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DESIGN AND PERFORMANCE OF A SAWDUST FUELED FURNACE MODEL

by

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A professional paper submitted in partial
fulfillment of the requirements
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ABSTRACT

Wood is used for many purposes. Economics and conservation require the efficient use of wood and its by-products. This study resulted in the construction and testing of a small-scale sawdust fueled furnace prototype. This furnace uses an often wasted wood resource, sawdust, in an efficient manner. The prototype furnace could be suitable for small shop or home heating purposes with further development.

Consistent fuel feed was a major problem in this study. This problem was minimized by the development of a fuel agitator to prevent the sawdust from forming internal cavities over the auger intake hole.

The furnace's operation is based on forced-air burning of sawdust in a turbulent airflow. In testing, it was found that temperatures up to 1610^{o}F were attainable. The most efficient combustion occurred using .028 lbs./min. of fuel and 1 S.C.F.M. of air. It was found that the sawdust burned more efficiently without a fluidizing medium. This was believed to be due to the relatively large surface area and low moisture content of the fuel.

The furnace produced large amounts of heat with relatively little air pollution when compared to air-tight wood stoves. Its efficiency was estimated to be above 67% using data reported in related literature.

Sawdust fuel costs were compared on a per BTU basis to natural gas and electricity. In a heating situation it was found that, at present, sawdust fuel is cheaper to use than electricity while not as cheap as natural gas.

Chapter I

Introduction

The energy crisis has sent conventional fossil fuel prices soaring, and future price predictions continue to reflect this as nonrenewable fuel supplies shrink. Alternative energy sources are perceived as a possible solution to this problem. This paper will attempt to provide new insights into the efficient use of one renewable resource--the forest. Wood sawdust waste as a fuel heating source will be examined specifically.

The use of wood as fuel is certainly not a new idea. In many underdeveloped countries it is the primary energy source for the poor. One-third of mankind uses wood as fuel, while one-half of all timber used in the world is consumed as a fuel source (Eckholm, 1975, p. 5).

In the United States, as late as 1850, estimates placed 91% of our fuel needs being derived from wood (Eckholm, 1975, p. 17). This figure decreased to less than 9% by 1967 but appears to be climbing again (Food and Agriculture Organization, 1967, p. 33). The increased demand for and use of wood will cause problems of supply, conservation, and pollution.

The most popular type of home wood heating device

in the United States is the airtight or Dutch oven stove. This stove is characterized by incomplete combustion. The volatile extractives are vaporized during the early stages of combustion and most escape to the atmosphere. Some of these volatile components form pyroligneous acid which coats the stack and bakes to form creosote (Vivian, 1976, p. 97). These volatile components have a heating value of 17,000 BTU/lb. compared to dry wood's 8,600 BTU/lb. (Cheremisinoff, 1980, p. 40). The waste of the volatile components' heat represents a considerable energy loss in airtight stoves.

A listing of some of the products of wood combustion shows many organic compounds which contribute to the volatile heating value. These compounds include: acetylene, ethylene, benzol, napthalene, methane, hydrogen, tar, paraffin, phenol, creosote, acetone, and wood alcohol (Ross, 1976, p. 13). Not all of the volatile components burn. Water and carbon monoxide retard the combustion process. Water content is the main reason that green wood burns inefficiently.

In efficient wood combustion, most of the volatile components burn. Approximately 98% of the material emitted by efficient wood combustion is carbon dioxide and

water (U.S.D.A., 1980, p. 317). Temperatures of 1100°F must be reached to efficiently burn the volatile components in wood (Hoadley, 1980, pp. 138, 139).

The airtight stove operates inefficiently compared to modern furnaces. It "produces 500 times as much carbon monoxide, 1500 times as much particulate matter, and 750 times as many hydrocarbons as an oil furnace heating the same space" (Coy, 1982, p. 31). Several communities have enacted legislation restricting wood stove use because of air pollution problems (Coy, 1982, p. 31). Because of incomplete combustion and the resulting air pollution problem, alternative ways of using wood as a heating fuel need to be explored. This study will explore one alternative to the airtight stove--a forced-air sawdust furnace.

Need for the Study

The need for the study has many aspects. First, as conventional fuels become scarce, their costs rise and may become prohibitive on an economic basis. Second, these fuels may be more efficiently used as raw materials for products rather than heat sources. Third, if more demand is placed on wood as a fuel source, conservation

demands that it be used as efficiently as possible. Fourth, as combustion efficiency decreases, pollution from wood increases. Last, if a small, high-efficiency sawdust fueled furnace can be developed, the sawdust which is now wasted would be better utilized by homes and small businesses.

Statement of the Problem

The goal of this study was to design a small wood sawdust burner so that it became suitable for a furnace. Problems due to inefficient combustion, air pollution, and waste can be minimized if a sawdust furnace were developed that would be reliable, efficient, and convenient to use. The problems to be solved were:

1. Assuring adequate and reliable means of sawdust fuel flow to the combustion chamber.
2. Providing a regulated air supply to precisely burn the sawdust without excess air.
3. Providing sufficient turbulence to insure adequate mixing of the fuel and air for combustion.
4. Determining as well as possible at least a minimum combustion efficiency for cost comparisons with gas and electric furnaces.

Definitions

The following definitions were used for the purposes of the study.

BTU	The quantity of heat needed to raise the temperature of one pound of water 1°F.
Calorimeter	An apparatus used for measuring quantities of heat.
Combustion Efficiency	The amount of heat produced compared to the theoretical heat available; expressed as a percentage.
Fluidized Bed	A bed of noncombustible materials suspended by means of air pressure from underneath.
Fluidizing Medium	A noncombustible material used in the fluidized bed.
Fuel Value	The theoretical heat content of a particular fuel expressed in BTU/lb.
Moisture Content	The ratio of the weight of water in wood to the weight of wood when dry; expressed as a percentage.
Retention Time	The time required for a particle to burn and its gaseous products to leave the stack.

Definitions (Continued)

S.C.F.M.	Abbreviation of standard cubic foot per minute. The amount of gas required to fill one cubic foot volume at 1 atmosphere of pressure and 60°F.

Objectives

The study's objectives are:

1. To design and build a forced-air sawdust fueled furnace that operates reliably at a temperature greater than 1100°F.
2. To compare the operating cost of this furnace to that of commercial gas and electric furnaces.

Limitations

The study has the following limitations:

1. A large calorimeter is not available for measuring total heat output. This required the use of previously reported values for efficiency comparisons.
2. The scale of the study is limited due to the lack of funds for additional test equipment.
3. Methods of sawdust selection may result in varying BTU output.
4. The sawdust used will be mixed hardwoods and softwoods of varying sizes.

5. Equipment is lacking to measure emissions from the furnace.

Assumptions

The following assumptions were used in this study:

1. That wood fuel use will continue to rise in this country.

2. That conventional fuels are limited in supply.

3. That careful storage of sawdust will result in a consistent moisture content and heating value from one load to the next load.

