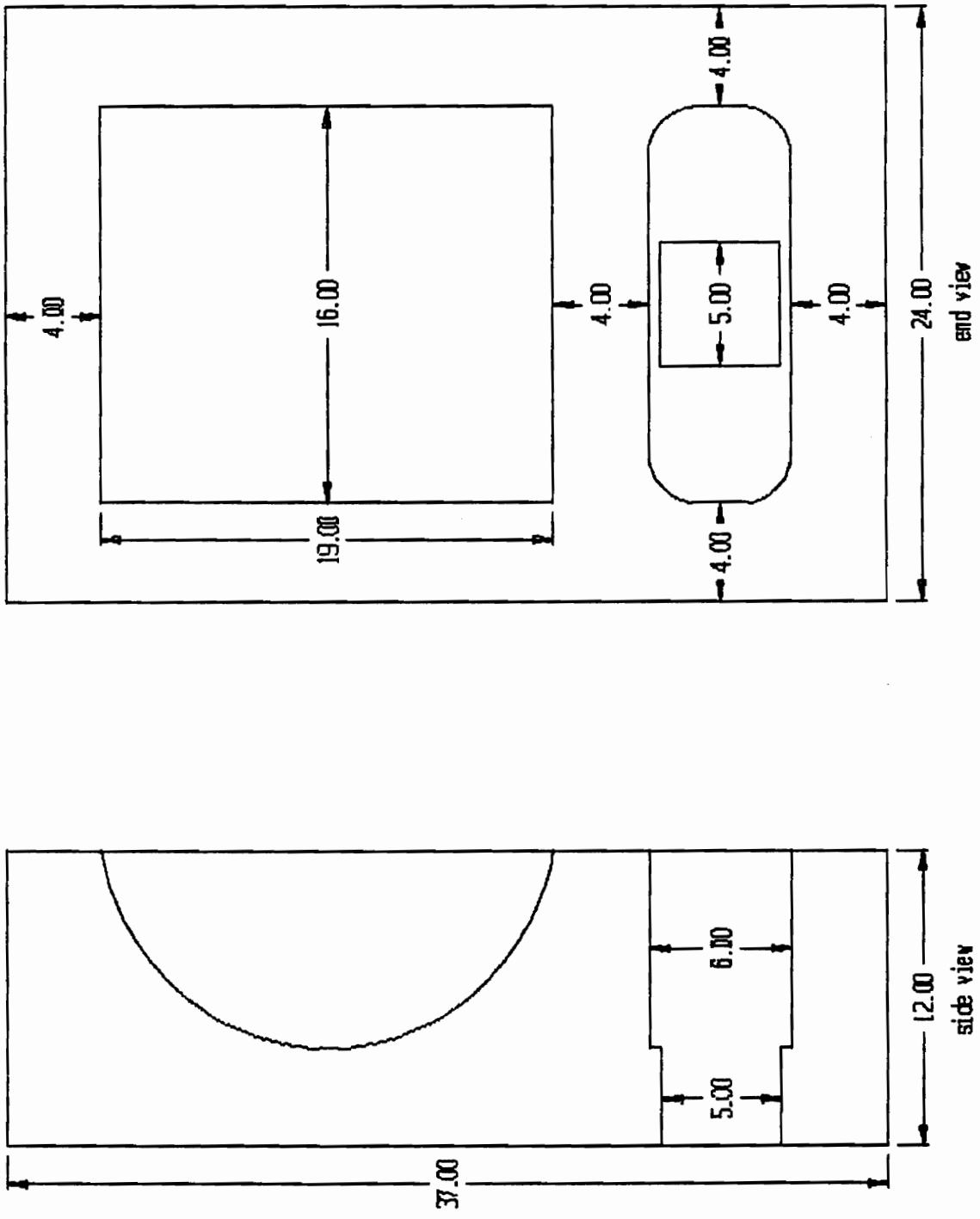
The firebox for the project burner was cast in sections as shown in Figures 20, 21, and 22. Morcicast-50-HS-LC, a refractory capable of withstanding temperatures up to 3000^oF, was used to eliminate the problems of meltdown. Morcicast can withstand very high heats but excessive thermal gradients can crack the castings. They must be heated slowly at a rate of 100^oF/HR on startup. The firebox was brought up to an external temperature of about 300^oF (internal temperature about 700^oF) using an oil burner rated at 70,000 BTU's/HR input. At this point, the internal temperature was sufficient to ignite the suspension of air and sawdust without the aid of the oil burner, and sawdust alone was burned to bring the burner up to its operating temperature.

SAWDUST BURNER TEST PROCEDURE

The test procedure was structured to measure net BTU's/HR output and thermal efficiency while varying moisture content and particle size of the sawdust.

The three moisture contents used were:

1. 0% (bonedry sawdust)



