THE SUSPENSION DRYING OF SAWDUST

by

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A THESIS

submitted to

OREGON STATE COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1955

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Date thesis is presented 6-11-54

Typed by Betty Jean Mock

ACKNOWLEDGMENTS

The author wishes to express his appreciation to A. D. Hughes, Professor of Mechanical Engineering, Oregon State College, for his valued suggestions and help in carrying out this project. Also the valuable aid of Stanley Corder, Charles Morris, and George Atherton, all of the Oregon State Forest Products Laboratory, is acknowledged for their assistance in conducting the laboratory tests. This project was conducted at the Oregon Forest Products Laboratory and would not have been possible but for their full cooperation.

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CHAPTER I

INTRODUCTION

The Importance of Drying Sawdust and Other Wood Particles

During this last decade, we have observed remarkable advances in the waste-utilization field as applied to the forest products industry. Most of the larger sawmills in the Pacific Northwest, prior to the last war, operated huge waste burners day and night. Many of these firms now incinerate very little of the residues previously considered as waste and regard practically each wood particle as having some usefulness. It is true that this trend is currently limited mainly to the larger concerns, but indications are that these practices will expand until embraced by the entire industry in the not-too-distant future.

Much of the previously wasted wood is now utilized in the production of hardboard, particle-board, container board, pulp, pressed-fuel logs, etc. The moisture content of the material used for the pressed type of product must be comparatively low and controlled within rather narrow limits. The reason for this control is that high pressure and temperature operations are involved and if the wood particles contain considerable moisture, pockets of high-pressure steam will be formed. Under these conditions the material is apt to be blown completely out of the press; such occurrences have not been uncommon in earlier investigations in the field of wood-waste utilization. The point to be made from the above considerations is this - the developments in the wood-waste program has been paralleled by the increasing importance of the removal of moisture from wood particles.

Moisture reduction of sawdust and other wood particles which are to be used as fuel is important in two aspects. First, when dry fuel is being burned, the boiler, the air heater, the induced draft fan, and the stack are required to handle only a portion of the gas weights normally produced to generate the same amount of steam. The absence of water vapor formed from the moisture in average wet fuel combined with a smaller quantity of excess air represents a considerable reduction in the loss to furnace gases over that resulting with ordinary wet-fuel firing. The combustion of wet sawdust is slow since all the free moisture must be evaporated before its temperature rises enough for it to decompose and yield volatile combustibles. Burning of wet sawdust requires, therefore, large amounts of excess air and larger combustion equipment.

Or, looking at the matter in another way, considerably more steam could be generated for a given size installation by burning dry fuel than by burning wet fuel. In the case of dry-fuel firing, the furnace, boiler, and auxiliary equipment capacities are utilized for the generation of steam and are not, as in the case of wet-fuel firing, required also to function as a fuel dryer which, as we have seen, reduces the portion of the capacity given over to the production of steam. Of course, whether or not the increased furnace-boiler efficiency resulting from dry-fuel firing represents an increase in overall plant efficiency depends on the efficiency of the dryer. One source, after conducting extensive tests on excess air requirements for the burning of wet sawdust, concluded that the overall recoverable heat would be increased by approximately 15 per cent if sawdust were first dried in a dryer with 75 per cent thermal efficiency.

The second aspect of the importance of having dry sawdust fuel is related to new furnace designs. One of these, with which the author is acquainted, is being investigated by the Oregon Forest Products Laboratory. This sawdust-fired furnace burns the sawdust particles in suspension. The furnace is cylindrical and a cyclonic action is obtained by admitting most of the combustion air tangential to the furnace. This tends to give an intense turbulence which results in low excess air requirements; also, the fuel particles tend to be retained in the furnace till burned, resulting in very low carryover. In this type of furnace, the ash in the fuel is removed as a molten slag. The temperature in the furnace must be above 2500 F in order to keep the slag molten and it appears that this will require a drier fuel than that available in "green" sawdust.

General Methods of Drying and Types of Dryers

Drying is usually defined as the elimination or reduction of water from solid or semi-fluid materials by the process of evaporation. Dewatering is the mechanical removal of moisture through the use of screens, presses, centrifuges, or similar devices. Dehydration is the removal of moisture by the application of heat or by mechanical means. This term is usually limited to moisture removal from food products at low temperatures. Dewatering is by far the most economical method available for the removal of moisture and should be fully explored in any water elimination problem. It is, of course, limited in the respect of final-moisture content obtainable; however, when used in combination with drying, dewatering has made many drying problems economically feasible which would not have been otherwise.

There are a number of ways by which dryers may be classified; however, they are more often classified by the predominating mechanism by means of which heat is transferred to the material. Heat may be transferred to the wet material by at least four methods such as (1) conduction from a warmer solid body; (2) convection from a heated fluid; (3) radiation from warmer surroundings or heated elements; (4) generation of heat within the material by dielectric loss in a high-frequency electrical field. Although all four methods may be employed simultaneously, in general, only one predominates.

Here, dryers will be classified as follows: those dryers in which convection is the predominating mechanism as "direct dryers"; those in which conduction is predominating as "indirect dryers"; and "infrared" and dielectric dryers as a miscellaneous class. Direct and indirect dryers may be broken down further to continuous and batch-type dryers. Thus, the various types of dryers may be listed as follows:

- Direct Dryers
  - Continuous
    - Suspension dryers
    - Spray dryers

Direct rotary dryers
Tunnel or continuous tray dryers
Continuous through-circulation dryers
Batch
Tray or compartment dryers
Batch through-circulation dryers
Indirect Dryers
Continuous
Drum dryers
Cylinder dryers
Vibrating tray dryers
Indirect rotary dryers
Screw conveyor dryers
Batch
Pan dryers
Vacuum shelf dryers
Vacuum rotary dryers
Miscellaneous Dryers
Infrared dryers
Dielectric dryers

Direct dryers, those depending upon convection to transfer heat to the material being dried, have a number of characteristics in common. The drying medium is usually air combustion gases or a mixture of the two. Temperatures of the drying medium ordinarily range up to 1400 F. When temperatures below the boiling point of water are used for drying, increasing humidity in the drying medium will tend to decrease the rate of drying. This follows from the fact that evaporation is directly proportional to the difference in vapor pressures of the water in the material and that of the drying medium; the vapor pressure of the drying medium being controllable by and corresponding to the absolute humidity. The vaporized moisture from the material is removed by the drying medium.

In indirect dryers, the heat required for drying is conducted through a solid retaining wall to the material to be dried. Temperatures range up to about 1000 F; the top temperature being limited by the material of which the retaining wall is constructed. The vaporized moisture is removed, either by natural or forced draft, into a gas stream over the material or by the application of a vacuum. The heat transferring capacity of the materials used in the retaining walls and the heating area employed determine, in general, the drying rate.

The batch-type drying operation is more flexible than the continuous type. Although, on the basis of equal output, the batch-type operation will take longer due to time required for loading and unloading. With batch-type drying, the material handling and time are quite flexible and small-lot production is best suited to this type.

The only suitable methods for drying sawdust and other small wood particles are the rotary and suspension type dryers. The use of rotary dryers for wood particles such as hog fuel has been studied by several people. They state that process control is difficult and that the thermal efficiency is approximately 35 per cent. Considerably higher thermal efficiencies are obtained with suspension dryers and process control with this type of dryer is very good. The capital cost of rotary dryers is very high; whereas, capital cost for suspension dryers is relatively low. As will be pointed out later, particle size is a limiting factor in the application of suspension drying. This consideration in some cases would favor the rotary type dryer.

The Suspension Drying Process

Fundamentally, the suspension drying process can be described as follows: hot gases are passed into an insulated drying duct; wet material is introduced into this duct and in turbulent flow carried to a cyclone separator where the drying gases are separated from the dried material. The drying is effected during the brief contact of the hot gases and the material in the duct and separator. The particles being suspended in the hot gases have their entire surface exposed to the drying medium. This feature, coupled with high drying temperature, produces very rapid drying of the material - the drying cycle is usually less than ten seconds.

One variation of this drying process is to use a mixing device to obtain better mixing of the material and hot gases. Such an agitator usually consists of some type of cage mill; however, some systems utilize the fan for this purpose by having an induced draft system and having the fan placed right after the material has been introduced into the duct. In such an arrangement, the fan is required to handle a larger volume of gases, and the increased power requirements must be balanced against an increased drying effect.

Also indications are that suspension drying might be adapted to a fluidized bed type of drying. This entrained and fluidized state is obtained by controlling the velocity of the drying gases so that the sawdust particles, instead of being carried at a high velocity through the duct, will remain more or less suspended in a given portion of the drying duct. The heat exchange between the hot gases and the wet particles is extremely rapid and as the particles reach certain states of dryness or lightness, they leave the fluidized bed and are carried along the duct to the cyclone separator.

It should be made clear that the term "suspension drying", which is described in the above, denotes a drying process which has been previously designated by such names as "pneumatic-conveying drying", "duct drying", "flash drying", etc. "Flash drying" is a registered trade-mark of the Raymond Division of the Combustion Engineering Company, and probably is more commonly used than the other terms mentioned to designate this type of drying. However, it is felt that "suspension drying" is more descriptive of the drying process under investigation, and it will be used throughout the remainder of this thesis.

Suspension Drying in General

There are a number of suspension dryers in operation in this country. These installations cover a variety of fields - mainly, sewage sludge, fine and pulverized coal, certain agricultural products, and certain chemical products. These materials which have been reported to have been dried successfully by this process have the common property of having at least one small dimension. Grass seeds and grains are examples. Another factor which is common to many of these applications of suspension drying is the requirement that the material pass quickly and uniformly through the system. If retained for long periods of time in the system, then some of the material may become bone-dry and overheated. Many chemical products are particularly subject to scorching and overheating, but have, however, been dried successfully by suspension dryers.

There are a number of suspension dryers that are being operated to dry sawdust. One of these installations is in Salem, Oregon, at the Capitol Lumber Company. The history of this particular installation illustrates to some extent the need for further investigation of the application of suspension drying to sawdust and other wood particles. The manufacturer of this dryer made the installation and spent several months attempting to obtain satisfactory operation. This was accomplished only after a "cut and try" process involving several unsuccessful arrangements. The dryer is now being operated with a considerably larger duct length than was designated in the original design. They have not investigated the dryer performance by altering and/or analyzing the drying variables.