Hypotheses

The following hypotheses were investigated:

1. That a fluidized bed will result in higher efficiency than nonfluidized combustion systems.

2. That temperatures over 1100°F can be attained using less than .1 lb./min. of sawdust and less than 2 S.C.F.M. of air.

3. That a wood fuel furnace can be operated in a more economical manner than either gas or electric furnaces given current fuel prices.

Chapter II

Review of Literature

Wood Availability

If wood is to be used as fuel, its availability is of importance both now and in the future. On a world-wide basis, one-third of mankind depends on wood as fuel, and one-half of all timber used is as a fuel. Approximately nine-tenths of the poor depend on wood as their primary fuel at a rate of 1 ton a year per person (Eckholm, 1975, p. 5). In areas of Africa, Latin America, and Asia, wood is in extremely short supply. In some areas reforestation efforts result in saplings being burned the night they are planted (Eckholm, 1975, p. 7). This loss of timber reserves leads to using manure as a fuel source. Without manure for fertilizer use, soil fertility is lost, leading to poor food production.

The loss of timber is due mainly to population density and lack of other fuel sources. An industrialized, high-density population is unable to support itself economically using wood as its sole fuel source. When wood became scarce in England in the 17th century, other fuel sources had to be found in order for industrial development to take place (Tillman, 1978, p. 3). Wood cannot

be used as the sole fuel source in any modern country without disastrous consequences in the form of deforestation and pollution (Eckholm, 1975, pp. 8-13).

Controlled harvesting of wood can result in a long-term renewable energy source for a limited population as well as supply the lumber, panels, and pulp industries with materials. As an example, Burlington, Vermont, has converted its coal-fired power plant to handle wood waste from local timber industries (Ridgeway, p. 159). The United States is an example of controlled harvesting, and estimated forest reserves are producing more wood per acre now than in the past (Harrington, 1977, p. 37).

In summary, wood is not suitable for urban fuel use on a continuous basis, nor can wood support an industrial society as a sole energy source. In low population density areas or on a limited basis, however, it will be readily available for many years to come.

Wood Combustion and Pollution

Wood is a fuel that has inherent pollution problems. These problems, however, are reduced greatly as the combustion efficiency increases. While some literature touts wood pollutants as natural (Harrington, 1977, p. 39) and

desirable, converse opinion declares that pollution problems endanger the user's health (Shelton, 1976, pp. 7-9; Tillman, 1978, p. 77; Vivian, 1976, p. 97). Most sources agree that, as combustion efficiency rises, pollution levels drop (Ross, 1976, p. 136). Some consider wood more pollution-free than any other fuel when used in an efficient manner (Tillman, 1978, p. 77; Harrington, 1977, p. 40). Therefore it is important that the most efficient combustion process should be used whenever possible to lower air pollution and reduce health risks while increasing energy output.

The Value of Wood as a Fuel

Wood is variable in chemical composition, moisture content, resin content, and in density. Some variability in heat output must be expected due to these characteristics.

The literature places dry wood in an intermediate position in energy value compared to coal and biomass, but this depends very much on the density of the wood involved, as is shown in Tables 1 and 2.

Table 1

Average Heating Values of Wood and Bark

Wood Species	Heating Value (BTU/lb., Oven Dried) Bark	Wood
Douglas Fir	9790	8890
Red Oak	8080	8050
Southern Pine	9360	8600
Western Hemlock	9400	8410
Western Red Cedar	8790	9700

Table 2

Density Versus Fuel Value

Relative Density	High Heat Value Per Cord[1] (Million BTU)
.30	12.6
.40	17.1
.50	21.4
.60	25.7
.70	30.0
.80	34.3
.90	38.6

[1]Assume: 1) 8600 BTU per pound of oven dry wood
2) 80 cubic feet wood per cord

The more dense the wood, the greater heating value it has per unit volume. Despite these differences in density, wood is remarkably consistent in heating value on a dry weight basis. The heating value of dry wood of a variety of species is 8,600 to 9,000 BTU/lb. (Shelton, 1976, p. 18; Hoadley, 1980, pp. 138, 139).

Variations in heat output are mostly due to moisture content. The more moisture present, the more heat it takes to evaporate the water present. Green wood has 30 to 70% of the heating value of air-dried wood. The loss of heat due to moisture is approximately 970 BTU/lb. of water present (Cheremisinoff, 1980, p. 42). It is therefore imperative to dry the wood as much as possible to obtain peak heating efficiency.

A comparison of the heating value of wood to other combustible fuels is shown in Table 3. This shows wood to be a transition fuel between the waste materials (5000-7500 BTU/lb.) and coal (10,000-14,000 BTU/lb.). Based on a volume basis, dry wood is approximately one-third as efficient as coal. Compared on a weight basis, it is one-half as efficient. This bulk factor drives up transportation costs, especially since 22 to 55% of the water content by weight is noncombustible (Tillman, 1978, p. 77).

Table 3

Heat Value of Selected Fuels

Fuel Material	BTU/lb.
Wyoming coal	14,400
Pittsburgh coal #1	13,650
Wood	9,000
Pine Bark	8,800
Bovine Waste	7,400
Raw Sewage	7,100
Paper Mill Sludge	5,350

Therefore, wood fuel is only economically competitive when short transportation distances are involved.

In conclusion, wood is a desirable energy source if the following criteria can be met:

1. The wood can be stored and dried to a low moisture content.
2. The efficiency of combustion can be maximized as much as possible.
3. Locally available, more efficient conventional fuel costs are high in relation to wood fuel costs.

These criteria can be met easily in rural or small urban areas with low population density and available forest reserves.

Design of Wood Fueled Heat Sources

Considerable variation exists in the design of wood heat systems. They range from fireplaces of less than 10% efficiency and airtight stoves of approximately 55% efficiency to furnaces with efficiencies near 70%. Claims of effectiveness are of doubtful value, however, since little independent scientific testing has been done (Shelton, 1976, p. 44). Most authorities agree that the design of wood heat sources can be improved but offer few ideas on the subject.

Three basic industrial combustion systems are the Dutch oven, the spreader-stoker, and the fluidized bed system. These systems are characterized as follows.

1. In the Dutch oven system, a heavy load of wood is placed on a combustion grating and a flow of air rises through the grate. This is the typical home wood heating system. The flow of air limits the combustion process and, in airtight stoves, combustion efficiency suffers. Partial oxidation and carbon monoxide burning characterize this system (Tillman, 1978, p. 99).

2. The spreader-stoker system uses smaller wood units (chips, flakes, or blocks) and continuously introduces the fuel above the grate where it dries partially and starts to combust. More complete oxidation occurs than in the Dutch oven

system and some gasification takes place (Tillman, 1978, p. 100; Cheremisinoff, 1980, p. 51).

3. The fluidized bed system uses a heated bed with an air stream from below keeping it in motion. This system uses smaller wood pieces as a fuel source. The fuel is introduced by an air blast or auger on top of the bed. Larger pieces combust in the bed where they are scrubbed by the sand which enhances combustion and others combust above the bed in the vapor space. Efficiency is comparable to gas or oil fired equipment, approximately 75% (Cheremisinoff, 1980, p. 61). Several large industrial designs produce from 500,000 BTU/hr. to 1,500,000 BTU/hr. (Gay, 1981, p. 21).