side view
end view
Figure 20: Inlet End Of Firebox

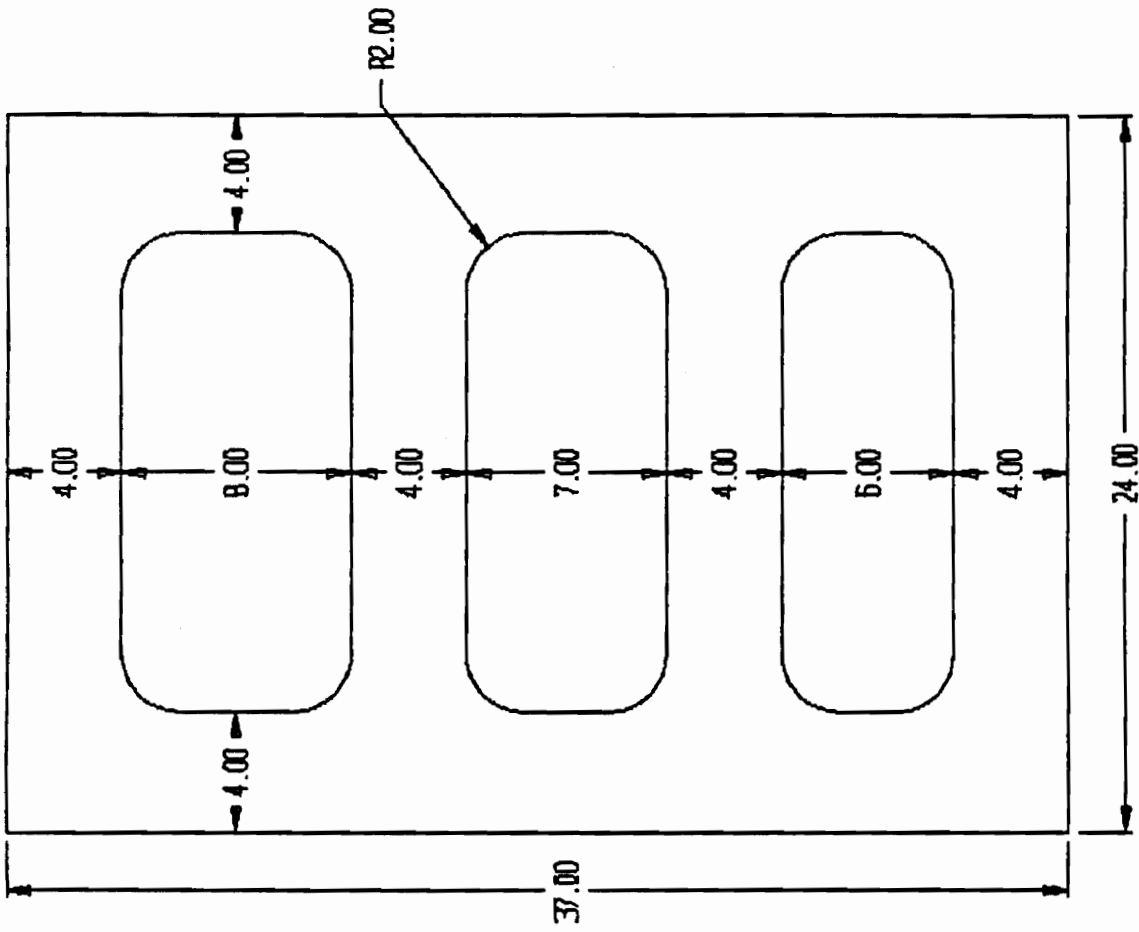


Figure 21: Center Section Of Firebox

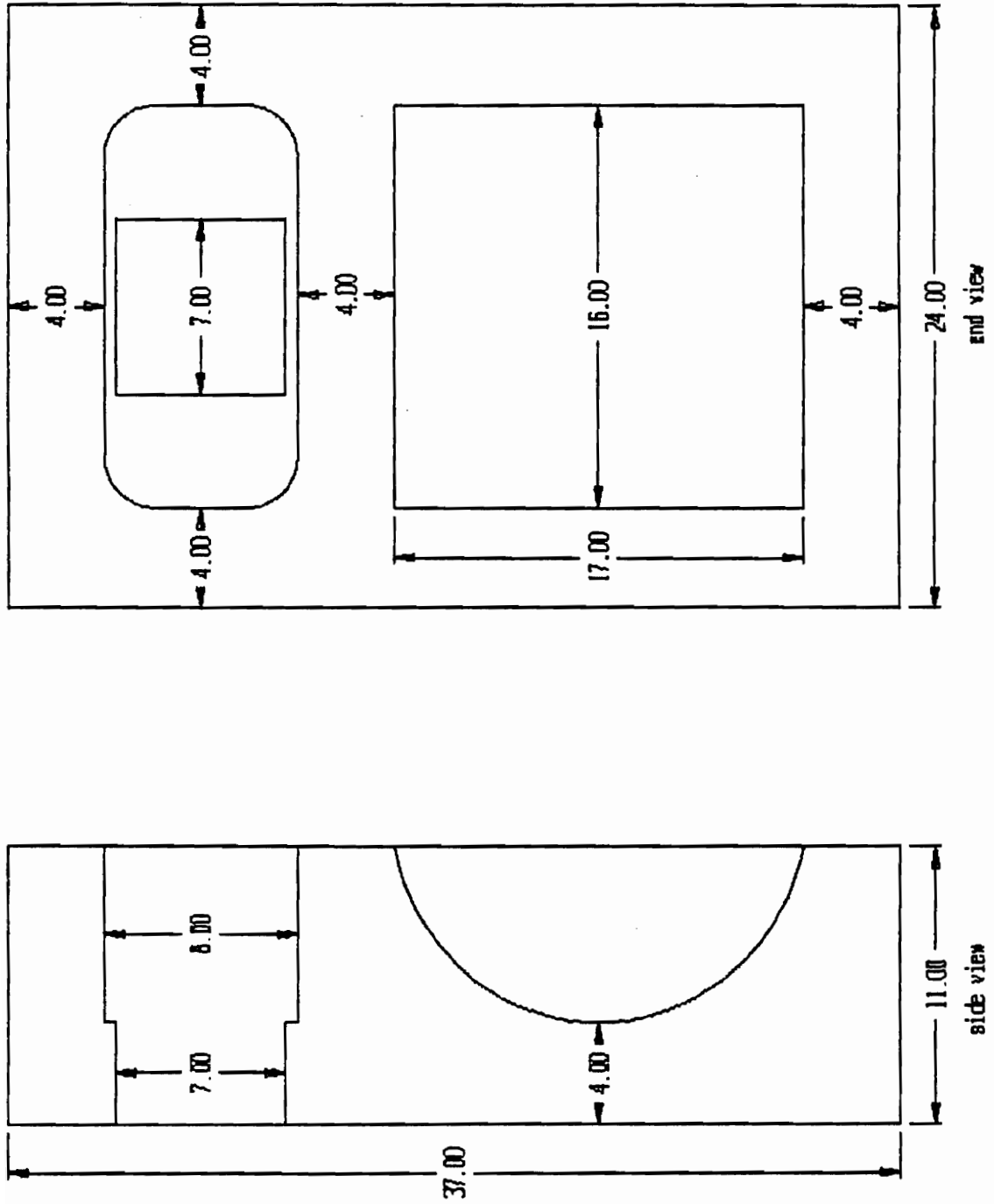


Figure 22: Outlet End Of Firebox

2. 20% (the approximate moisture content for sawdust from kiln-dried lumber)
3. 30% (the maximum moisture content, from the literature for suspension burners, that was thought to support sustained burn)

The two particle sizes were:

1. 3/8 inch and under
2. 1/8 inch and under

Other measurements taken to document performance were:

1. atmospheric pressure,
2. burner inlet and exhaust temperatures,
3. weight of the sawdust fuel, and
4. velocity of airflow into the burner

Air pressure was measured by taking a barometer reading at the beginning of each test. Air inlet and exhaust temperatures were measured every minute with type K thermocouple probes and a digital thermometer. The sawdust feed rate was calculated by weighing the sawdust before each test and dividing that weight by the time required to consume the sawdust. An average air pressure at the air inlet tube was measured with a pitot tube and was used to calculate inlet air volume.

Pine sawdust was used for all of the tests. It was screened, oven dried at temperatures between 125-150⁰F, and sealed in airtight containers for a minimum of 24 hours to equalize the moisture content. The testing was conducted over a several month period, so sawdust had to be obtained wherever it was available at the time of each trial. As a

result, the sawdust was not always consistent in species, particle size, moisture content, and freshness.

Before each test, the burner was brought up to the maximum obtainable temperature at a rate of 100^oF/HR. The preweighed sawdust samples were then fed into the burner at a constant feed rate and with a constant airflow rate. Each test lasted for a period of 40 to 130 minutes, during which time inlet and exhaust temperatures were measured at one minute intervals. Measurements of velocity of airflow were taken at the conclusion of each test.

DERIVATION OF SAWDUST BURNER HEAT OUTPUT AND EFFICIENCY

Heat output in BTU's/HR was calculated using the formula:

$$H = w * C_p * (T_{out} - T_{in})$$

where H = change in heat expressed in BTU's/min

w = weight of air expressed in #/min

C_p = specific heat of exhaust gases = .31 BTU's/#/^oF

(Moscahlaidis et al, 1991)

T_{out} - T_{in} = average output temperature - average input temperature

The weight of air was calculated using Charles' law

$$Pv = wRT$$

where P = atmospheric pressure expressed as #/ft²

v = volume of air input expressed as ft³/min

R = constant = 53.3

T = $^{\circ}\text{R} = 460 + \text{ambient temperature in } ^{\circ}\text{F}$

w = weight of air expressed in #/min

Thermal efficiency was calculated using the equation:

$$\text{Efficiency} = \frac{\text{Total sensible heat of exhaust gases generated from 1 \# of test sawdust (H from previous page)}}{\text{heat value of fuel}} * 100\%$$

where heat value of pine sawdust = 8600 BTU's/ovendry # (Koch, 1972)

RESULTS AND DISCUSSION

PRELIMINARY DRYER TESTS

The only data on the dryer were obtained during preliminary tests conducted to determine operating parameters. Data were collected during two preliminary tests and these tests showed that all the different systems of the dryer were functional and capable of dropping the moisture content anywhere from 20 to 65% in one pass and to 0% in multiple passes. Each test was conducted with somewhat different operating parameters, so the tests will be discussed separately rather than together.

Test number 1 (Figure 23) was the first attempt to produce brown wood in the dryer while using the sawdust burner as the heat source. Rather than supplying a steady flow of sawdust to the dryer, batches were fed into the dryer and cycled through three or four times until the sawdust appeared to be dry. Moisture content was reduced from an input at 75%, to an average output of less than 10%, with little difference in moisture content drop between the two particle sizes. The batch feeding method resulted in none of the previously mentioned mechanical problems with the dryer because the dryer was operating well below its capacity. This test proved that the dryer, coupled with the burner, was able to produce brown wood, although not in a single pass.