The British Columbia Research Council, feeling that suspension drying had potential application to British Columbia industry, conducted an investigation of this drying process as applied to sawdust. An experimental dryer was constructed and operated for the purpose of obtaining more fundamental knowledge of the drying process which might lead to better drying unit design. By the Council's own admission, their investigation was quite incomplete and their program calls for more extensive research in the near future. However, by extrapolation of the data that was obtained, they have been able to outline a program for future investigations which they feel will be fruitful. These suggestions have been received by the author and the present work has been aided considerably by them.

Mr. W. G. Tamblyn, assistant-plant engineer for the Great Lakes Paper Company of Fort William, Ontario, has published an interesting report on suspension drying of bark. Mr. Tamblyn relates the experiences and accomplishments of their suspension dryer. Bark disposal at their plant had become an exceedingly difficult problem - the bark pile that had been accumulated up to the time of the suspension dryer installation was estimated at 100,000 tons. The moisture content of the bark was approximately 80 per cent and by reducing the moisture content to approximately 35 per cent (10 to 15 per cent of the reduction was accomplished by mechanical pressing), they were able to utilize it for fuel in their power plant. He estimated that the suspension dryer has effected savings up to the equivalent of 75 tons of coal per day and has eliminated the problem of bark disposal. Recent correspondence from this company atated that the bark is hogged and reduced to particle sizes varying from 1/8 to 1/4" prior to drying.

The Development Center of Weyerhaeuser Timber Company at Longview, Washington, is at the present time experimenting with suspension drying of wood fibers to be used in the manufacture of pressed boards. Air is passed through steam-heated coils and heated to about 350 F. Three drying stages are being used; presumedly, air at 350 F is supplied to each stage as the drying medium. This experimentation has only recently commenced and very little information is available at this time.

Purpose of this Investigation

In general, the objective of this investigation is to obtain dryer performance and characteristics. The determination of dryer characteristics is similar to that of any other thermal or mechanical system; there are a number of variables which effect the function of the drying unit and it is the effect of these variables which is to be investigated.

The operation of a dryer varies with the material being dried; this is true to the extent that some types of dryers have satisfactory application only for one material. Even when a given type of dryer is suitable for a large group of materials having similar properties, its operation will probably have some variation for each particular material within that group. For instance, suspension drying of grains is unlike suspension drying of sawdust in the respect that grains will have different initial moisture content than sawdust and most likely different final moisture contents will be desired in the two type of materials. Also the ease or reluctance with which the bound moisture is given up, the permissible gas temperatures and gas velocities, etc., will be quite different for the two materials. These factors effect the operation of the dryer and, hence, the physical design of the dryer. To obtain the same drying production (pounds of dry material per hour) of grains and sawdust, the dryer design (duct diameter and length, temperatures, velocity) would certainly be different. Thus, when the objective is stated as the determination of the suspension dryer performance and characteristics, it is meant more specifically those characteristics resulting from sawdust drying.

The effects of the variables on the removal of moisture from the material being dried make up the design criteria for the dryer unit.

Materials are dried for a variety of purposes; moisture reduction in a single type of material, also, may be desired for different reasons. Whether or not the drying of a given material is justified depends upon the advantage to be gained from having the material dry and the drying efficiencies obtainable for that material. Thus, the inquiry of the feasibility of drying sawdust by the suspension drying process is ambiguous from the standpoint that the application of this method of drying might be quite practical or even extremely profitable in one case where the dry material is desired, whereas, in another case, the application of the method is not warranted at all. For example, a suspension dryer might be used for drying sawdust for the manufacture of pres-to-logs on the basis that it was necessary that the material be dried and that it proved more efficient than any other method; however, the efficiency obtainable might not warrant the drying of sawdust as fuel in boiler furnaces. It is hoped that this work will give some indication as to the feasibility of suspension drying of sawdust for the latter case because, in all probability, this would represent the largest benefit to be derived from the drying of sawdust.

CHAPTER II

PRINCIPLES OF DRYING

Drying Terminology

There are several terms which are used repeatedly in any discussion on drying and due to some non-uniformity in the usage, it might be well that some attention be given to terminology before proceeding with the following sections concerning the fundamentals of drying.

Materials consist of solids and moisture. Bone dry state of the material implies complete absence of moisture. The amount of moisture contained within the material is expressed in terms of percentages on wet or dry basis. The following shows these two types of percentages and the relation between them:

$$\text{Per cent M C, wet basis} = \frac{\text{Wt. of moisture in the sample}}{\text{Wt. of the wet sample}}$$

$$\text{Per cent M C, dry basis} = \frac{\text{Wt. of moisture in the sample}}{\text{Wt. of solids in the sample}}$$

Therefore:

$$\text{Per cent M C, wet basis} = \frac{\text{Per cent M C, dry basis}}{100+\text{Per cent M C, dry basis}}$$

$$\text{Per cent M C, dry basis} = \frac{\text{Per cent M C, wet basis}}{100-\text{Per cent M C, wet basis}}$$

where M C = moisture content. The wet basis has the advantage that the summation of the percentage of solid and moisture must always equal 100. It is quite easy to convert from percentage moisture content to actual weights of moisture or solids.

Numerous dry materials when exposed to moist air will absorb a fixed amount of moisture from the air depending on the temperature and humidity of the air. Conversely, the same materials when quite moist and exposed to air at an identical temperature and humidity will lose a certain amount of moisture to the air. Such materials are called hygroscopic, and it is said that they reach equilibrium with the surrounding air when no further changes (absorption or removal of moisture) take place. Wood is of this nature; that is, wood is a hygroscopic material. The amount of moisture remaining in wood after thorough air seasoning will vary from 12 to 20 per cent, dry basis; this might be termed the minimum equilibrium moisture content for wood. To obtain wood of lower moisture content, it is usually necessary to use artificial heat.

Moisture in wood is divided into two kinds. The water held in the cell cavities and other spaces is called free or unbound moisture; the water soaked up in the cell walls is termed bound moisture (sometimes, called combined or hygroscopic moisture). It is supposed that this applies equally well to other materials. The expression of moisture content includes both the bound and unbound moisture. When wood dries the unbound moisture is the first to evaporate and after it has all left and only the water in the fibre walls remains, we have reached what is termed the fibre saturation point. Or, conversely, if water is added to dry wood, it is first soaked up in the cell walls and when the walls are fully saturated, the wood is said to have a fibre-saturation moisture content. If further water is added, it will go to the cell cavities as unbound moisture. The fibre-saturation moisture content varies from 20 to 30 per cent of the dry weight of the wood, depending on the particular species of wood. In practice, 25 per cent is usually taken as the saturation point.

The expression of dryer performance in terms of percentage efficiency is quite often misleading. Strictly speaking, efficiency is an indicator of achieved or contemplated results in relation to a possible perfection. Unless both the results and the goal are clearly defined, the expression of the efficiency of a dryer or any other mechanism is not too informative, nor can the performance of one dryer be compared to that of another. The dryer is primarily a heat machine with the prime function being the removal of moisture from the material by evaporation. Factors such as preparation of material prior to drying, conditions of make-up air, power consumed by fans and other machinery, etc. have direct effect on the drying cost and are inter-related with efficiency. Other considerations which illustrate the difficulties of dryer comparisons are: the corresponding amounts of bound and unbound moisture varies with different materials, the drying loads may consist of numerous moisture content ranges (the heat required to extract the first 10 per cent moisture is usually less than required for the last 10 per cent), the rate which the moisture in the material is removed is often critical, the exactness required in the final moisture content. In this thesis, dryer efficiency will designate the ratio of the heat to evaporate the water removed in the dryer to the heat supplied to the dryer.

One more distinction to be observed is the use of the terms osmosis and diffusion. Osmosis refers to the moisture passage through the membrane or cell wall of a material. The term diffusion, in spite of its close relation to osmosis, should be used to designate the internal moisture flow through the slab of the material as a whole, rather than out of an individual cell.

Mechanism and Thermodynamics of Drying

Drying consists of an interchange of heat between the drying medium and the material being dried, and the removal of the water vapor from the surface of the material. Thus, drying can arbitrarily be divided into two parts - an analysis of conditions external to the material proper. The first is here termed the mechanism of drying and the latter the thermodynamics of drying.

By what manner moisture passes from the inside of the material to the surface is still a scientific mystery, but several theories have been advanced to explain it. Undoubtedly, the type of material has something to do with the internal movement of moisture. In that this work is primarily concerned with the suspension drying of wood particles, this particular discussion will be confined to wood and the factors influencing the internal flow of moisture in that material.

One theory given considerable weight is that the water travels from the interior of a board to the surface by following the cell walls. It is a law of physics that water seeks its own level; in other words, it tries to distribute itself uniformly throughout the board. Since evaporation is occurring at the board's surface, due to its contact with the drying medium, the outer portions begin to dry, upsetting the equilibrium. This causes a flow of moisture from the adjacent areas to balance it and the drying has started. If the surface evaporation is more rapid than the internal movement can make up, the surface portions will drop to a much lower moisture content, which in turn helps to speed up the movement of the internal moisture.

It is probable also that water is converted to vapor within the cells and moves in this form through connecting tubes to the surface. Except in a few instances these tubes are not long nor continuous to the surface. It is also possible that water moves to the surface by capillarity. Without a doubt a great deal of water does move through the tubes or vessels either as water or water vapor wherever the wood is sufficiently porous to permit it. Confirmation of this is the fact that sapwood always dries faster than heartwood. Heartwood is the darker center core of the tree and is more porous than the sapwood which is the lighter-colored portion of the tree that encircles the heartwood. Heartwood usually contains less water than the sapwood but is more difficult to dry and requires a longer time.

In the previous section, free or unbound moisture was defined as that portion of the moisture content held in the cell cavities; bound moisture as that soaked up in the cell walls. It is fairly certain that unbound moisture evaporates more readily than bound moisture. The reason being that the cell wall substance has an attraction for water and a certain amount of heat must be used to separate them. The drying characteristics of wood (also the majority of hygroscopic materials) can be grouped rather loosely into three stages. The first stage consists of an adjustment period where the materials are acquiring heat; after the material temperature has been stabilized, the drying rate remains constant until the surface of the material begins to dry out due to the fact that moisture could be or is removed faster than it comes to the exposed surface. The drying rate begins to decrease and the start of this change corresponds to the critical moisture content or the fibre-saturation moisture content. It will be noted that for wood the fibre-saturation moisture content is approximately 25 per cent. During the last stage, the drying rate depends upon diffusion of mostly bound moisture to the surface.