In the smaller, residential wood heat sources, the designs are so varied that only generalities will be discussed. The physical size and material used in the system is important for several reasons:

1. The greater mass holds more heat.
2. The greater surface area distributes the heat faster.
3. More fuel can be added to a larger furnace at one time and therefore burns longer and releases more heat.
4. A longer flame or hot gas path can be used in larger stoves. This lengthens retention time which permits more combustion and more heat transfer.
5. Larger stoves draw more air which can result in greater turbulence and therefore better combustion.

The wood particle size also affects combustion efficiency in furnaces. The time required for particle combustion varies inversely with the ratio of surface area to particle weight (Bungay, 1981, p. 116). This is expressed as

$$CT \approx \frac{1}{SA/W} \approx \frac{W}{SA}$$

where CT is combustion time, W is weight, and SA is surface area. Large particles take correspondingly longer times to burn. Clumping of the fuel, where particles pack tightly together, causes greatly lengthened combustion times due to poor airflow in the interior of the clump.

In summary, there are considerable variations in wood heating systems. Three basic industrial systems are the Dutch oven, the spreader-stoker, and the fluidized bed system. The fluidized bed has the highest efficiency, approximately 75%.

The material the furnace is made of and the physical size of the furnace affect the combustion efficiency in several ways. Generally, larger and heavier furnaces will perform better than smaller and lighter furnaces of the same type.

The surface area to weight ratio of the fuel used in the furnace affects both combustion time and efficiency. As the surface area to weight ratio increases, the combustion time decreases. The combustion efficiency increases as the surface area to weight ratio increases. Fuel clumping can decrease the effective surface area and lower efficiency.

Chapter III

Methods

Several furnace configurations were built using standard pipe sizes and fittings. Modifications were made to improve performance based on temperature measurements made at several locations above the grate.

The basic furnace operation was to introduce the fuel, using an auger, above a grate with air flowing upward through the combustion chamber (See Figure 1 in the Appendix). Both fluidized bed and no bed systems were tested. The airflow and the fuel feed were varied to obtain the maximum temperature for the particular configuration of pipe used. The main criteria for development were consistent high temperature as measured by a pyrometer and low particulate emission as observed visually. Generally, the furnace emitted particulates heavily when not operated at its maximum temperature. The furnace emitted little or no particulates when at maximum temperature.

Fuel Source and Characteristics

The fuel source used was obtained from the Montana State University woodshop dust collection system. It

consisted of hardwood and softwood wastes of the following varieties: ash, birch, maple, red oak, white oak, cedar, Douglas fir, Phillipine mahogany, and pine. As the BTU output of varying wood species is closely consistent when compared on a weight basis, approximately 8600 BTU/lb., no attempt was made to quantify the fuel by species.

The wood these sawdust wastes were obtained from was kiln-dried. The waste was further dried after machining to an average value of 6.3% moisture content in the dust house. This average value was obtained by weighing 64-cubic-inch samples of unpacked sawdust waste and then oven-drying these samples at 214°F until subsequent weighings showed no further weight loss. All the water had been evaporated at this point. The following formula was used:

$$MC = \frac{IW - ODW}{IW} \times 100$$

where MC is percent moisture content, IW is initial weight, and ODW is oven-dried weight. A standard moisture determination method was used (Hoadley, 1980, p. 92).

The size range of fuel used varied from .001 in. to .073 in. in thickness and from .001 in. to 3.43 in. in length. Widths up to 1.0 in. were encountered. It can

best be characterized as fine dust and shavings with a large surface area to weight ratio.

Combustion Chamber Size Variations

Variations in combustion chamber pipe size were studied first. Given the maximum airflow of 6 S.C.F.M. available, at this facility, it was found that a 5-inch diameter pipe was too large to either fluidize .08 in. sand or sufficiently agitate the sawdust to prevent clumping. Due to the large volume and longer stack gas retention time, this size of combustion chamber released few particulates to the atmosphere compared to smaller chamber sizes while burning.

A 2-inch diameter combustion pipe easily fluidized .08 in. sand at less than 2 S.C.F.M. airflow and agitated the sawdust to prevent clumping. Stack gas retention times were much less than with the 5-inch pipe. The 2-inch diameter pipe was used throughout the rest of the testing due to the aforementioned reasons and because fittings are readily available for this size. Larger size fittings are not commonly available.

The Fuel Feed System

The auger fuel feed system was tested next. Using

a 1-1/4-inch pipe as the auger feed pipe and a 1/4 in. x 1-1/4 in. x 38 in. steel bar to twist into an auger, several twist rates were examined. Since a 1725-rpm electric motor was the final power source for the auger, the slowest possible twist that would feed the sawdust was desirable to prevent overfeeding. The steel bar was twisted and tested until reliable feeding occurred as determined by weighing samples produced in actual operation. This involved repeated assembly and disassembly of the fuel feed system. The auger was then measured and the twists counted to determine the twist rate. The twist rate was 1.35 turns per foot. During testing it was found that higher rpm operation (above 200 rpm) tended to throw the fuel out of the auger back into the supply drum. Less than 200 rpm was used in further tests.

Irregular pieces of wood, approximately 1/4 in. square, in the fuel sawdust mixture would occasionally jam in the auger intake hole, stopping the auger. It was necessary to reduce the auger diameter at the intake hole by 3/16 in. (See Figure 1 in the Appendix). This prevented occasional jamming due to inadequate clearance. No change in feed rate was observed because of this change.

Agitator Development

By far the most troublesome part of the study was the sawdust's ability to bridge over the auger intake hole. The sawdust was observed to form arches over the auger intake hole up to a 9-in. radius. This caused fuel starvation and frequently stopped combustion. This problem has also been noted industrially (Gay, 1981, p. 22).

Several means of preventing this bridging were tried. An inclined fuel ramp (See Figure 2 in the Appendix) was not successful. Next, increasingly heavy weights were placed on top of the fuel supply. Weights up to 40 lbs. were tried without success. Finally, after testing several shorter or wider versions, the agitator shown in Figure 2 in the Appendix was successful in preventing fuel bridging. A 3/16 in. x 1/2 in. x 15 in. mild steel bar was bent to the shape shown and welded to a strap hinge which was bolted to the fuel supply drum. Several rubber bands were attached to the top of the agitator as shown. The agitator's lower curve rides directly on the auger which imparts motion to the agitator as it turns. The resultant 2-inch stroke at the top of the agitator effectively eliminates bridging. The rubber bands, or spring, are necessary to keep the agitator against the

auger. Several types of rubber bands and springs were tested without any apparent variation in feed rate as long as sufficient elasticity was present to keep the agitator against the auger. A metal coil spring may be more durable. It is important that the agitator be at least 12 inches high. The developmental agitators are shown in Figure 3 in the Appendix. Table 4 shows a statistical agitator performance breakdown.