Test number 2 (Figure 24) attempted to determine maximum moisture content drop during a single pass, while feeding as much sawdust as possible. From minutes 0 to 43, green sawdust at an average moisture content near 80% was fed through the dryer. From minute 43 to the

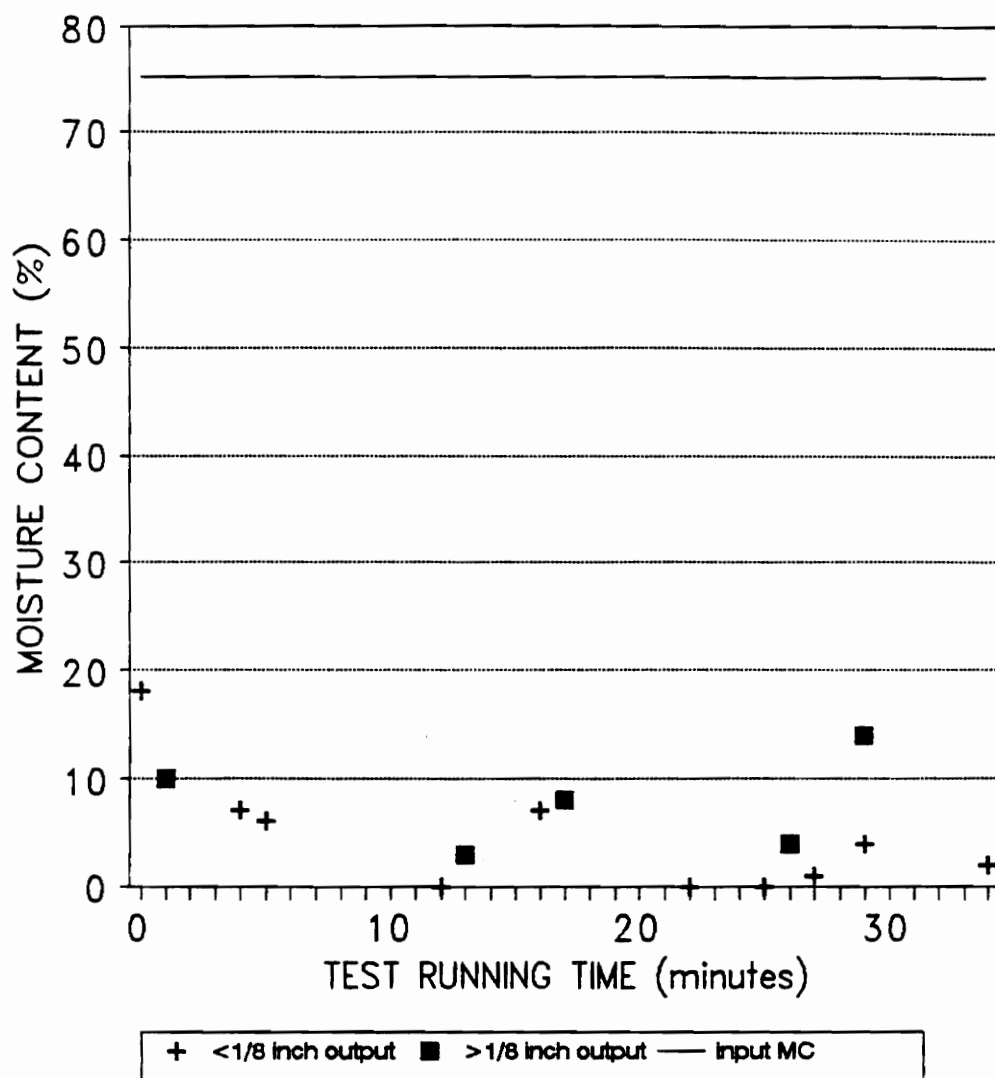


Figure 23: Change In Moisture Content For Dryer Test #1 Using Batch-Mode Operation

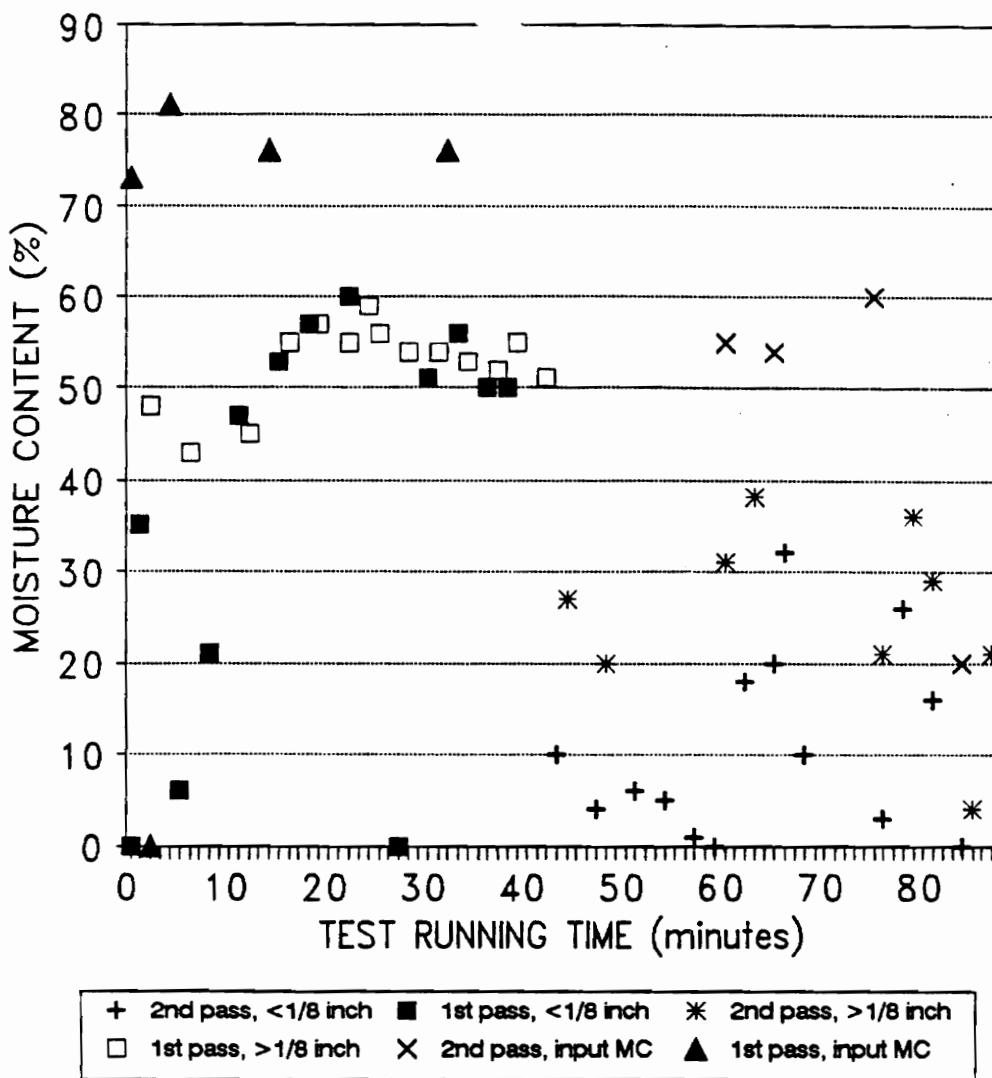


Figure 24: Change In Moisture Content For Dryer Test #2 Using a Constant Feed Rate and Cycling The Sawdust Twice

termination of the test, the same sawdust was cycled through a second time. During the first pass, the moisture content dropped a fairly consistent 20 to 25% MC with no difference between the two particle sizes.

However, during the second pass, the data began to show the design limitations of the dryer. Plugs in the auger tubes resulted in moisture content readings near 0%, because sawdust remained in the dryer much longer than it would have otherwise. These plugs occurred either at the bottom of the tube or near the top of the tube. While it was known that these plugs were caused by an auger tube angle that was too steep to efficiently move sawdust, there were two possible reasons why these plugs occurred during the second pass and not during the first.

Firstly, the very fine particles were wet during the first pass and remained attached to the larger particles. In effect, there was only one particle size. However, during the second pass, the moisture content of these fine particles reached a point where the bond was broken. The slope of the auger tubes and the churning action of the augers, caused particles to segregate with the smaller particles settling to the bottom of the tube where they would pack and form a plug.

Secondly, plugs near the tops of the auger tubes appeared to be caused by the gas collection system. The airflow through the duct system required to remove the steam generated, carried the fine particles reaching the tops of the auger tubes into the ductwork. A period of a few minutes was all that was necessary for the ductwork to become constricted by fine sawdust to the extent that there was no longer sufficient airflow to remove the steam. The steam recondensed at the

tops of the auger tubes and ran back down the tubes, causing rewetting of the sawdust which led to packing near the top.

While most variances in the data can be attributed to mechanical problems in the dryer systems, some can be attributed to learning on the part of the test crew. Since the tests were only preliminary, the test crew was still developing familiarity with the dryer operating parameters, and attempting to get all the various systems synchronized. At times, the augers were feeding the sawdust too fast, the dryer temperature was not hot enough, or the gas collection system was not pulling as much air as it should have been. Each of these individual systems affected how the others would operate, and an adjustment to one usually required adjustments to the others. During the limited number of tests conducted, the optimum settings were never found and as a result the dryer never operated at its potential. During the last test conducted, ignition of the pyrolytic gases within the auger tubes and gas collection system caused structural damage that prevented further refining of the operating procedure and the collection of more test data.