It was suggested that when wood dries the free water is the first to evaporate and after it has all left, then the bound moisture commences to evaporate. This is only partially true in that bound moisture near the surface either evaporates or starts moving to the surface long before the free water in the center has had time to come to the surface and evaporate. In fact, checking and warping of lumber are consequences of this. However, it is proper to say that, in general, the greater portion of the unbound moisture is removed before much of the bound moisture starts to evaporate. The fact that unbound moisture evaporates quite readily, but bound moisture comes off slowly is the reason that wood can be dried down to a 25 per cent moisture content much easier than to moisture contents below 25 per cent.

It has been stated that by thermodynamics of drying is meant a study of the conditions external to the material proper. The evaporation of water from a material by drying can occur at normal atmospheric temperatures; e.g., the drying of roads, trees, etc., after rain. Heat quickens the process of evaporation, and use is made of it in practice in all types of drying machinery so as to complete the process with maximum speed and economy. The theoretically perfect dryer would be one that heated and evaporated the moisture readily without heating the material containing it, since then there would be no waste of heat resulting from the warming of the solid material. Practically, this is an impossibility, however, so that some heat energy has to be expended on warming the solid material as well as the moisture it contains. A maximum limit to the temperature used is, therefore, set by the heat sensitivity of the material, and this maximum temperature, different for each material, must not be one that impairs any of the commercially-important properties of the material. Although it is the ability of the material proper to withstand the high temperature that determines the working level, distinction should be made between the spoilage caused by excessive temperature and that due to use of improper drying methods or conditions. As an illustration of the latter, the overdrying of a surface will leave the inside impregnated with moisture which, upon further receipt of heat, may violently escape by cracking and sometimes completely bursting the material into small pieces. Thus, it is the case that under some conditions it is necessary to add moisture to the surface of the material at the start of the drying process.

To accelerate the outward migration of moisture, its vapor pressure should be kept as high as possible.

Thus, the temperature of the moisture in the material is of prime importance, whereas the temperature rise of the material proper may be considered purely incidental, though unavoidable. Evaporation occurs whenever the vapor pressure of the moisture in the material is greater than that of the vapor in contact with it. Evaporation does not necessarily mean "boiling". Boiling takes place whenever the liberated vapor possesses sufficiently high pressure to displace or literally push back all gases above it, be that air-water vapor mixture under atmospheric pressure, vapor in a vacuum, or steam under a positive pressure. Thus, in drying pressure differences are dealt with rather than absolute vapor pressures, and it is this vapor pressure difference that is the force or the potential that causes drying. The maximum drying speed is achieved at the highest possible temperature. It has been stated that the vapor pressure of the moisture in the material increases with temperature; consideration will now be given to the temperature effect and other influencing effects on the vapor of the atmosphere surrounding the material.

That the vapor pressure in the air decreases with an increase in temperature is readily illustrated in terms of relative humidities. Relative humidity is defined as the ratio of the partial pressure of the water vapor to the pressure which saturated water vapor exerts at the same temperature of the air. The vapor pressure at a temperature of 60 F and a relative humidity of 40 per cent equals 0.206 inches of Hg. The vapor pressure at the same temperature, but with a relative humidity of 10 per cent is 0.0521 inches of Hg. Of course, assuming a constant temperature, the only way relative humidity can change is by and with a corresponding change of absolute humidity. Relative humidity is often used to indicate the amount of moisture in air at a given temperature as compared to the amount it will hold if fully saturated. Observation of a psychrometric chart shows that at a constant absolute humidity the relative humidity decreases with an increase of temperature. In other words, the moisture holding or absorbing power of air increases with temperature. Thus, in the drying process, the absorption of moisture from the material continually depletes the capacity of the air to absorb more moisture, and also retards the drying rate by increasing the vapor pressure in the air.

Convection Drying

In convection drying, air is usually used as the heat and vapor-carrying medium. The vapor content of the circulated air is increased at a rate at which the material gives up its moisture. Increase in the moisture content of air signifies corresponding increase in its saturation or dewpoint temperature. Air and vapor existing at the dewpoint temperature are said to be saturated, and any reduction in temperature will cause some of this vapor to be condensed as water. Conversely, if the temperature is above that of saturation, the vapor is said to be superheated. Hence, in convection drying we always deal with superheated vapors, the degrees of superheat being the difference between the dry bulb and dewpoint temperatures.

Saturated steam at 212 F exerts full atmospheric pressure and can only exist in complete absence of air. Atmospheric pressure is the summation of air and of vapor or steam pressures. Presence of even a small quantity of air will displace some of the steam and cause corresponding reduction in the steam pressure or in the pressure of the saturated vapor present. A dryer, not being a completely enclosed vessel, will always contain some air. Therefore, we can conclude that saturated air cannot exist at temperature in excess of 212 F and, in reality, can only approach this limit. Wet bulb temperatures, regardless of how high the dry bulb temperature may be, can also only approximate and never exceed 212 F. Thus, we have established the upper limit of the working range when dealing with moisture. Saturation of air will indicate the attainment of the maximum possible utilization, and preheated air can theoretically pick-up a maximum quantity of moisture represented by the difference in its initial and final (saturation) moisture contents.

After the first adjustment stage during which both the material and the dryer came up to the working temperature, the only heat losses from the dryer are those of radiation and conduction from its housing. The circulated air does not give up any appreciable quantity of heat, and its heat content remains practically unaltered during its contact with the material. This is manifested by a constant wet bulb temperature. The convection drying by preheated air is in reality a heat conversion process in that the sensible heat in the air is converted into the latent heat of vapor which in turn becomes a component part of the circulated air.

These dryers are called adiabatic or constant-heat content dryers. Figure 1 shows on a psychrometric

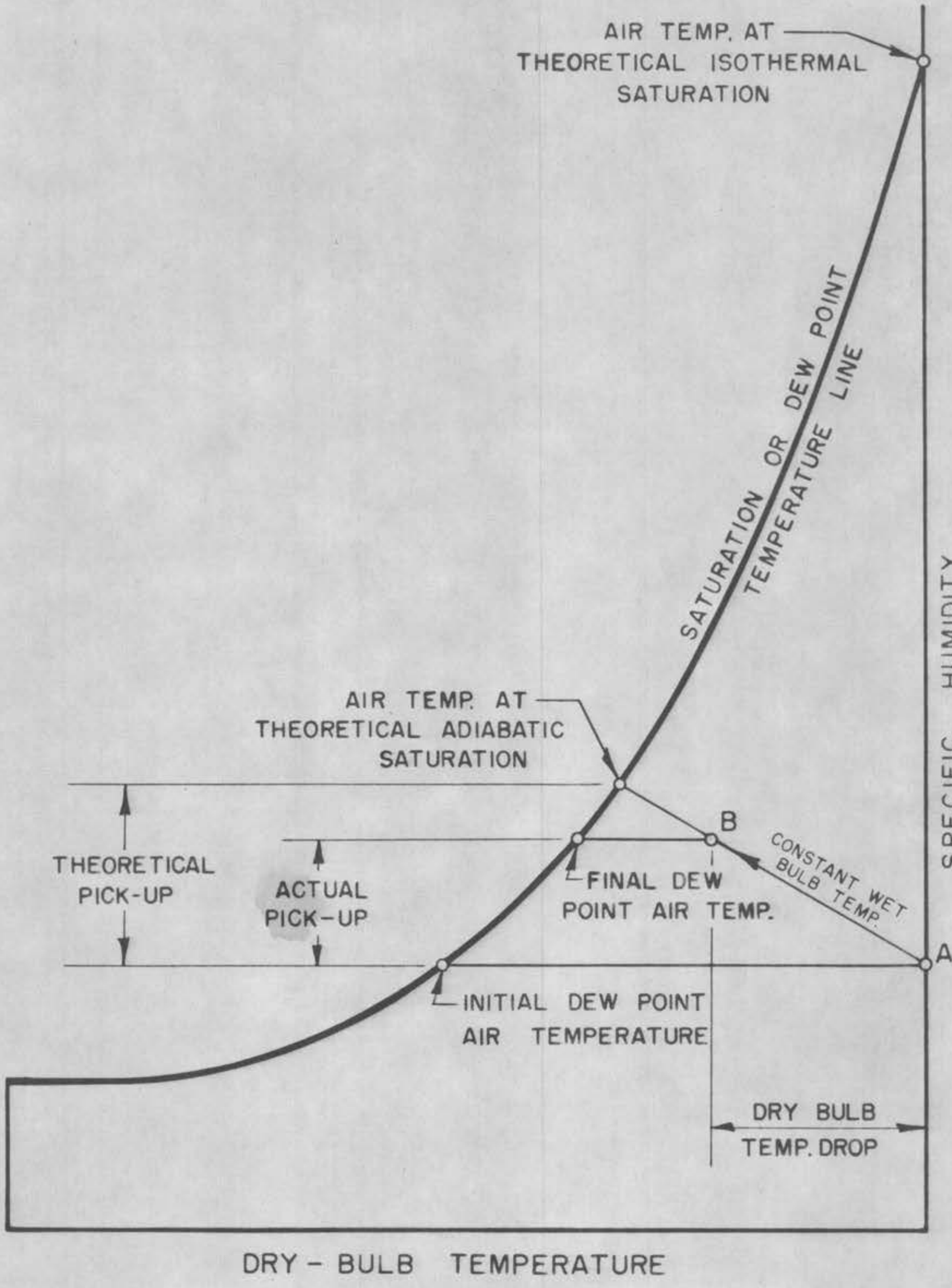

FIGURE 1. PROGRESS OF AIR THROUGH DRYER

chart the progress of air through the dryer. Point A represents conditions of the air entering the dryer; point B represents the conditions of the air leaving the dryer. The air path through the dryer is the constant wet bulb temperature line between the points A and B. The theoretical ability of air to increase its vapor content, shown on the same chart, has been called theoretical pick-up. In adiabatic drying the magnitude of the theoretical pick-up is approximately equal to the difference between the moisture content of air saturated at the supply wet bulb temperature and the initial moisture content of the same supply air. For example, if the dry and wet bulb temperatures of supply air are 180 F and 100 F respectively, the corresponding dewpoint temperature is 81 F, and the initial moisture content is 161 grains per pound of dry air. At 100 F dewpoint temperature, air contains 301 grains of moisture. Hence, the theoretical pick-up is equal to 301-161 = 140 grains per pound of dry air.

Heat economy can be achieved not only by increasing the percent pick-up but also by elevating the working humidity level as high as possible. In other words, the dewpoint temperature of exhaust air should be maintained at a maximum, provided this will not retard the drying speed.