Table 4

Statistical Analysis of Feed Rates

Feed Method		Standard Deviation grams	Mean grams	Variance grams	Range grams
No Agitator	98.6 rpm	N.A.	N.A.	N.A.	N.A.
	185 rpm	10.33	8.79	96.16	24.46
Agitator 1	98.6 rpm	N.A.	N.A.	N.A.	N.A.
	185 rpm	8.71	12.71	68.27	21.07
Agitator 2	98.6 rpm	2.99	7.69	8.05	8.42
	185 rpm	1.98	22.63	3.53	5.79
Final Agitator	98.6 rpm	.99	12.62	.88	2.74
	185 rpm	1.08	24.80	1.05	3.33

Note. N.A. denotes nonapplicable because feed rate will not sustain combustion.

This bridging of the fuel supply can occur wherever agitation is not present. If the auger does not extend to the combustion chamber, the fuel will form clumps which

cause sporadic combustion efficiency changes. The auger used extended slightly into the combustion chamber to prevent fuel clumping.

The mechanical problems were considered to be solved at this point. The unit was then tested using the configuration shown in Figures 1, 2, 4, and 5 in the Appendix.

Furnace Testing

The power supply was a 1 hp. electric motor. A system of jackshafts and pulleys was used to provide final speeds of 98.6 rpm, 185 rpm, and 350 rpm as required. (See Figure 1 in the Appendix)

To determine feed rates and agitator effectiveness, the auger was allowed to run without combustion taking place and the fuel collected at 1-minute intervals. The fuel thus collected was weighed on a triple beam balance. A statistical analysis for the standard deviation, mean, variance, and range was used to determine improvement as shown in Table 4.

Testing was also done using 5-minute intervals. The 1-minute intervals were felt to be of more value because, if the fuel supply is stopped for more than 1-minute, the furnace will not re-ignite reliably by itself. The

5-minute values are not reported as they agreed closely with the 1-minute values.

The igniting procedure used was as follows:

1. Check for fuel in drum and start auger.
2. Open first inspection hole above grate and wait until fuel starts feeding.
3. Light fuel by means of propane torch while turning air supply slowly on.
4. When fuel is burning, turn air supply up to desired value.

The burning is self-sustaining thereafter unless the auger stops for more than 1 minute.

The combustion process is stopped by shutting off the auger. The airflow is continued until no sparks are visible in the combustion chamber.

Nonfluidized Bed Behavior

During combustion testing without a fluidizing bed, it was found that using a feed rate of .028 lbs./min. and an airflow of 1 S.C.F.M. produced the highest consistent temperatures. This occurred at an auger speed of 98.6 rpm. The 185-rpm auger speed fed .055 lbs./min. of fuel into the combustion chamber. This necessitated the use of so much air that very short stack retention times resulted. Incomplete combustion was evident and the small temperature

gain resulting was offset by erratic performance. With an auger speed of 350 rpm, no combustion was possible due to smothering by a high fuel to air ratio.

Fluidized Bed Behavior

Testing using various fluidizing medium consisting of .04 in. sand, .08 in. sand, and .25 in. gravel in amounts incrementally varying by .044 lb. up to .132 lb. total produced lower temperatures than nonfluidized beds and a visible increase in particulate emissions. This behavior is contrary to what the literature reports for larger scale fluidized bed systems using wood chips as fuel (Bungay, 1981, p. 116; Cheremisinoff, 1980, pp. 58-61; Tillman, 1978, pp. 100-101).

This difference in behavior was believed to be due to size and moisture variations between the fuel types used. The ideal wood fuel is dry and has a large surface area to weight ratio (Bungay, 1981, p. 116; Harrington, 1977, p. 51). The reported behavior was based on much larger wood particles up to 1 inch thick which had much higher moisture contents up to 40%. In the larger systems, the fluidizing medium constantly abrades the charred surface of these larger chips exposing fresh material for

oxidation. In the system developed by this study, the fuel particles had a high surface area to weight ratio and were dry enough that it is theorized the bed material interfered with oxidation.

Air Preheat

As is shown in Figure 6, testing was done with preheated air in a nonfluidized combustion process and using varying airflows.

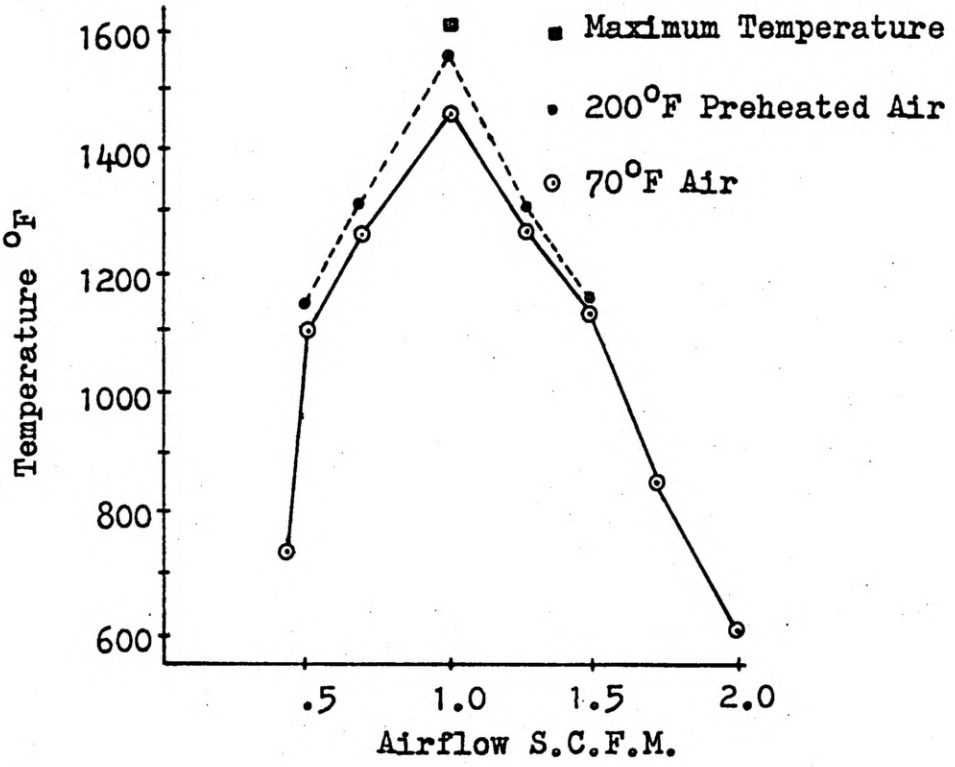


Figure 6. Temperature in °F versus Airflow at a feed rate of .028 lbs./min.

The air was heated by means of several propane torches applied to the outside of the air pipe just after leaving the flowmeter. The air's temperature was measured, with the furnace off, just above the grate. Higher combustion temperature resulted with the preheated air as expected and reported in the literature (Bungay, 1981, p. 116; Sande, 1976, p. 1).

Temperature versus Distance from Grate

Temperature readings were taken at various distances above the grate. The furnace was operating using .028 lbs./min. of fuel and 1 S.C.F.M. of air. Flames were observed up to 24 inches from the grate. Figure 7 depicts the results.