SUGGESTED DESIGN CHANGES FOR NEXT PROTOTYPE

The four-tube dryer was constructed using knowledge gained from testing the single-tube dryer. Both the single-tube dryer and the four-tube dryer met their original objectives. The four-tube dryer worked well at drying sawdust and even at producing brown wood when it was heated with the oil burner. In attempting to produce brown wood in a single pass, problems developed when working with the higher temperatures generated by the sawdust burner. Heat input increased from about

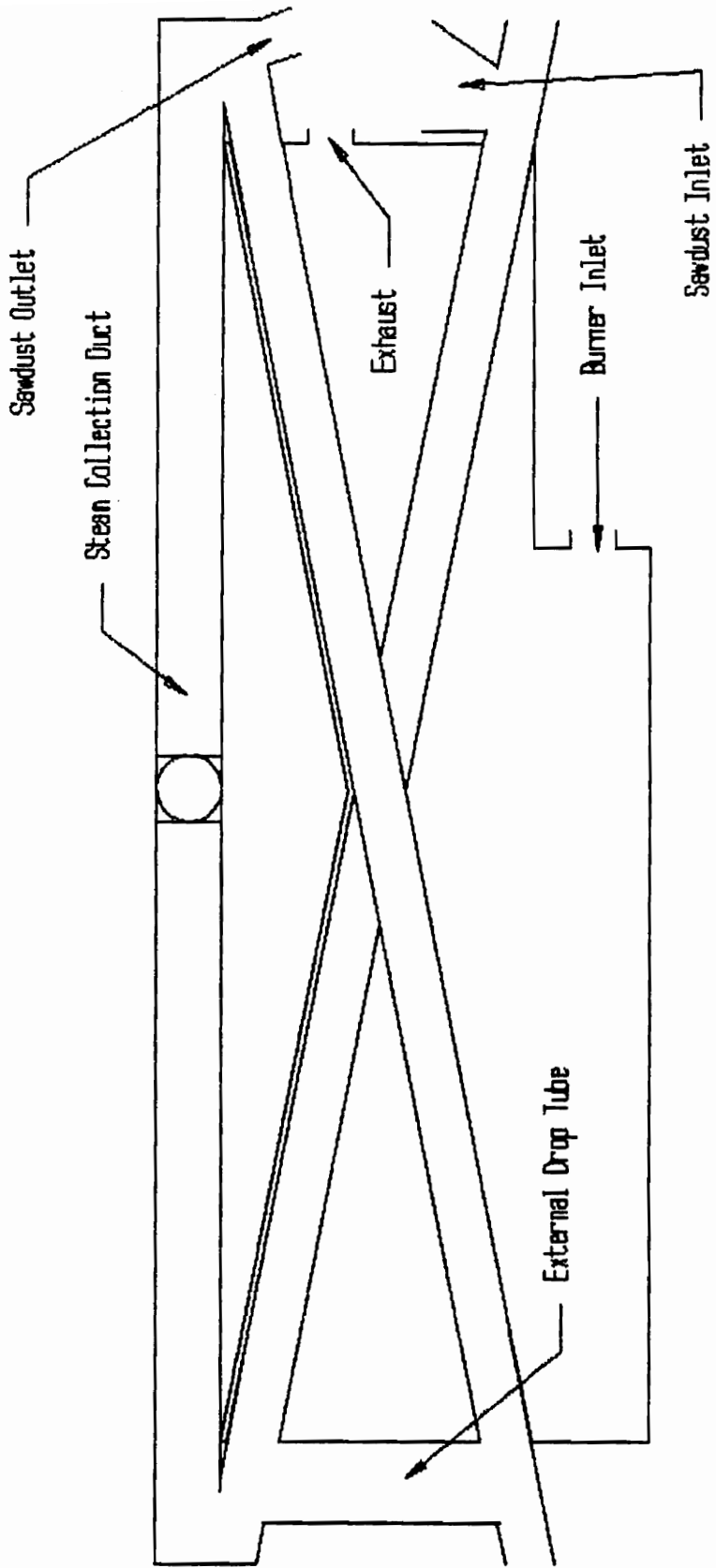


Figure 25: Two-Tube Dryer

250,000, to close to 600,000 BTU's/HR and the resulting dryer temperature increased from about 600^oF to over 800^oF.

From the knowledge gained by these tests, the design for the next prototype shown in Figure 25, was conceived. As mentioned, the major problem with the test prototype was with the angle of the auger tubes. The next prototype will have auger tubes placed at an angle that is approximately 20 degrees or less from horizontal. The expected improvements from this change are twofold. First, the flatter angle will not allow the auger tubes to fill completely, therefore requiring less power to turn and more room for steam to escape. Second, with the flatter angle, the auger can be turned slower and still move sawdust. This increases the dwell time of the sawdust and reduces the total required length of auger, which allows a reduction in the number of auger tubes from 4 to 2, simplifying the design.

Some of the sawdust packing inside the auger tubes was caused by steam recondensing at the tops of the tubes and saturating the sawdust. The new design incorporates two changes that address this problem. The first is to scale up the size of the blower and ductwork. Larger ductwork will allow the movement of greater volumes of air at lower speed, which should keep more of the fine particles in the dryer. The second is to increase the area where steam can escape from the sawdust. Although the water in the sawdust was converted readily to steam as it passed through the dryer, it could only escape at the top of each auger tube. The new design adds 4 inches of headspace to the auger tube above the auger to allow the steam to separate from the sawdust and escape over the entire length of the auger tube and not just at the top.

While the first 2 prototypes were experimental, the next is expected to be an engineering prototype, or full-scale operational prototype. The whole system has been scaled up to handle the one to two green tons per hour output of a typical small to medium-sized sawmill. The diameter of the auger tubes are increased to 8 inches, a 56% increase in cross sectional area.

The objective of the tests conducted for this project was to produce brown wood in a single pass. The results show that the dryer, as constructed, is much more efficient and capable of reducing the moisture content of the sawdust by 20 to 25% in a single pass, rather than down to bonedry sawdust by recycling. While reduced moisture content sawdust does not have as high a market value as bonedry sawdust, the market is more widespread, the cost of necessary equipment is much less, and there is much more interest from the forest products industry. These factors have led to different objectives than those for the brown wood dryer. The final product objective will be 40 to 50% MC sawdust produced in a single pass. Since the sawdust will not be dried to 0% MC, no pyrolytic gases will be released and the need for an airtight and fireproof duct system is eliminated. However, there will still be a blower to facilitate removal of steam from the sawdust.

One final lesson learned from the preliminary tests was that if there ever is a desire to produce sawdust with a moisture content below 40%, it would be better to increase the number of auger tubes passing through a 600^oF firebox, rather than increasing the heat supplied to the present number of auger tubes. Higher temperatures can lead to structural damages and increased safety hazards from fires and meltdowns.

BURNER TESTS

Although the sawdust burner could not be tested using the dryer as a heat exchanger, operating parameters were outlined and thermal efficiency and heat output were calculated. The design parameters for the burner were around 250,000 BTU's/HR at efficiencies in the 70 to 80% range. Test results greatly surpassed initial expectations. Calculated heat output ranged from 342,000 BTU's/HR to 387,000 BTU's/HR and calculated overall thermal efficiencies ranged from 83.5 to 95.8% (Figures 26, 27). Complete calculations of heat output and thermal efficiencies for the first test are contained in Appendix A and a summary of calculations for all tests is contained in Table 3.

HEAT OUTPUT

Since the burner could not be tested while connected to the dryer, the operating objective became to achieve the maximum efficiency and heat output without a heat exchanger. Exhaust temperatures were measured at the burner exhaust so the highest efficiencies could only be obtained by containing as much of the combustion within the burner as possible. Therefore, the maximum amount of sawdust that could be fed to the burner was the amount that did not produce flames extending outside the burner. This resulted in much lower magnitudes of heat output than would have been possible had a heat exchanger been coupled to the burner.