Fundamental Factors in Suspension Drying

Since in all drying operations it is essential to interchange heat, a primary object of any dryer is to ensure the maximum intimacy of contact between the particles of the material to be dried and the heating medium. The greater the intimacy, the more effective the heat transfer and the quicker its rate. This is the advantage of using air to convey heat to the material. It is able to work on each particle directly and can be accurately controlled. Furthermore it furnishes a simple method of removing the evaporated moisture. The suspension drying process provides for even greater intimacy of contact of air and material than do most other convection drying processes.

In suspension drying, we have the following variables:

a. Duct diameter
b. Duct length
c. Material feed rate
d. Initial drying gas temperature
e. Final drying gas temperature
f. Initial moisture content
g. Final moisture content
h. Velocity of drying gas
i. Particle size

The information at hand in most drying situations consists in knowing the quantity of the dry material and the initial and final moisture contents. Thus, the drying requirement can be expressed in weight of moisture removal per unit of time. The most efficient way of obtaining this moisture removal is to have the highest initial gas temperature and the largest temperature differential between the initial and final or vented gas temperatures. The initial gas temperature depends upon the heat sensitivity of the material; also, often times, the heating source fixes the quantity as well as the temperature of the drying gas, for instance, the utilization of stack gases for drying. The temperature of the vented gas is limited to its dewpoint. With varying quantities of material and different moisture contents, the quantity and temperature of hot gas required to maintain a near dewpoint vent temperature will change accordingly.

Increasing the material feed rate will lower the vented gas temperature and will remove more total water, but a wetter material will be discharged. The increased feed rate decreases the available heat per lb. of material, but it does increase the exposure surface; hence, a larger final moisture content and a lower exhaust temperature. The size of the duct diameter is then mostly determined by the feed rate and the moisture differential. These two factors establish the heat requirement or, if given the initial gas temperature, the weight of the required gas. With the further assumption of gas velocity, the duct diameter is established.

The minimum gas velocity is determined by the minimum carrying velocity of the material. This latter is a function of the particle size, the density of the material, and the amount of moisture. As the gas passes through the duct, its temperature is continually decreasing; thus, assuming a constant duct diameter, the velocity is likewise decreasing. If all other factors remain constant, the vented gas temperature increases and the final moisture decreases with an increase in the velocity. These effects are just the reverse of those caused by an increase in feed rate. This follows because both are in essence a variation of the ratio of heat available for evaporation to weight of material. Agitation or the mixture of particles with the gas increases the heat transfer and this is effected by the velocity. However, the time available for moisture evaporation decreases with increased velocities - assuming a constant duct length.

In suspension drying, evaporation occurs very rapidly. Nevertheless, a certain time period is required for the drying effect and the actual period of contact is a function of the velocity and duct length.

Earlier discussions have indicated that particle size will materially effect the drying rate. In larger particles, the internal moisture has greater distances to travel to the surface. Due to the very short drying cycle, this process is limited to materials having at least one small dimension.

CHAPTER III

THE EXPERIMENTAL DRYER

Dryer Description

Figure 2 shows a sketch of the experimental dryer. The main elements composing the dryer are: the air blower, propane burner, drying duct, feed hopper with a motor-driven screw feed, cyclone separator, and dry return duct. The dryer is located in the Turbine Room at the Oregon Forest Products Laboratory. When the decision was made to conduct this investigation of suspension drying, the problem of dryer location immediately presented itself. At first, considerations favored the use of a horizontal drying duct due to the difficulties involved in erecting and fastening a duct placed vertically. However, it was felt that better particle distribution in the drying gas would be obtained if the duct was placed vertical and, therefore, the greater construction task was accepted. Figures 3 and 4 show different views of the experimental dryer.

The deciding factor in the final location of the dryer was that certain pieces of equipment which were also required for the dryer were already located within the Turbine Room as part of another project.