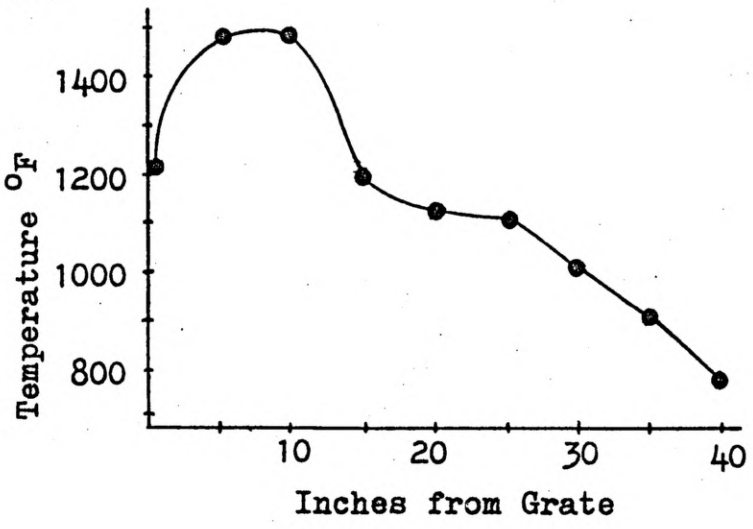


Figure 7. Temperature °F versus Distance from Grate in Inches.

Chapter IV

Presentation of Results

This chapter will present the pertinent results of the experiments conducted during the course of this research. It is hoped that this will serve to guide further research into the efficient use of sawdust wastes for heating applications.

Combustion Chamber Size and Airflow

It was shown that for a 2-inch internal-diameter pipe, with a cross-sectional area of 3.14 sq. in., approximately 1 S.C.F.M. of air (with a feed rate of .028 lbs./min.) gave the best results in terms of temperature and particle emissions. The 5-inch diameter pipe, with a cross-sectional area of 78.54 sq. in. would have required 25 S.C.F.M. of air if the fuel to air ratios remained constant and the fuel feed rate was increased accordingly.

Temperatures of 1480°F were easily attainable, with short-term peaks of 1610°F, using .028 lbs./min. of fuel and 1 S.C.F.M. of air. Larger furnace configurations should result in higher temperatures due to increased mass.

Fuel Agitation and Delivery

The sawdust fuel source was observed to form large internal cavities in the fuel drum necessitating some means of agitation to keep fuel flowing. A 12-inch-high agitator actuated by the auger effectively kept fuel flowing to the combustion chamber.

Larger fuel storage containers may require other means of agitation. For a 55 gal. drum modified as shown in Figure 2 in the Appendix, reliable fuel feeding occurs.

The auger used in this study had a twist rate of 1.35 turns per foot. When operated at 98.6, 185, or 350 rpm, it reliably transported the fuel to the combustion chamber. It was found necessary to have the auger extend slightly into the combustion chamber to prevent fuel clumping. The auger diameter should be reduced at the auger pipe intake hole to accommodate larger chips.

Fluidized Bed versus Nonfluidized Combustion

Testing showed that the fluidized bed caused lower temperatures and erratic performance in this system. It is believed this is primarily due to the small size and low moisture content of the fuel.

It is recommended that similar furnaces using this

type of fuel not use a fluidized bed. Larger furnaces using thicker and or higher moisture content fuel respond better with a fluidized bed according to the literature.

Combustion Efficiency

The combustion efficiency of this furnace design could not be experimentally verified due to the lack of a large calorimeter to measure heat output. The literature reports combustion efficiency values of 67 to 72% for fluidized bed furnaces (Tillman, 1978, p. 104) and "efficiencies comparable to oil or gas fired equipment" (Cheremisinoff, 1980, p. 61).

These values were obtained using:

1. Wood wastes with moisture contents much higher than 6.3% (up to 40%).
2. Larger particle sizes of wood wastes (up to 1-inch cubes).
3. Massive fluidized beds.

Facts 1 and 2 would lower combustion efficiency for reasons previously discussed. Fact 3 would tend to raise efficiency. The mass of the furnace is less important in determining combustion efficiency than moisture content or particle size.

The author's small-scale furnace had higher temperatures without a fluidized bed and, considering the ideal fuel conditions, it seems reasonable to believe the efficiency is at least comparable to the reported values for a fluidized bed if not higher. In order to permit comparison of the sawdust furnace with gas and electric furnaces, a worst case efficiency of 67% was assumed. Transportation costs were assumed to double fuel costs on a BTU basis.

Cost Comparison Between Wood, Gas, and Electricity

Assuming the lowest efficiency reported, 67%, for a fluidized bed wood waste furnace, the BTU output per pound of fuel should be:

$$8600 \text{ BTU/lb.} \times .67 = 5762 \text{ BTU/lb.}$$

A range of costs were available locally for sawdust waste from various sources. These ranged, on a per pound basis, from 3.2 cents per pound down to zero.

Taking the maximum cost of 3.2 cents per pound leads to a cost per BTU of:

$$\frac{.032 \text{ dollars/lb.}}{5{,}762 \text{ BTU/lb.}} = 5.55 \times 10^{-6} \text{ dollars/BTU}$$

Sawdust fuel transportation costs would vary depending on distance and mode of transport. Taking an extreme case as an example will double the cost to 1.11×10^{-5} dollars/BTU.

Electric heating costs are dependent upon the kwh consumed according to the schedule in Table 5.

Table 5

Electricity Rate Schedule

Amount per Month	Cost in Dollars
First 20 kwh or less	1.868753
Next 80 kwh	.060489 per kwh
Next 1700 kwh	.051843 per kwh
Next 3200 kwh	.031923 per kwh

Source: Public Service Commission Schedule GS-80 Supplement No. 1, 1981.

Assuming 1800 kwh per month is used, the price per kwh would be:

$$\frac{\$94.83}{1800 \text{ kwh}} = \$.0526/\text{kwh}$$

Since electric heat sources are usually assumed to be 100% efficient, the cost per BTU is obtained by converting kwh to BTU. This is done as follows:

$$\frac{\$.0526}{\text{kwh}} \times \frac{}{3.413 \times 10^{3}} = \frac{\$1.54 \times 10^{-5}}{\text{BTU}}$$

It is evident that even using the high value for wood waste, electricity costs 1.39 times as much.

Natural gas has approximately 950 BTU/cu. ft. depending on its source. Furnaces using natural gas operate at approximately 75% combustion efficiency. This results in:

950 BTU/cu. ft. x .75 = 712.5 BTU/cu. ft.

The 712.5 BTU/cu. ft. of heat produced are sold according to the schedule in Table 6.

Table 6

Natural Gas Rate Schedule

Amount	Cost per MCF in Dollars	
	Winter	Remainder
First 15 MCF	3.502	4.672
Excess MCF	4.672	4.672

Note. Winter rate applies to December 15 through April 14 inclusively.

Source: Public Service Commission Schedule FNG-82, 1982.

If 15 MCF or less of natural gas are used during the winter, the cost per BTU would be:

$$\frac{\$.003502}{\text{cu. ft.}} \times \frac{1}{712.5 \text{ BTU/cu. ft.}} = \frac{\$4.91 \times 10^{-6}}{\text{BTU}}$$

Compared to the highest wood waste cost of 1.11×10^{-5}/BTU, it was found that the wood waste is 2.26 times more expensive than natural gas per BTU of heat produced. It must be remembered that wood waste is often available for little or nothing.