Neither of the test variables, moisture content or particle size had the expected influence on heat output and efficiency. It was thought that the larger particles would not be completely burned within the firebox, lowering combustor efficiency. But the air velocities were low

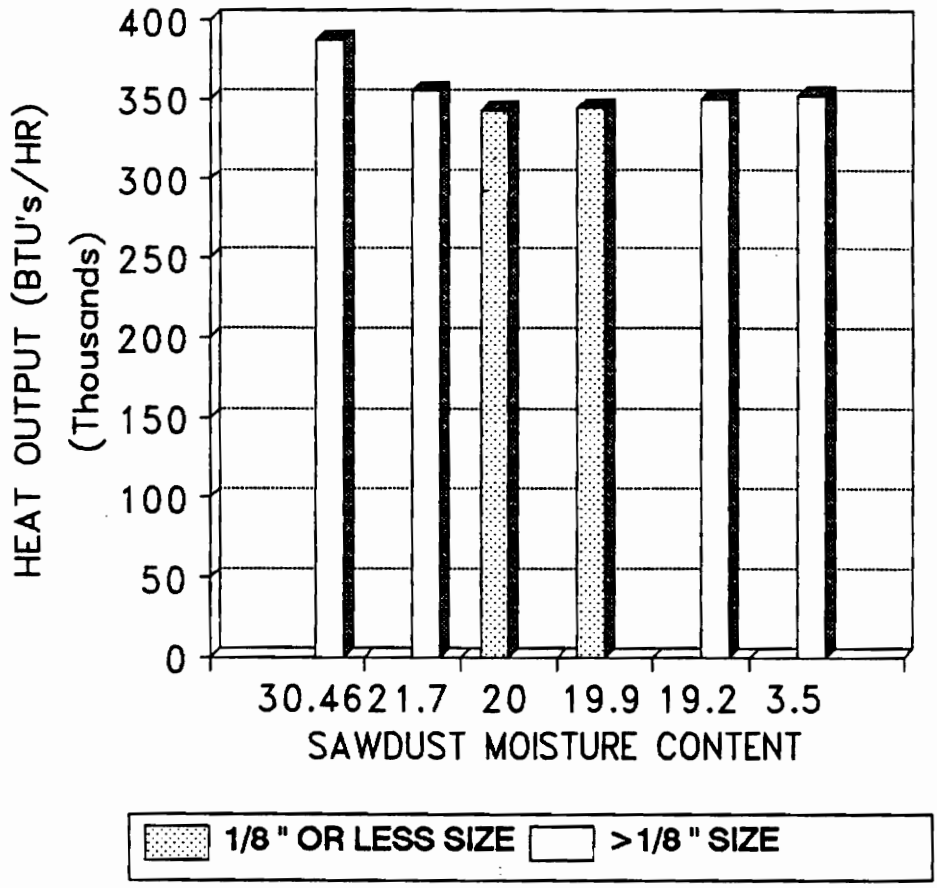


Figure 26: Comparisons of Sawdust Burner Heat Outputs Versus Sawdust Particle Size and Moisture Content

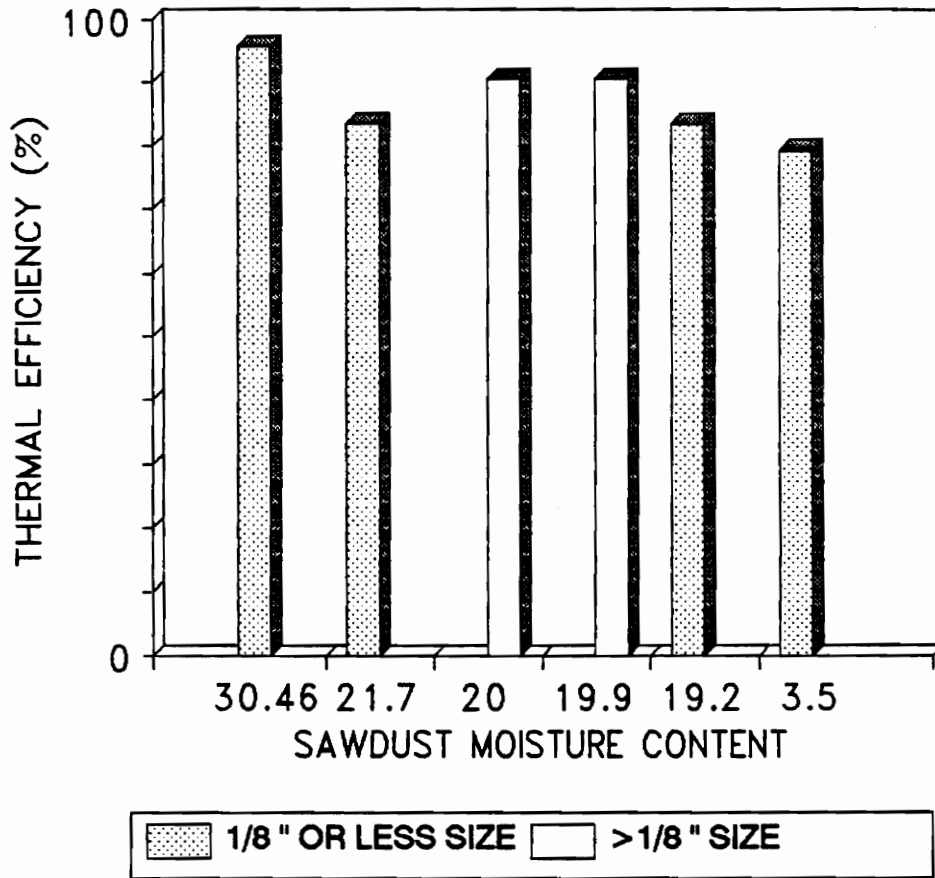


Figure 27: Comparisons of Sawdust Burner Efficiency Versus Sawdust Particle Size and Moisture Content

TABLE 3: SUMMARY TABLE OF CALCULATIONS FOR BURNER EFFICIENCY AND HEAT OUTPUT

	Volume Of Air (ft ³ /min)	Barometric Pressure (in Hg)	Weight Of Air (#/min)	Sawdust Feed Rate (#/HR)	Average Output Temperature (° F)	Heat Output (BTU's/HR)	Burner Efficiency (%)	Excess Air (%)
3.5% MC, <1/8 Inch Particle Size	120.95	29.84	9.219	51.8	2112.1	351,965	79.4	62.1
19.2% MC <1/8 Inch Particle Size	118.55	30.12	9.167	49.9	2111.3	350,269	83.5	73.2
19.9% MC <3/8 Inch Particle Size	118.55	30.12	9.275	45.3	2047.0	344,340	90.5	93.4
21.7% MC <1/8 Inch Particle Size	118.55	30.12	9.221	50.6	2123.0	354,862	83.6	71.8
20.0% MC <3/8 Inch Particle Size	118.55	30.12	9.293	45.0	2028.5	341,989	90.5	94.8
30.5% MC <1/8 Inch Particle Size	139.55	30.31	10.798	48.3	1985.8	386,783	95.8	111.2

enough that the larger particles fell out of the airstream at the first bend in the firebox and remained burning there until they were light enough to be picked back up by the airstream and carried further along. The net effect was a combination pile burner and suspension burner. This settling out of heavier particles resulted in very few sparks in the exhaust because most particles were completely consumed before they could exit.

Figures 28 through 33 show the temperatures recorded during each test. Although the moisture content of the sawdust increased by 27%, the average output temperature only fell by 107^oF. The fact that the average temperature difference between two different particles sizes of the same moisture content was less than 100^oF was also of significance. Both of these results demonstrate the adaptability of the burner to a wide range of fuel particle sizes and moisture contents.

Plugs in the sawdust feeding system that occurred during the trials demonstrate how controllable the system could be. In Figure 28, each of the 4 large drops in temperature were caused by large sawdust particles temporarily stopping the feed system. Shutting off the sawdust dropped the exhaust temperature dramatically, but once the sawdust feed was restarted, the temperatures climbed as quickly as they had fallen.

Heating the firebox to an average temperature of 1850^oF stores approximately 1,000,000 BTU's in the refractory. This large storage capacity allows the burner to hold a high temperature over a long period of time, suggesting its use in pulse firing applications where the burner could be shut off for several hours and re-ignited from residual heat when air and sawdust feeds are restarted. Since startup time would be of