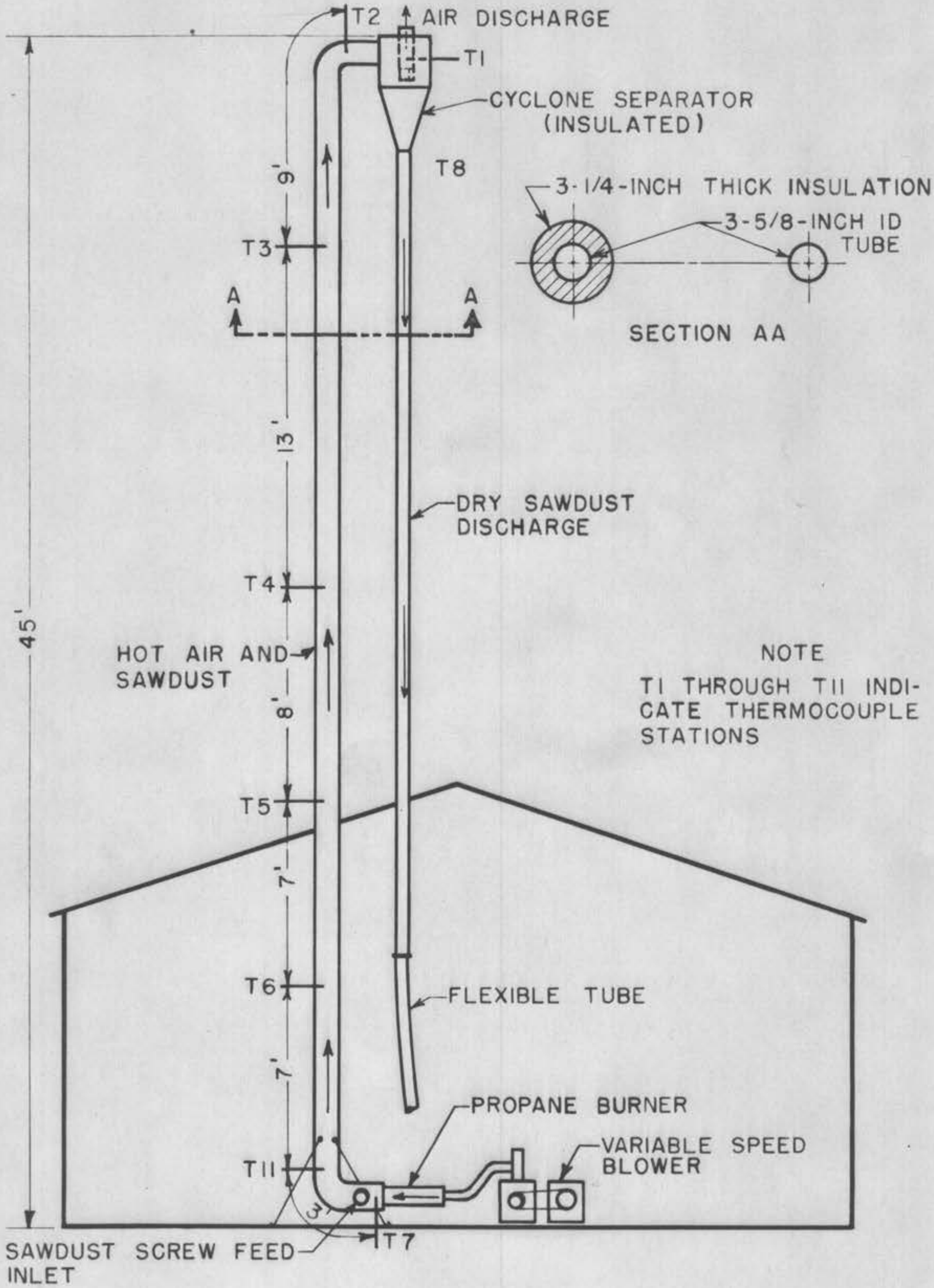

FIGURE 2. SKETCH OF EXPERIMENTAL DRYER

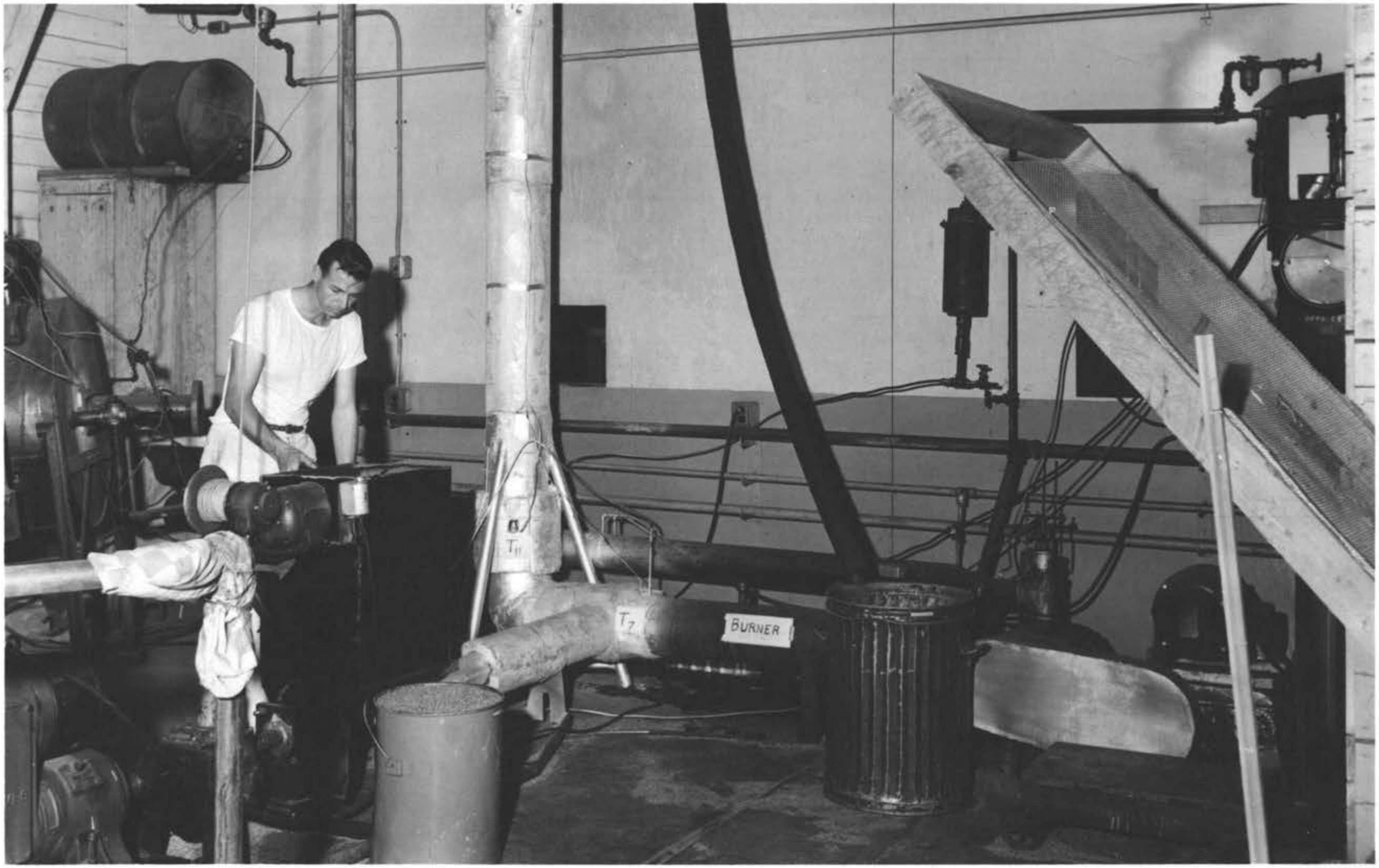

FIGURE 3. BLOWER, BURNER, AND FEEDER

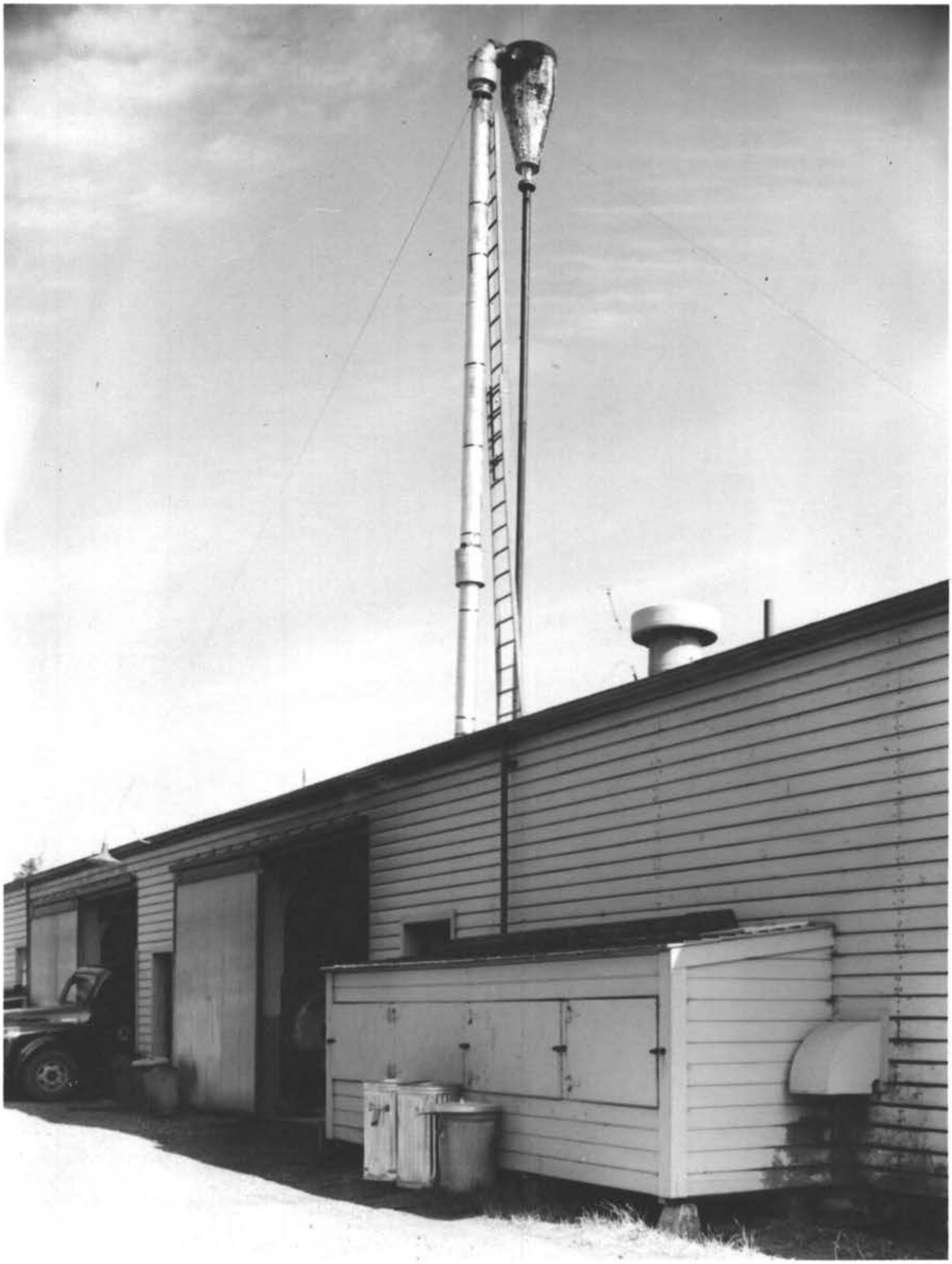

FIGURE 4. DRYING DUCT, CYCLONE, AND RETURN DUCT

After preliminary considerations had been given to the approximate dryer size and capacity that would be suitable, it was recognized that this equipment could also be utilized for the dryer. This equipment included the propane burner, air blower, and screw feed system. Another factor which proved advantageous for the present dryer location was that bracing of the duct where it extended through the roof was possible.

Dryer Design

(A) The Drying Duct. Simplicity and cost favored restricting the duct diameter to a single size. It would be desirable to have at least two ducts of different diameter so that predictions made from tests on one could be checked on the other; also with a number of diameter sizes, this variable could be more properly evaluated. There are certain factors which limit the minimum size of the diameter. The duct could be so small that difficulties of feeding the sawdust would be encountered; the duct must be large enough to permit unrestricted passage of the particles; the duct must be large enough so that the effect of heat losses is not critical. If the duct is quite small then the ratio of heat transfer surface to gas flow is large and a large proportion of the heat supplied will be dissipated through the duct wall. One further consideration is that the diameter should be of sufficient size as to provide a reasonable feed rate. The point here is that errors in measurements would be magnified by very small amounts of sawdust being dried; better testing accuracy is achieved by handling larger quantities of the material. It was estimated that a duct diameter of 4 inches would satisfy the above considerations. On the basis of diameter comparison with one suspension dryer in actual operation, the 4-inch diameter would provide for a duct loading up to approximately 300 pounds of sawdust per hour.

The final selection of the duct diameter was made on the basis of availability and cost. It was not apparent that a small variation from a 4-inch duct would be critical. This value was only approximate and as well as could be judged, duct sizes of one-half inch larger or smaller would prove equally satisfactory. The drying duct of the experimental dryer is composed of steel boiler tubing having a 4-inch outside diameter and a 3.625 inside diameter. As indicated, the cost determined this selection.

The determination of duct length was made on the basis of the longest duct that could be erected by the means available. The largest crane owned by the College had a boom length of 50 feet. Thus, by considering the inclination which the crane boom would be extended due to the fact that the duct base set within the building, a maximum duct length of 47 feet was derived.

To restrict heat losses, it was necessary to insulate the duct. It was planned to vary initial gas temperature up to 1200 F. These high temperatures required special high-temperature insulation. Representatives from firms handling insulation recommended that two layers be used; the inner layer to consist of the special high-temperature insulation and the outer layer of 85 per cent magnesium insulation. The experimental dryer has a one and nine-sixteenths inch thickness of Johns-Manville Temchek on top of which is a one and five-eighths inch layer of 85 per cent magnesia.

(B) The Air Blower. The maximum air flow occurs with the maximum velocity and the lower initial gas temperature. It was planned to vary velocity in the vertical duct from 2000 to 6000 feet per minute and the initial gas temperature from 600 to 1200 F. As can be seen by the arrangement in Figure 2, the blower handles air at atmospheric temperature. Knowing the duct diameter and the velocity, the volume required of the blower in cfm can be calculated from the relation $Q = VA$, where V equals velocity in fpm and A the area in sq. ft. Account must be taken of the difference in atmospheric and duct temperature. On this basis, the maximum required blower volume capacity was 215 cfm.

The pressure loss was estimated on the following basis. It was assumed that with a gas temperature of 600 F entering the duct, that exhaust temperatures would be in the order of 200 F. The velocity in the drying duct will vary directly with the ratio of absolute temperatures in the duct; thus the exit velocity would be 1870 fpm and the average velocity would be 3935 fpm or 65.5 fps. The equivalent duct length including the two elbows is 57 feet. Kent's Mechanical Engineer's Handbook states that pressure loss for standard air flowing through 100 feet of smooth duct can be estimated by the formula

$$h = 0.00055\ v^2/D$$

where h = pressure loss in inches of water; v = velocity of air in fps; D = diameter of duct in feet. Correction was made for the temperature difference between standard air and the mean duct temperature; this correction factor is the ratio of the absolute temperatures. By this method the pressure loss was estimated to be 2.74 inches of water. The pressure drop in the cyclone separator under the above conditions was estimated by the manufacturer to be approximately 0.5 to 1.0 inches of water. The material pressure loss was considered as being negligible. Thus the static pressure required of the air blower would be 2.74 + 1 = 3.74 inches of water.

The air blower on hand was a Size 59, Roots positive displacement blower which was rated at 220 cfm and 27.72 inches of water at 860 rpm and requires 1.3 hp. The Roots blower is powered by a 3-hp Century polyphase, 220-volt induction motor through a Reeves vari-speed changer. Data which had been accumulated through actual experience with the blower indicated that by changing the drive pulley on the Reeves speed-changer, the blower would prove satisfactory in achieving the range of velocities that was desired. The dryer testing unit utilizes this blower.

(C) The Burner. The maximum burner output occurs at a time when the initial temperature and velocity are a maximum - 1200 F and 6000 fpm. Under these conditions, there is an air flow of 10.3 lb per minute, and a heat input requirement above a 60 F datum temperature of 169,000 Btu per hour.