In summary, it was found that the sawdust furnace tested in a highest cost situation cost $\$1.11 \times 10^{-5}$/BTU, an electrical furnace $\$1.54 \times 10^{-5}$/BTU, and a natural gas furnace $\$4.91 \times 10^{-6}$/BTU to operate. Natural gas was the cheapest to use, followed by wood and then electricity. Standard efficiency values were used for electrical and natural gas furnaces. The lowest published efficiency for a fluidized bed wood waste furnace was used in the calculations for the experimental sawdust furnace.

Chapter V

Conclusions, Implications and Recommendations

Conclusions

As a result of this study, several conclusions were reached:

1. The sawdust fueled furnace system used operated more efficiently in a nonfluidized than in a fluidized mode.
2. Temperatures of 1480°F were readily attainable with this furnace with peaks of 1610°F.
3. Relatively small quantities of sawdust fuel can produce high temperatures.
4. Consistent fuel delivery was essential in attaining efficient operation of this type of furnace.

Implications

The research revealed that several implications can be drawn:

1. Sawdust fueled furnaces appear to be competitive economically with gas or electric furnaces under the limitations discussed.
2. Higher temperatures and greater combustion efficiency can be attained by increasing the size of the system, matching feed rates and airflows, and modifying the shape of the combustion chamber to increase retention time.
3. A self-contained system could be built that would be thermostat-regulated, self-starting,

and shut itself off automatically for convenient home use.

4. Switching from the Dutch oven airtight stove to the system described in this paper would substantially reduce particulate emissions into the air.

Recommendations

Because of the work done in this study, the researcher would recommend further testing in these areas:

1. Heat output measurements in a superinsulated building of various wood heating systems to arrive at verifiable combustion efficiencies for comparison purposes.

2. Modifying the furnace used in this study to enlarge the combustion chamber approximately 1 foot above the grate by means of various fittings and introduce a secondary airflow tangentially in this area. This should increase retention time and insure complete combustion of volatile gases given off during the early stages of burning.

3. Modify the furnace system so that the motor not only feeds the fuel but drives a forced air fan. This would eliminate dependence on an outside air supply.