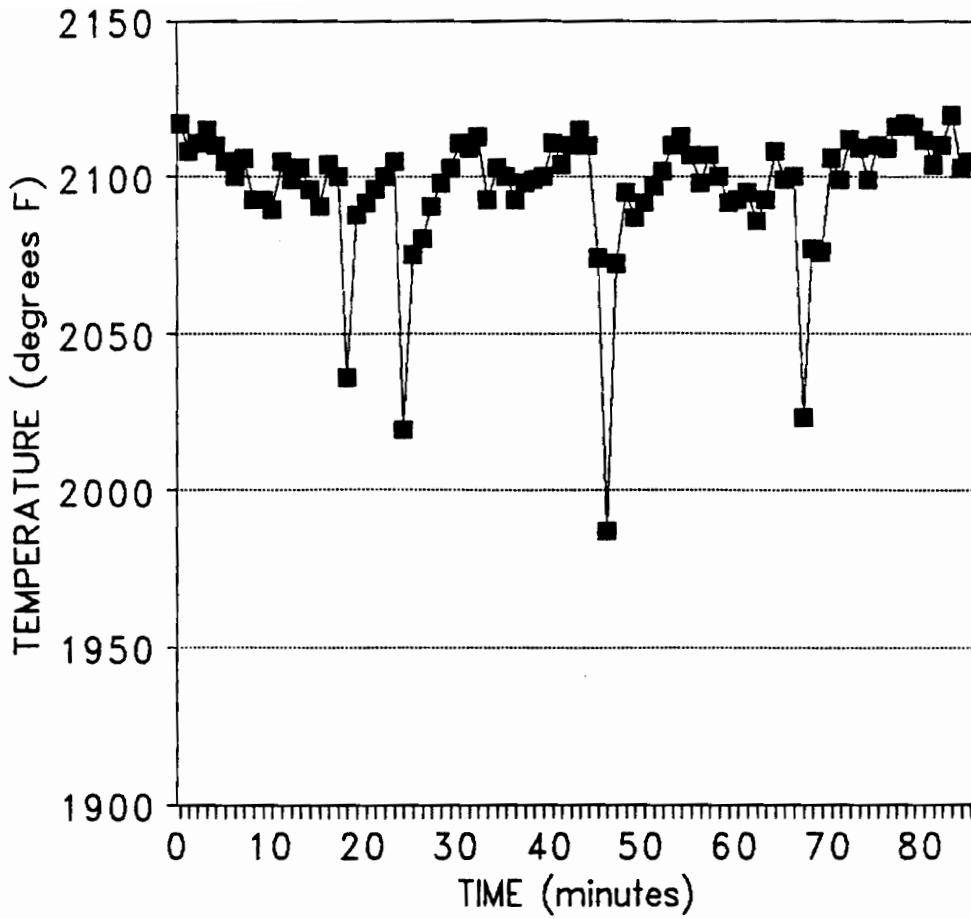


Figure 28: Burner Temperature Data For Test #1
Using 3.5% MC Sawdust and $\lt; 3/8$ Inch Particle Size

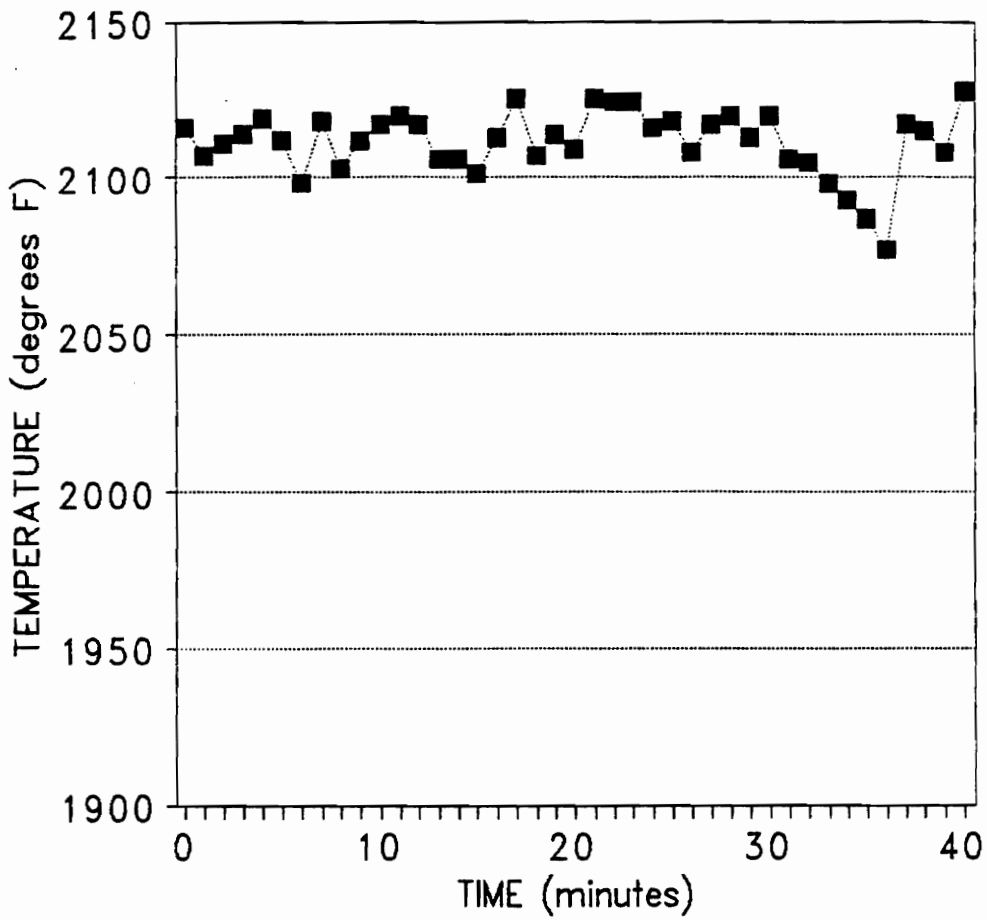


Figure 29: Burner Temperature Data For Test #2
Using 19.2% MC Sawdust and <1/8 Inch Particle Size

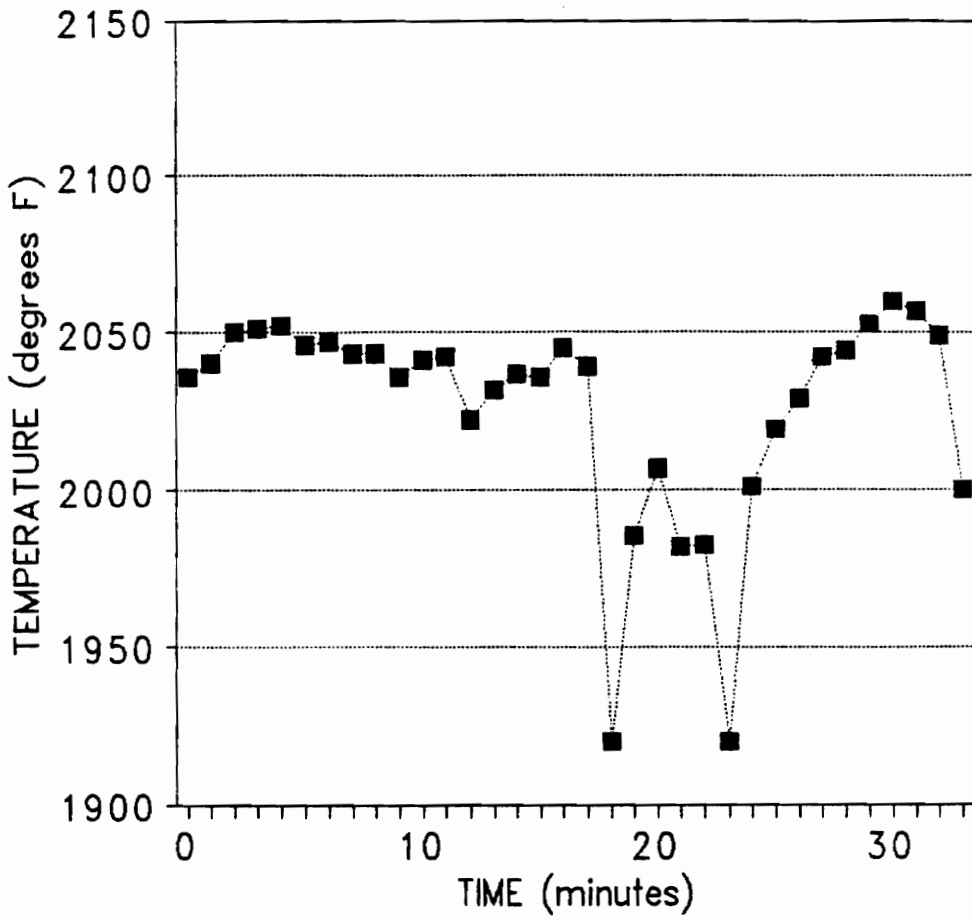


Figure 30: Burner Temperature Data For Test #3
Using 19.9% MC Sawdust and $\lt; 3/8$ Inch Particle Size