The propane burner which was available was known to provide upward of 20 lb of air per minute at 1400 F. The excellent control of this burner made it easily adaptable as a component of the test dryer. Figure 5 shows a diagram of the burner and the safety devices employed. The mercury switch operates to shut-off the propane should the drying duct become plugged

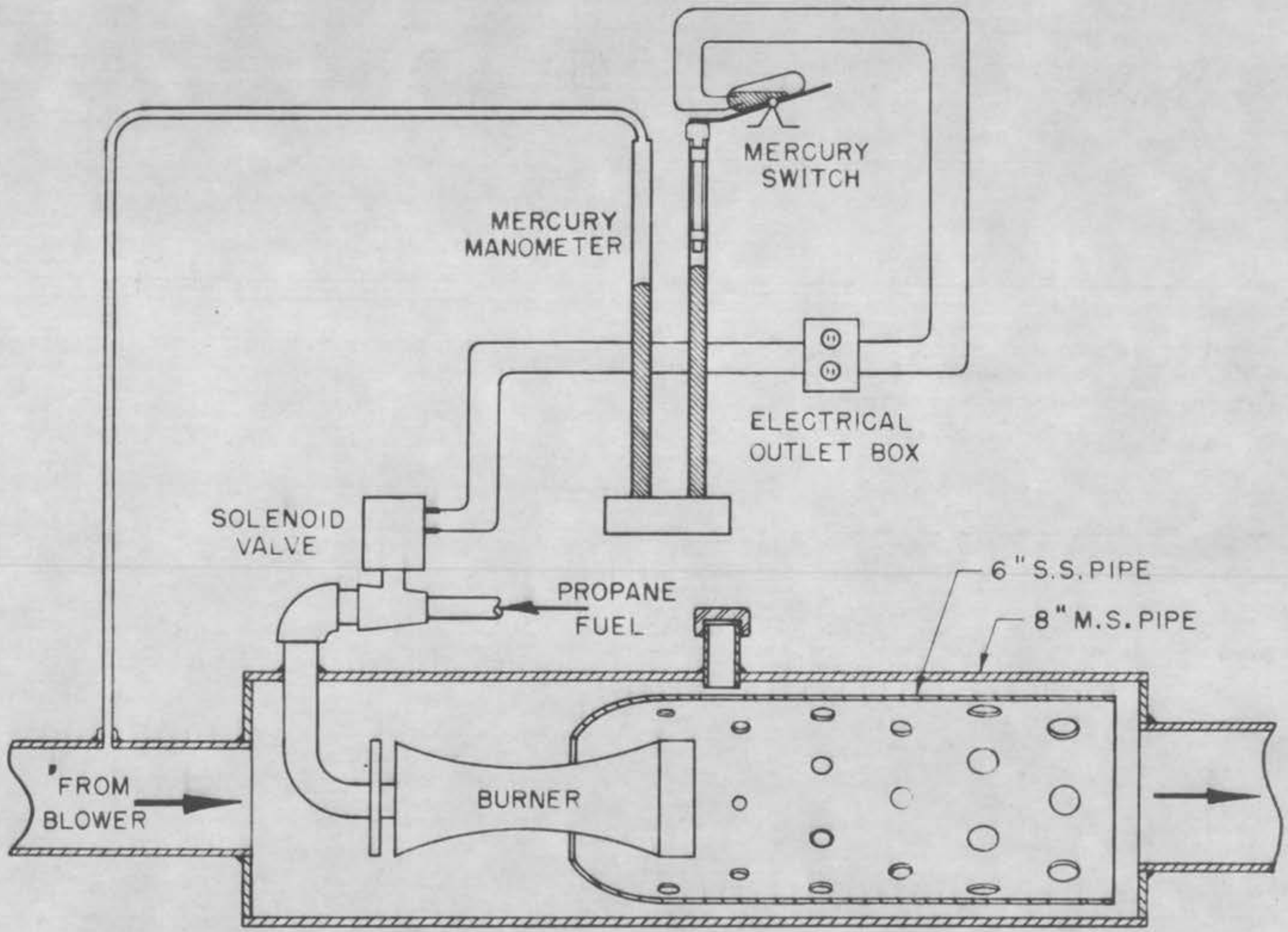

FIGURE 5. PROPANE BURNER

with sawdust. Should this happen the pressure immediately builds up and this pressure increase is applied to one side of the twin mercury columns. The depression in this column raises the mercury in the other column. In turn, the pivoted mercury tube is tipped so as to break the electrical circuit of the solenoid propane valve.

(D) The Feeder. For the purpose of estimating the maximum and minimum feed rates, it was assumed that initial moisture contents would vary from 30 to 60 per cent (wet basis), that final moisture content would be 10 per cent, that exhaust gas temperature would be 300 F, and that a 50 per cent efficiency would be obtained. The maximum feed rate occurs when initial gas temperature and velocity are at a maximum and with the lower moisture reduction or the lower initial moisture content. Under these conditions, air flow is 10.3 lb per minute and there are 2220 Btu per minute available heat for moisture evaporation. Assuming a 50 per cent efficiency, this amount of heat would evaporate 0.99 lb of water, or would dry 4.95 lb of wet feed per minute from 30 per cent to 10 per cent moisture content.

The minimum feed rate by the same method, but with a minimum initial gas temperature and velocity, and with a moisture reduction from 60 to 10 per cent is 0.35 lb per minute.

The screw type feeder that was previously mentioned as being available proved to be satisfactory for the above requirements. It consists of a 9-cubic foot hopper and a 4-inch screw. The feed screw is 6 feet in length and extends from the hopper through a 4-inch steel pipe to the drying duct. The feeder is driven by a General Electric 1-hp Reeves vari-speed motor drive which is connected through a regular automobile transmission. The combination vari-speed drive and transmission provided a range of wet feed rates from 5 to 20 lb per minute. However, by switching the transmission around, the feeder could be operated within the range of feed rates desired for the dryer unit.

(E) The Cyclone Separator. It was important that a minimum material loss occur at the separation from the drying gas. The cyclone type separator is one of the simplest devices for accomplishing the separation of the wood particles from the drying gas and it operates at near 100 per cent efficiency; that is, nearly all of the particles are separated from the gas and very little loss occurs. The component separator is of the standard type used quite extensively in the wood industry. The relatively high temperatures made it necessary to use a heavier metal construction, but other than this it is a standard design. The separator is insulated with one and five-eigths inches of 85 per cent magnesia insulation. The Archer Blower and Pipe Company of Portland, Oregon constructed and donated the separator for this investigation.

(F) The Dry Return Duct. The dry return is of the same size pipe as the drying duct. Both are constructed from 3.625-inch inside diameter boiler tubing. The dry return is uninsulated. For the purpose of obtaining dry material temperature a one and three-fourths inch orifice was placed in the duct where it is flanged to the separator. Just below and extending across the orifice is a thermocouple well. This arrangement provides for a more accurate material temperature than would be obtained if taken after the material has traveled through the duct.

Also placed near the top of the return duct are two one-inch nipples so that an observer can see the dry particles as they leave the separator. If a stop watch is started simultaneously with the feeder and stopped when an observer sees the particles leaving the separator, then the contact time of the sawdust particles and drying gas can be estimated. A three and one-half inch flexible rubber hose is connected to the bottom of the return duct to facilitate the collection of the dried particles.

Instrumentation

Thermocouple wells were placed along the duct so that temperatures of the drying gas as it passed through the duct could be recorded. In this way, temperature drops could be noted and would give an indication of the point where most of the drying was taking place. The wells were made of one-fourth inch stainless steel tubing and were machined to a thin wall to prevent as much heat loss by conduction as possible. These wells were welded in the duct or just a little beyond the center. Figures 2 and 6 indicate the placement of these wells. Figure 6 is a flow diagram and also indicates the instrumentation for the test unit.

The following nomenclature has been used in temperature recording:

T_1 Cyclone exhaust gas temperature

T_2 through T_7 Duct temperatures (T_7 is the initial gas temperature)

T_{11} Duct temperature

T_8 Dry sawdust temperature

T_9 Wet sawdust temperature

T_{10} Air orifice temperature

Temperatures T_1, T_2, T_3, and T_g were recorded by iron-constantan thermocouples which were connected to a