4. Using the exhaust gas to preheat both the fuel and the intake air which should increase the efficiency considerably.

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APPENDIX

Dimensioned Drawings of Furnace

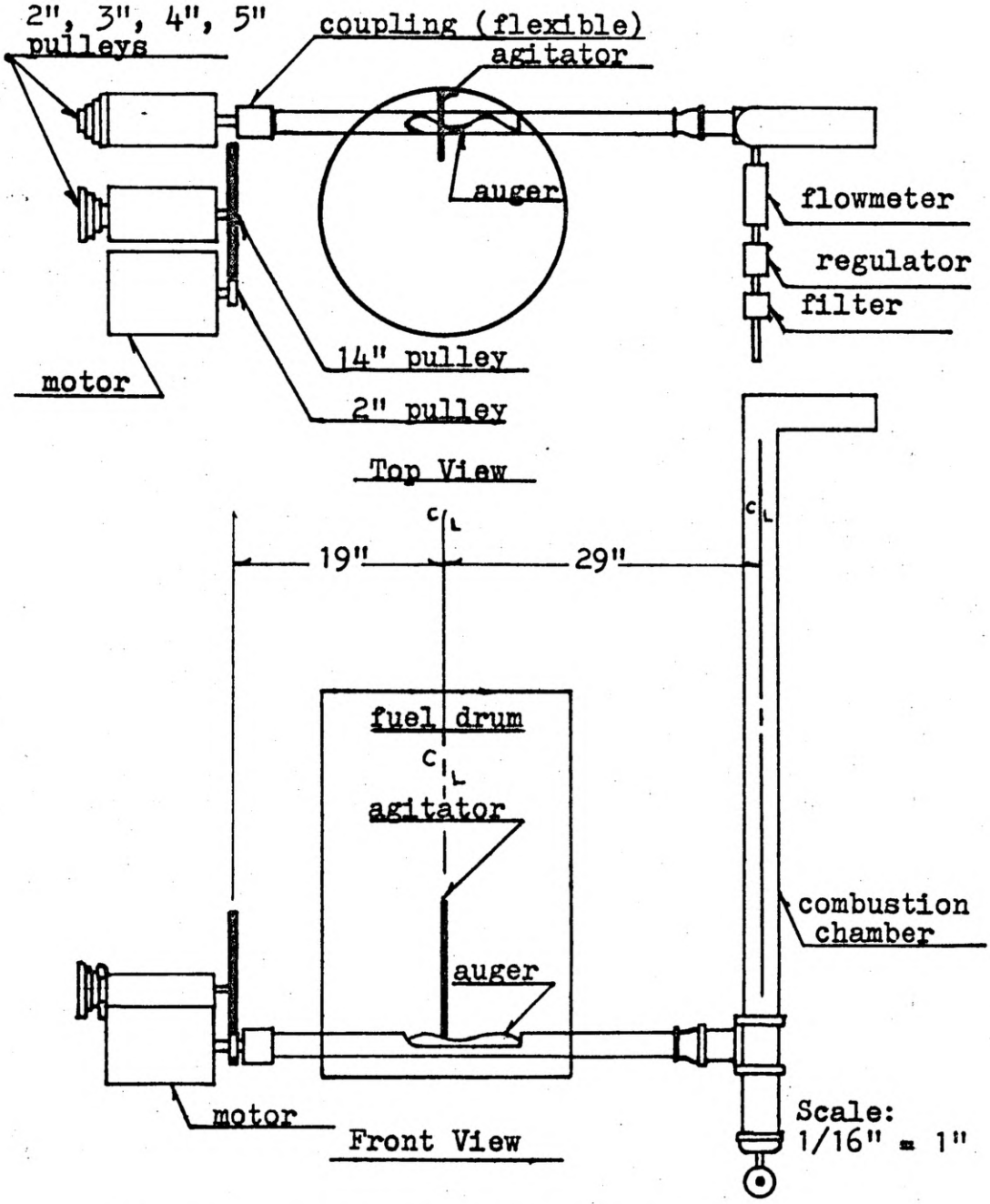


Figure 1. Front and Top Views of Furnace

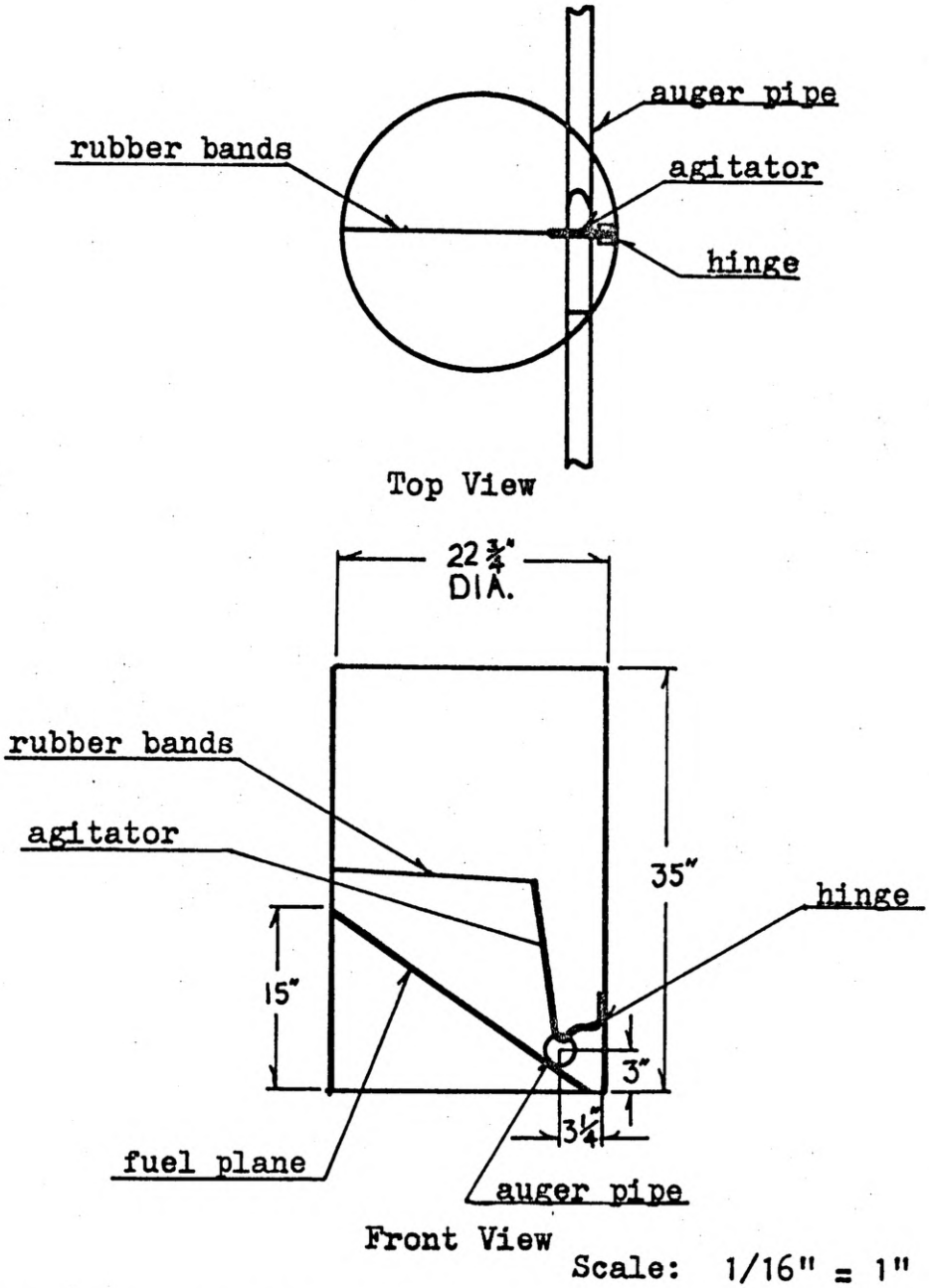
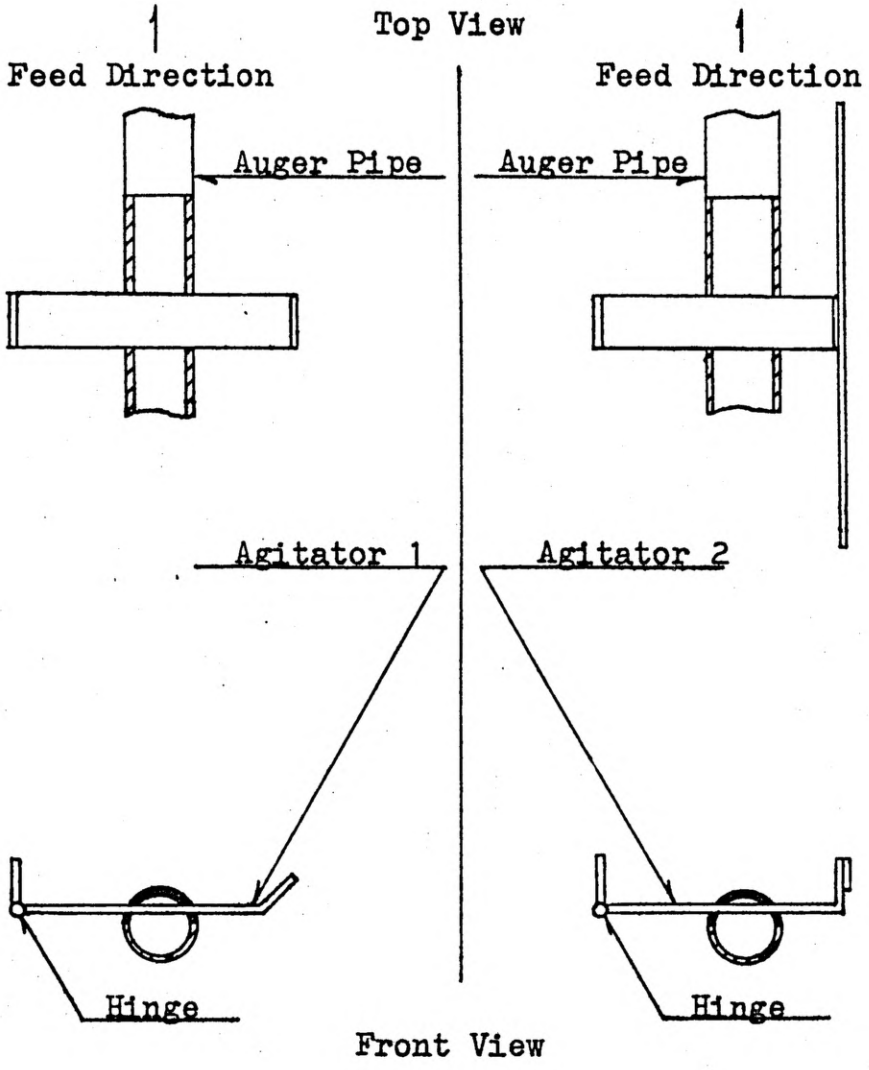


Figure 2. Fuel Drum, Auger, and Agitator System



Scale: 1/4" = 1"

Figure 3. Front and Top Views of Developmental Agitator Systems.