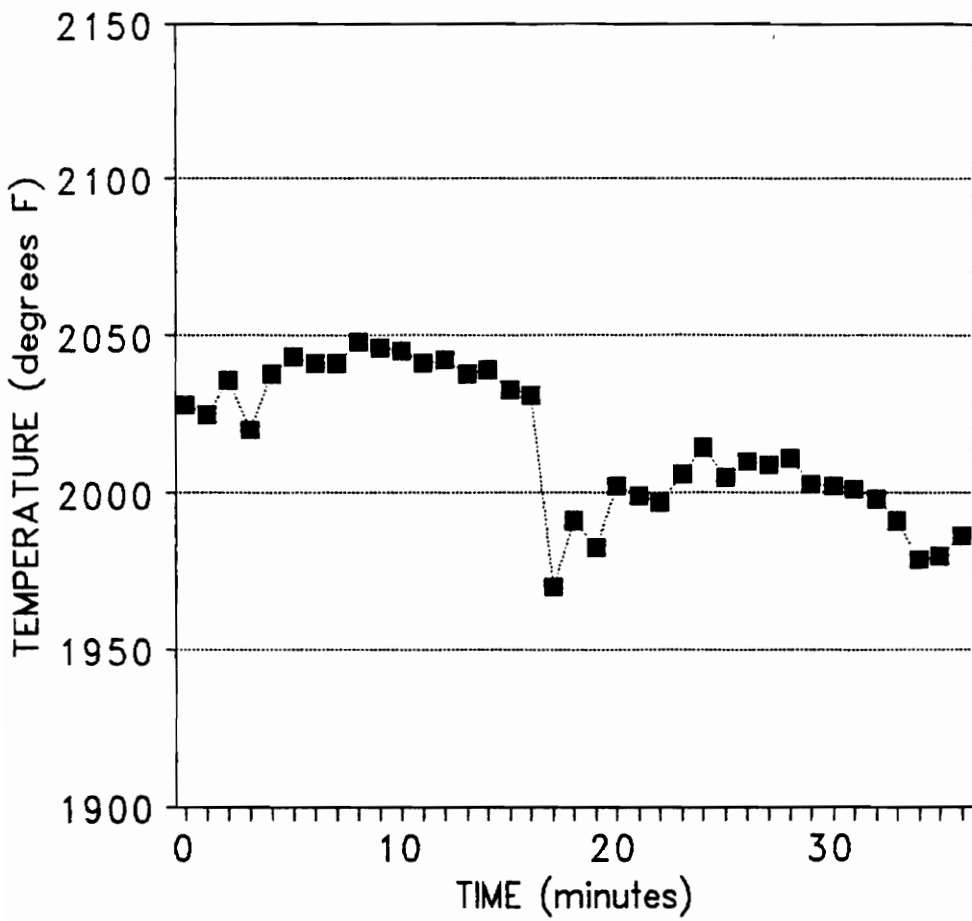


Figure 31: Burner Temperature Data For Test #4
Using 20.0% MC Sawdust and $<3/8$ Inch Particle Size

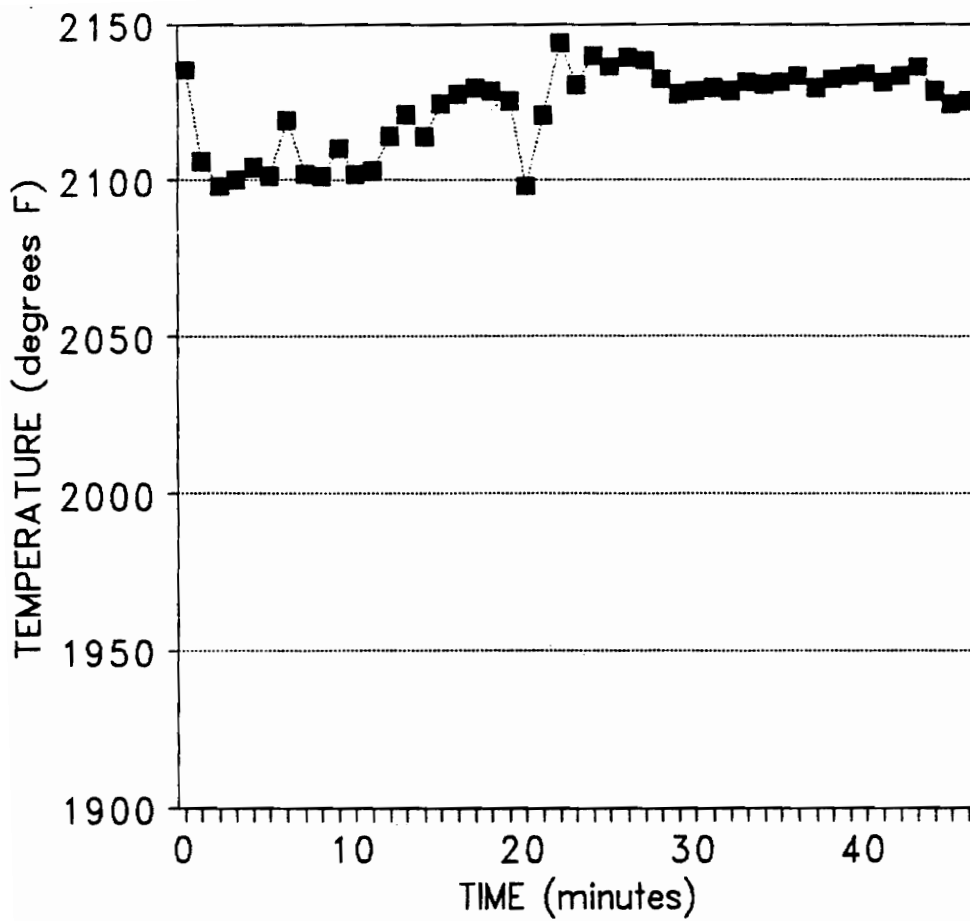


Figure 32: Burner Temperature Data For Test #5
Using 21.7% MC Sawdust and <1/8 Inch Particle Size

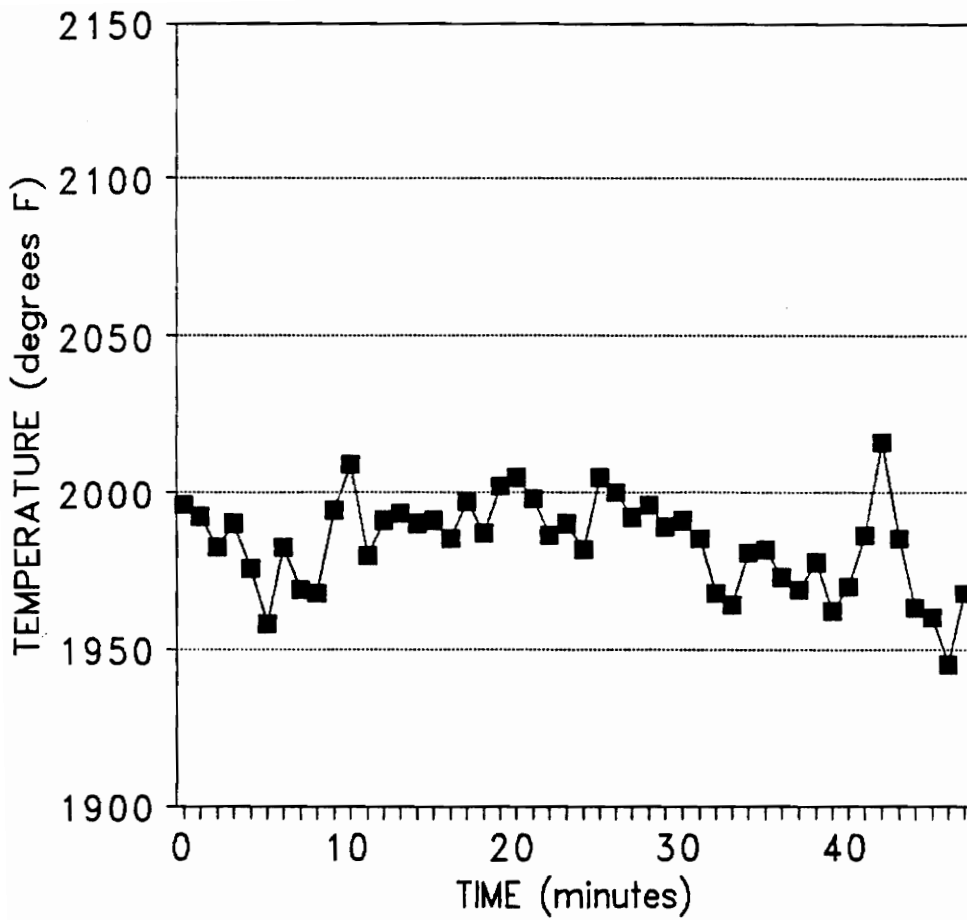


Figure 33: Burner Temperature Data For Test #6
Using 30.5% MC Sawdust and <1/8 Inch Particle Size

concern in an actual operating situation, the burner could be insulated to contain as much heat as possible, and fired for a few minutes every half-hour or hour in order for the burner to retain its operating temperature overnight.