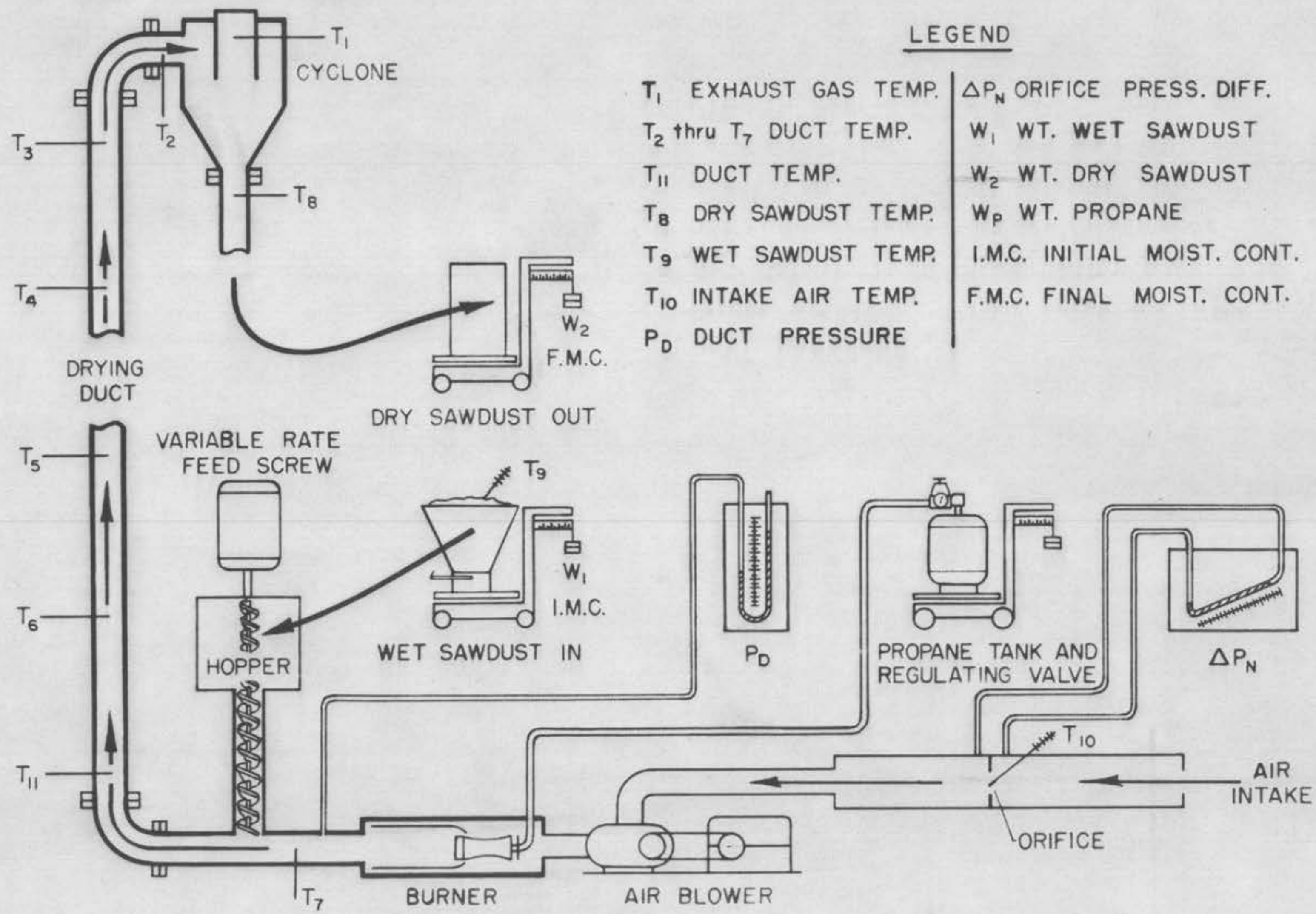

FIGURE 6. PROCESS DIAGRAM OF DRYER

Leeds and Northrup 4-point recording potentiometer pyrometer. This particular pyrometer was scaled to 500 F. The thermocouples for T_4 and T_5 were also iron-constantan; T_4 thermocouple was connected with a Wheelco portable potentiometer indicator, T_5 thermocouple to a Leeds and Northrup portable potentiometer indicator. The iron-constantan thermocouples may be used for temperatures up to 1000 F and it was most probable that these temperatures would not exceed 1000 F.

The thermocouples for temperatures T_6, T_7, and T_{11} were chromel-alumel. T_6 and T_{11} were recorded by a Foxboro potentiometer pyrometer; T_7 was recorded by a separate but similar pyrometer. Both of these pyrometers had a 0-2000 F range. The chromel-alumel type thermocouples are good for temperatures considerably above those which would be encountered in this investigation. Figure 7 shows a view of the instrument panel. The inlet sawdust and the air orifice temperatures were taken with mercury thermometers.

The quantities of sawdust in and out were weighed by platform scales. The moisture contents of the sawdust were obtained by weighing out a certain quantity and then placing it in a drying oven. These moisture content samples were left in the oven until completely dried, then taken out and weighed. The difference in weight is the amount of moisture

FIGURE 7. INSTRUMENT PANEL

evaporated; this divided by the original weight equals the per cent moisture (wet basis).

The propane fuel weight was obtained by placing the propane tank on a platform scale. Provisions were made to keep the propane tank from frosting. This was accomplished by surrounding the tank with a steam coil and by directing a fan over the tank.

Air flow was measured by a two and one-half inch orifice placed in the suction line. The pressure differential across the orifice was measured with an Ellison inclined draft gage. To obtain the pressure in the duct (discharge pressure), a Uehling Type U manometer was provided. Barametric pressure was measured by a Meriam Type W mercury manometer.

CHAPTER IV

TEST PROCEDURE

Proposed Procedure

The numerous variables in the suspension drying process have been enumerated in an earlier chapter. Here consideration will be given to the test procedure for evaluating these variables. The evaluation of the different variables consists in changing the value of the variable over a sufficient range such that the produced effects can be related to the variable. The end result of any drying operation is the removal of moisture. Thus, the testing procedure should provide data which relate the variables to moisture removal from the material. Here, moisture removal does not simply mean total weight of water eliminated from the material; it also includes the rate which the moisture is removed and the range of the reduction in terms of initial and final moisture content. The procedure which would provide a fairly complete evaluation of the suspension drying process as applied to sawdust is as follows: 1. With the velocity, initial moisture content, particle size, and feed rate remaining constant, the initial gas temperature is varied. Note that when the velocity of the gas remains constant, the weight of gas flow (lb per minute) de-

decreases with an increase in initial gas temperature. Weight of gas flow, velocity, and temperature are interrelated and only one can be held constant if one or the other is varied. A change in the velocity changes the contact time and also effects the turbulence of the gas-particle mixture flow, whereas changes in the weight of gas flow affect the quantity of heat supplied to the system. 2. With the initial gas temperature, initial moisture content, particle size, and feed rate remaining constant, the gas velocity is varied. This will give some indication of the relative effects of contact time, agitation, and weight of gas flow on the moisture removal. This test should be repeated with each initial gas temperature value. 3. The feed rate is varied with each initial gas temperature value. The other variables are kept constant. 4. The particle size and initial moisture content are each varied separately while the other variables remain constant. It is only necessary to vary these two factors for one given set of conditions; that is, for selected values of initial gas temperature, velocity, feed rate, and initial moisture content, tests are conducted with different particle sizes. The same should be done for a range of initial moisture contents.

Actual Procedure

In the previous section the procedure for testing the dryer which would provide for a fairly complete evaluation of this type of dryer was presented. If a range of five values for each variable were checked as outlined, then a total of 60 tests would have to be conducted. This required more time than would have been possible to give to this investigation. Therefore, it was necessary to deviate from the proposed procedure and the tests actually conducted for this thesis were as follows: The initial gas temperature values were taken at 600, 800, 1000, and 1200 F. The weight of gas flow values were 5, 7, 9, 11, and 13 lb per minute. This gave initial gas velocities ranging from approximately 2000 to 6000 feet per minute. The feed rates were 1.25, 2.50, 3.75, and 5 lb per minute of wet sawdust. The initial moisture content was not varied and remained at approximately 40 per cent which is the average "as received" condition. No attempt was made to vary particle size and all tests were conducted with sawdust passing through a 4-mesh screen. The particle size distribution is shown in Figure 8. This chart indicates the percentages by weight of the various particle sizes; e.g., 10.7 per cent of the sawdust particles were larger than a 6 mesh, 16.5 per cent larger than a 8 mesh but smaller than a 10 mesh, etc. Nearly 30 per

PERCENTAGES INDICATE THE PROPORTION BY WEIGHT COLLECTED IN THE VARIOUS SIZE SCREENS.

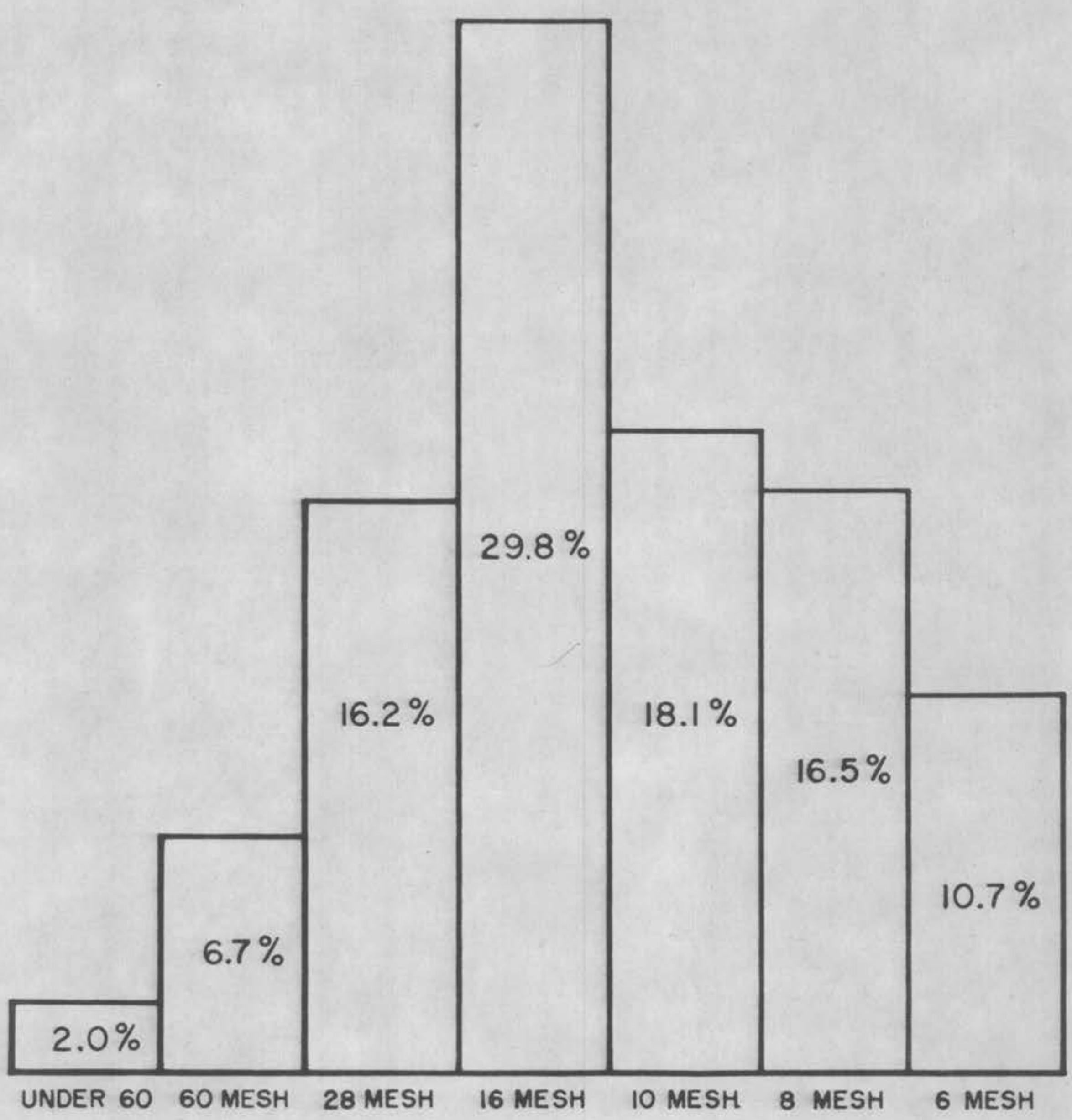

FIGURE 8. SAWDUST PARTICLE SIZE

cent of the particles were between a 16 and 10-mesh size. These tests compiled in chart form are:

Initial Gas Temp. (F)	Feed Rate (lb per min)	Weight of Gas Flow (lb per min)
600	5	5, 7, 9, 11, 13
800	5	5, 7, 9, 11, 13
1000	5	5, 7, 9, 11, 13
1200	5	5, 7, 9, 11, 13
600	3.75	7
600	2.50	7
600	1.25	7
800	3.75	7
800	2.50	7
800	1.25	7
1000	3.75	7
1000	2.50	7
1000	1.25	7
1200	3.75	7
1200	2.50	7

The tests were conducted in the following manner.