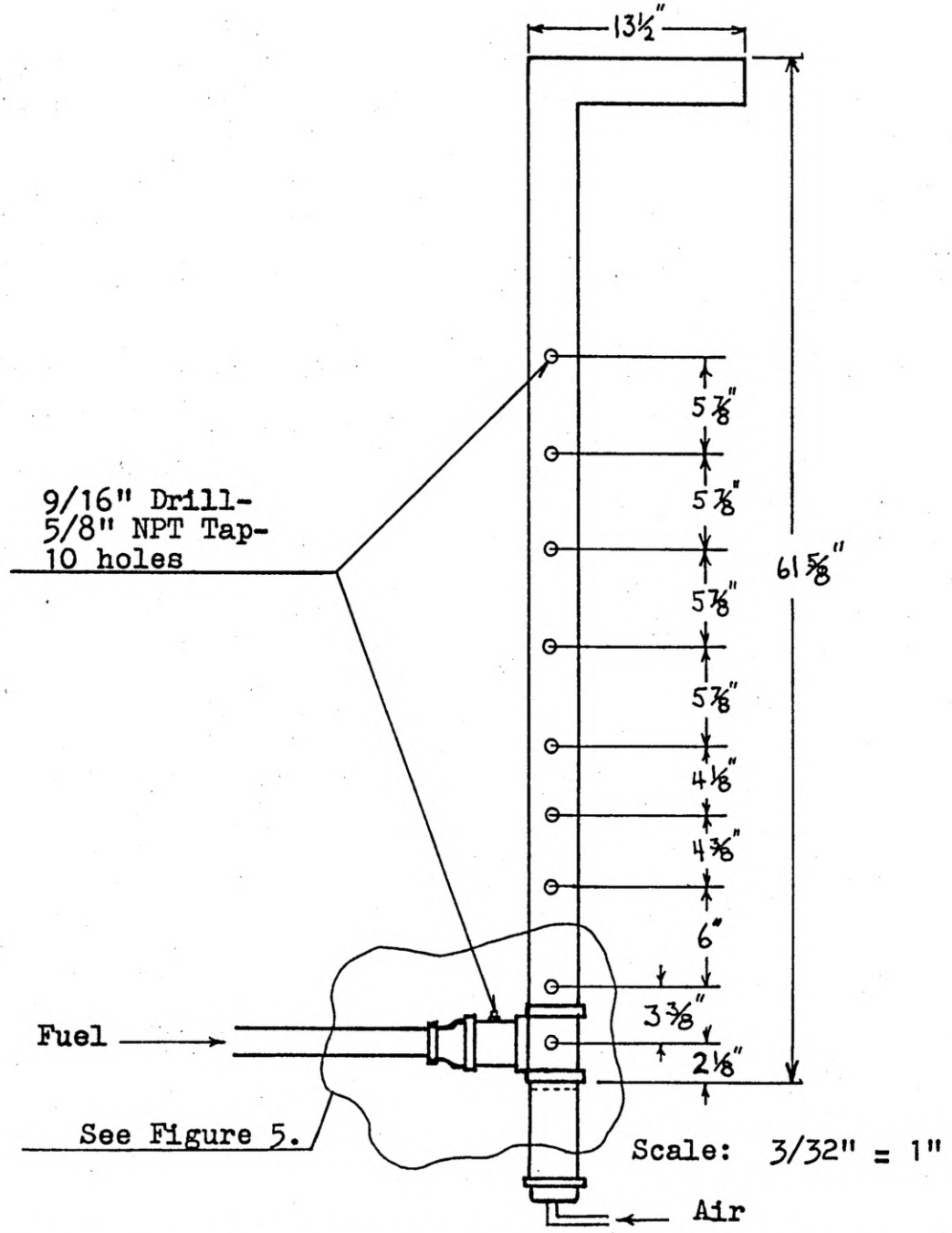


Figure 4. Combustion Chamber and Inspection Holes.

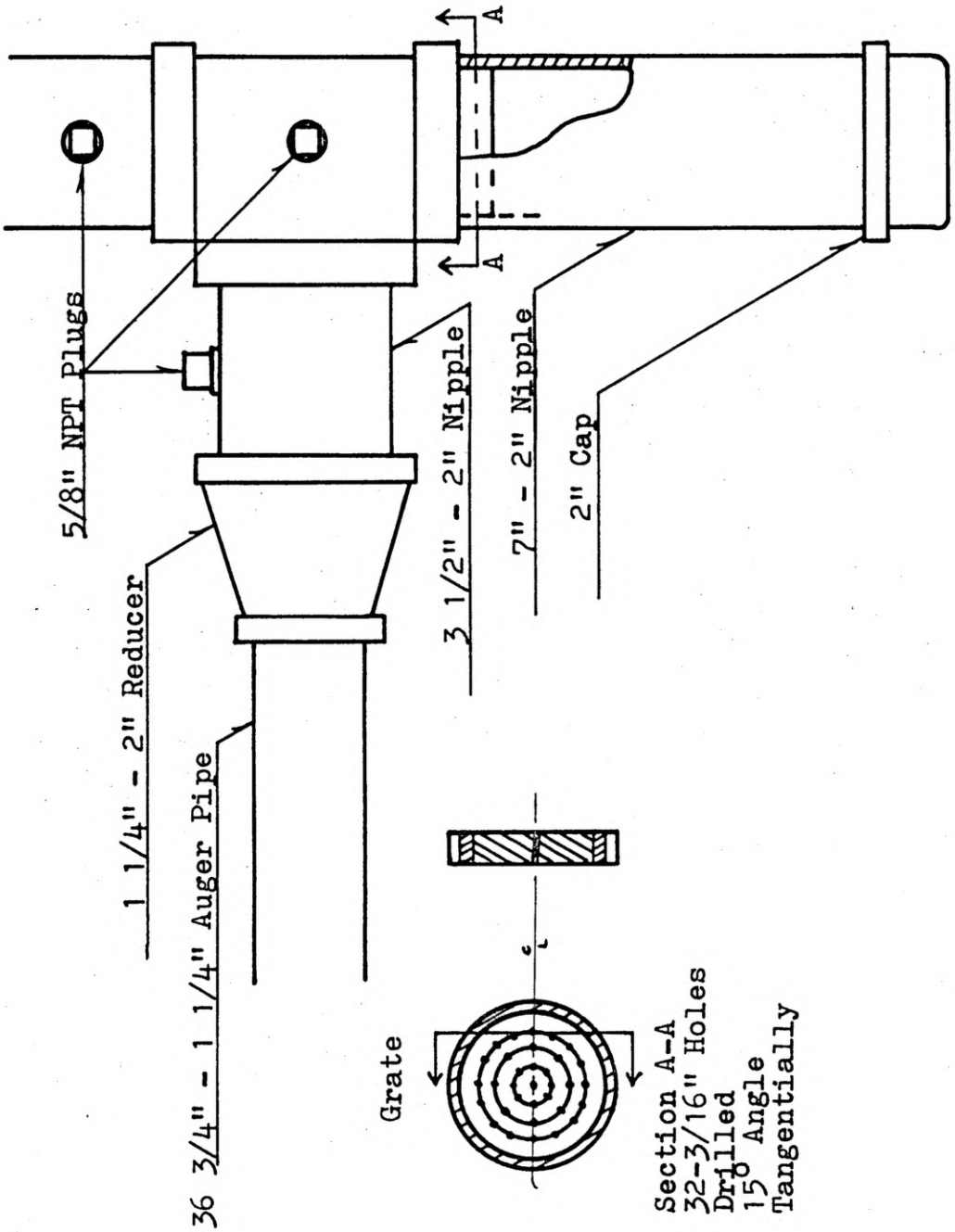


Figure 5. Detail of Grate Area

Scale: 3/8" = 1"