BURNER EFFICIENCY

The literature indicated that the efficiency of suspension burners tends to drop off dramatically as the moisture content of the fuel approaches 30%. This was the reason that the wettest test sample was only 30%. The tests showed a relationship between efficiency and moisture content that was exactly the opposite of what was expected. Figure 25 shows that rather than the downward sloping curve representative of most types of burners, the relationship slopes up, suggesting an increase in efficiency with an increase in fuel moisture content. While there is clearly something wrong with this relationship, there are several factors that contributed to it. First, and most influential, is operating technique. Rather than using the same feed rate for each test, the sawdust and air feed rates were adjusted for each test to the maximum possible that would not produce flames in the burner exhaust. Higher moisture content fuels weighed more initially and tended to settle out of the airstream almost immediately, and hence more air could be supplied without blowing the particles out of the burner before complete combustion. This increased excess air led to increased efficiencies which led to higher magnitudes of heat output. Supplying the same weight of sawdust and air for each moisture content test would have undoubtedly provided the expected curve shape.

The literature shows that most suspension burners operate at peak efficiency when supplied with 100 to 140% excess air (Discussion, 1980) and if this holds true for this burner, then even higher efficiencies should be obtainable by increasing excess air even more through the addition of a heat exchanger.

OTHER FACTORS AFFECTING RESULTS

The feed characteristics of each sawdust sample were different and there was no way to measure fuel and air ratios entering the burner instantaneously, so the volumes and ratios of fuel and air were different for each test.

The drier the sawdust, the more difficult it was to feed. The fine, dry particles clung to each other, preventing a consistent gravity feed into the paddlewheel and through the drop tube into the air supply tube.

There was a lack of precision in the equipment used for measuring volume of airflow into the burner. Therefore the calculations for efficiency were best characterized as approximations. It is unlikely that efficiencies exceeded 90% because this was an uninsulated prototype burner. The efficiencies were all measured in the same manner and therefore serve as an index by which the tests can be compared. Fitting the blower intake with a calibrated nozzle would provide much more precise measurements of inlet air volumes.

SUGGESTED DESIGN CHANGES

The first prototype burner worked well, but could not withstand the temperatures generated. The second prototype was a scaled-up version capable of withstanding combustion temperatures and had almost no basic design changes from the first. It exceeded design expectations but it became apparent during testing that the following design changes could further improve both efficiency and heat output.

1. Increasing the capacity of the sawdust and air feed system
2. Insulating the firebox
3. Adding a heat exchanger

The sawdust and air feed system on the second prototype was unchanged from the first burner. The paddlewheel feeder was capable of metering about three times as much sawdust as was used during the tests, but the drop tube and the air supply tube were both undersized. The fuel feed rate and air supply had to be reduced to match the inadequacies.

Insulating the firebox would reduce heat lost from radiation, helping to increase both efficiency and usable heat output.

SUMMARY AND CONCLUSIONS

Both the dryer and burner were successfully modified and tested. The dryer demonstrated an ability to remove up to 65% of the moisture from green sawdust. It is hoped that a new prototype, featuring improvements based on research conducted for this project, will be a fully functional production model capable of reducing moisture contents to 40% in one pass, at a rate of one to two green tons per hour.

The burner surpassed original expectations and is also ready for a production prototype. Although the calculated heat output and thermal efficiency are probably high, the burner was operating above 80% efficiency. With the addition of insulation to the firebox and the design of a more consistent sawdust feed system, efficiency could reach the 90%+ level of commercially available suspension and pellet burners.

The controllability and adaptability of the burner to variations in particle size and moisture content suggest the possibility of uses other than the sawdust dryer, such as a heat source for direct-fired dry kilns, or in conjunction with a heat exchanger to generate steam.

The addition of a heat exchanger should allow the burner to operate in the 500,000 to 600,000 BTU's/HR range with no modifications to the feed system or the firebox. During one trial, when the burner was connected to the dryer, the burner consumed about 85 pounds of sawdust per hour. Assuming 85% efficiency, this heat output was roughly 600,000 BTU's/HR.

Scaling up the feed system after an adequate heat exchanger is added, should allow heat output near the 1,000,000 BTU's/HR level or about 135 pounds of sawdust per hour at 85% efficiency.

The burner is cast as two end pieces and a center section. This allows increasing firebox capacity by the addition of one or more center sections. The addition of a center section, a heat exchanger, and upscaling the feed system to handle 200 pounds of sawdust per hour should allow heat production in the range of 1,000,000 to 1,500,000 BTU's/HR at efficiencies similar to those calculated from the tests.

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APPENDIX A

Calculations of Efficiency and Heat Output For Burner Tests

Sample Calculations For 3.5% MC, <1/8 INCH PARTICLE SIZE SAWDUST

Volume of air

(size of outlgt-area of obstructions)
 $(2''*4''-.638in^2)/144*2367ft/min=120.95 ft^3/min$

Weight of air

$Pv=wRT$
 $P=pressure=29.84in Hg=14.66 PSI*144=2111.14 PSF$
 $v=120.95 ft^3/min$
 $R=53.3 (constant)$
 $T=^oR=59.64^oF+460=519.64$
 $w=weight\ of\ air$
 $2111.14*120.95=w*53.3*519.64$
 $w=9.219\#/min$

BTU's/hr output

$H=w*C (T_{out} - T_{in})*60min/hr=BTU's/hr$
 $w=weight\ of\ air=9.219\#/min$
 $C =specific\ heat\ of\ exhaust\ gases=.31 BTU's/\#^oF (Moscahlaidis\ et\ al,\ 1991)$
 $T_{out} - T_{in} =2112.13(average\ output\ temperature)-59.64(average\ input\ temperature)$
 $H=9.219*.31*2052.49*60=351,965.75 BTU's/hr$

Thermal efficiency

Efficiency=total sensible heat of exhaust gas/heat value of sawdust*100
 total sensible heat of exhaust gas=351,965.75 Btu's/hr
 heat value of dry sawdust
 higher heat value of sawdust=8600 BTU's/# (Cheremisinoff, 1980)
 MC of sawdust=3.5%(wet basis)
 $(8600*51.77\# sawdust/hr)-1.88*1000=443,342 BTU's/hr$
 $351,965.75/443,342*100=79.39\% efficiency$

Amount of excess air injected

weight of air required to burn C in 1# sawdust
 $C+O_2 \rightarrow CO_2$ (Koch, 1972)
 $2.66\#O_2$ required to burn 1# C
 air is 23.1% O_2 by weight so 11.52# air required to burn 1# C
 pine sawdust is 51.8% C by weight (Cheremisinoff, 1980)
 $11.52*.518=5.965\#$ air required to burn C in 1# sawdust
 weight of air required to burn H in 1# sawdust
 $2H_2+O_2 \rightarrow 2H_2O$ (Koch, 1972)
 $8\# O_2$ required to burn 1# H
 Air is 23.1% O_2 by weight so 34.63# air required to burn 1# H
 pine sawdust is 6.3% H by weight (Cheremisinoff, 1980)
 $34.63*.063=2.182\#$ air required to burn H in 1# sawdust
 weight of air equivalent to O_2 present in sawdust
 pine sawdust is 41.3% O_2 by weight (Cheremisinoff, 1980)
 $4.33\#$ air contains 1# O_2
 $4.33*.413=1.787\#$ air equivalent in wood
 $5.965+2.182-1.787=6.36\#$ air required to burn 1# sawdust
 $.894\# sawdust/min @ 9.219\# air/min = 10.312\# air/\# sawdust$
 $10.312\# air\ injected / 6.36\# air\ required = 162.14\% stoichiometric\ air$
 $= 62.14\% excess\ air$

VITA

The author, son of Donald R. And Sara P. Egolf, was born December 17, 1967 in Cheverly, Maryland. He graduated from Largo Senior High School in Largo, Maryland in 1985. He spent two years at the University of Maryland in the Pre-Forestry program before transferring to the School of Forestry and Wildlife at Virginia Polytechnic Institute and State University in the Fall of 1987. He received a Bachelor of Science Degree in Forestry in May, 1990. While there, he became a member of the Society of American Foresters, Xi Sigma Pi, and the Forestry Club. He enrolled in the Industrial Forestry Operations graduate program in January, 1990 and received the degree of Master of Science in May 1992.


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