1. The sawdust was screened through a 4-mesh screen and thoroughly mixed to insure constant moisture content throughout the particles.
2. The air blower was started and adjusted for the correct flow rate.
3. With the propane regulating valve opened and the solenoid valve circuit closed, the burner was lighted.
4. The recording pyrometers were now switched on so that the burner could be regulated to the approximate initial gas temperature desired.

5. Wet sawdust was shoveled into the feed hopper and with the feed rate adjusted the feeder was started.
6. Before commencing the actual test, the dryer was run until thermal equilibrium had been established. When the duct temperatures on the recording instruments become straight lines, equilibrium had been reached. Depending upon the temperature and air flow, the period required for equilibrium varied from one to two hours. It was necessary to continually adjust the propane valve to maintain the desired initial gas temperature.
7. During this equilibrium stage, dry and wet bulb air temperatures were taken near the inlet of the air blower. Also the barometric pressure was taken.
8. After equilibrium had been reached, the person handling the sawdust filled the feed hopper, switched the dry return hose to the receiving drum, and declared the test to be started. At the same time, another person balanced the propane scales and noted the time which the test was started. Testing of the dryer required two men.
9. At five-minute intervals, the various temperatures and pressures were recorded on the data sheet.
10. The wet sawdust was weighed in fifty-pound lots on a platform scale and then dumped into the hopper. The weight of sawdust in was recorded on the data sheet.

11. The dry sawdust was collected in receiving drums, weighed and recorded.
12. Three moisture content samples were taken during the run for both the sawdust in and the sawdust out.
13. The duration of the tests was governed by the feeding of the last 50-lb lot of wet sawdust. At this time, the dry return hose was switched from the receiving drum, the propane scale was again balanced, and the time was noted.
14. If sufficient time remained for further testing, then the conditions for the next test were established and the procedure outlined above was repeated. Usually, the time required for thermal equilibrium of the system was less when tests were run without shut down between the runs. If no further testing was to be made, then the screw feeder and burner were shut off. The air blower was operated for another ten or fifteen-minute period for the purpose of cooling the duct. This procedure lessened the possibilities of fire commencing in the drying duct after testing personnel had left the scene.
15. The moisture content samples were placed in the drying oven. Later the moisture content percentages were calculated for each sample and recorded on the data sheet.

CHAPTER V

RESULTS

In this chapter attention is limited to the description of the results obtained from the tests which were outlined in the previous chapter. The explanation of the various phenomena delineated here is presented in the following chapter.

The test data are presented in tabular form in Tables 1, 2, 3, and 4 appearing in the appendix. In all of these tables, tests with initial gas temperatures of 600 F are presented first and these are in order of increasing air flow rates; then the 800 F initial gas temperature series was given, etc.

Table 1 shows the correction that was necessary for the initial gas temperature values recorded. All tests were conducted with the dryer arrangement illustrated in Chapter III. It will be observed that the thermocouple for recording initial gas temperature was originally in a direct line of sight of the burner flame. This placement of the thermocouple was a serious error in the design of the experimental dryer unit in that the thermocouple received direct heat radiation from the flame and therefore recorded a higher temperature than the actual initial gas temperature. To correct the temperatures that had been recorded, the burner was raised and moved away from the sawdust inlet. In this new arrangement, the thermocouple was no longer exposed to the flame. The corrections shown in Table 1 were obtained by duplicating the conditions of each of the tests that had been made and recording the initial gas temperature in the new arrangement just described. In the following, where it is not made explicit, the uncorrected even-numbered values will be used for the various initial gas temperatures.

Table 2 gives the duct temperature distribution for the various tests. For a given initial gas temperature and a constant sawdust feed rate, the temperatures along the drying duct increase with increased air flows. In Run 53 which corresponds to an initial gas temperature of 600 F and the lowest air flow (317 lb per hr.), nearly all of the heat of the drying gas is dissipated by the time the mixture of drying gas and material has reached T_6 which is only 10 feet from where the sawdust is introduced. Runs 54, 46, and 26 represent the same air flow as Run 53 but have initial gas temperatures of 800, 1000, 1200 F, respectively. Also in these conditions, the greater portion of the drying occurs in the first 10 to 15 feet of the duct. This is indicated in Table 1 which shows very small temperature drops beyond the first 10 or 15 feet of duct. As the air flow increases, the duct temperatures increase and a higher exhaust temperature results. The same effect in temperature distribution along the duct is caused by raising the initial gas temperature.

The effect of changing air flows on the rate of water evaporated from the material is illustrated in Figure 9 which is a graph of air flow and water removed for initial gas temperatures of 600, 800, 1000, and 1200 F (sawdust feed rate being constant). The curves of this graph are identified for the different initial gas temperatures. However, this is only approximately true in that each curve is for a range of initial gas temperatures approximating the value given; e.g., the curve labeled 600 F represents a range of temperature from 525 to 570 F (Table 1). As the air flow increases, the rate of water evaporation increases for each given initial gas temperature. However, the rate of this increase diminishes at the higher air flows as is shown by the decreasing slopes of the curves in Figure 9.

Table 3 contains the air, sawdust feed, and moisture removal rates for the different runs. Also included in Table 3 are the air velocities at the duct inlet. The velocity at duct inlet is a function of the air flow and the initial gas temperature. The decrease in velocity of the drying gas as it travels through the duct corresponds with the decrease in temperature of the gas.

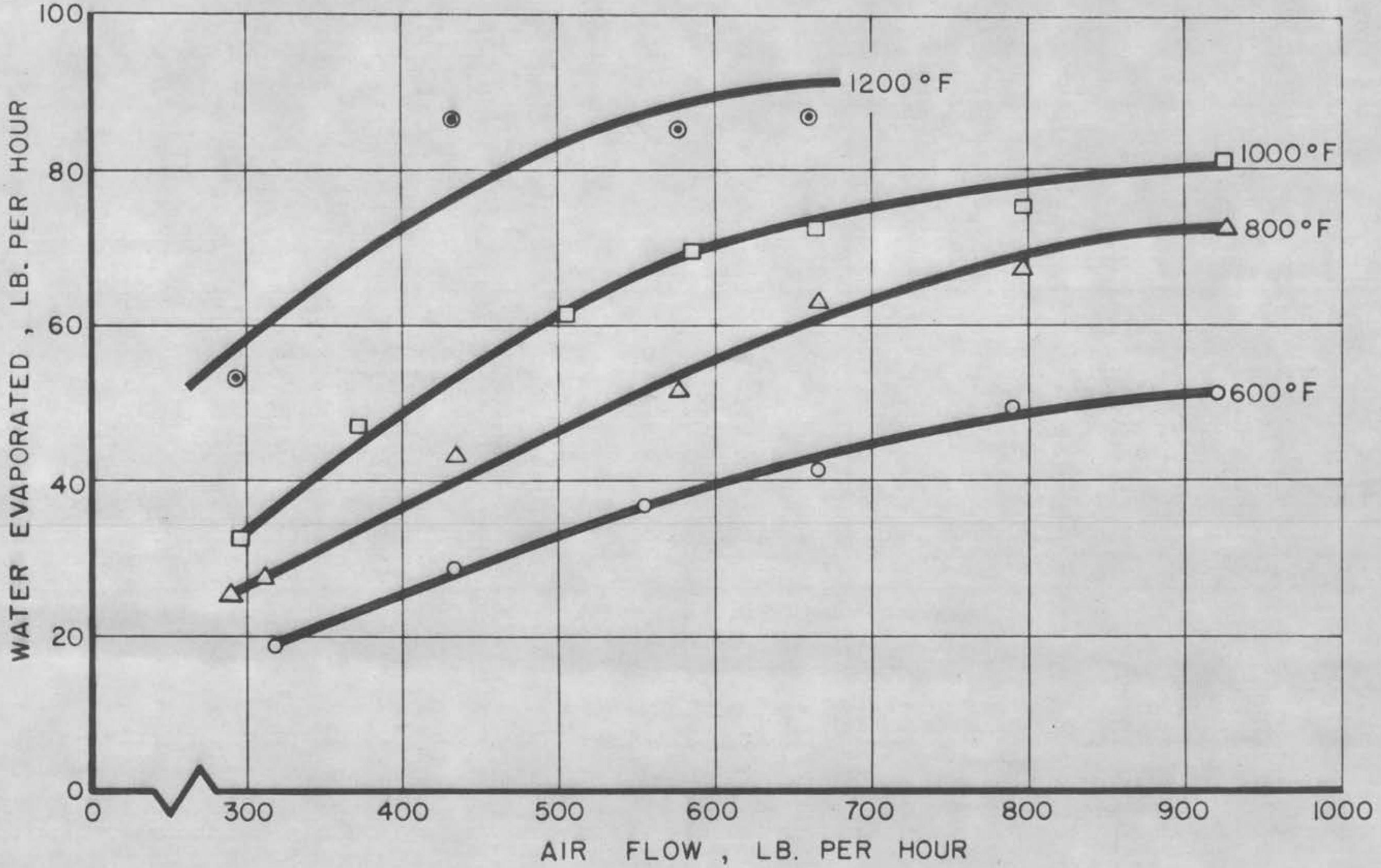

FIGURE 9. AIR FLOW VS DRYING RATE, CONSTANT SAWDUST FEED RATE

The heat balances for the various runs are included in Table 4. The calculations for a sample run are given in Appendix A. The percentage of the heat supplied to evaporate water from the sawdust is characterized by being at a maximum at the second lowest air flow (430 lb per hour) for each of the initial gas temperatures. This is shown in Figure 10 which is a plot of initial gas temperature and dryer efficiency. The term efficiency is used in this thesis to represent the ratio of the heat required to raise the temperature of the water removed from the material to the boiling point plus the heat of vaporization to the heat supplied in the drying gas. The heat, if any, to superheat the water vapor is not taken into account by the expression of efficiency as here defined. Thus, the top curve in Figure 10 shows that the maximum efficiency occurs at an air flow of approximately 430 lb per hour. This is for a wet sawdust feed rate of 300 lb per hour and an initial moisture content of around 40 per cent, wet basis. Referring still to Figure 10, the curve for an air flow of 550 lb per hour gives a nearly constant efficiency for varying initial gas temperatures; whereas for air flows exceeding 550 lb per hour, the efficiency decreases with an increase in initial gas temperature. For air flows less than 550 lb per hour, the reverse of the above holds true.

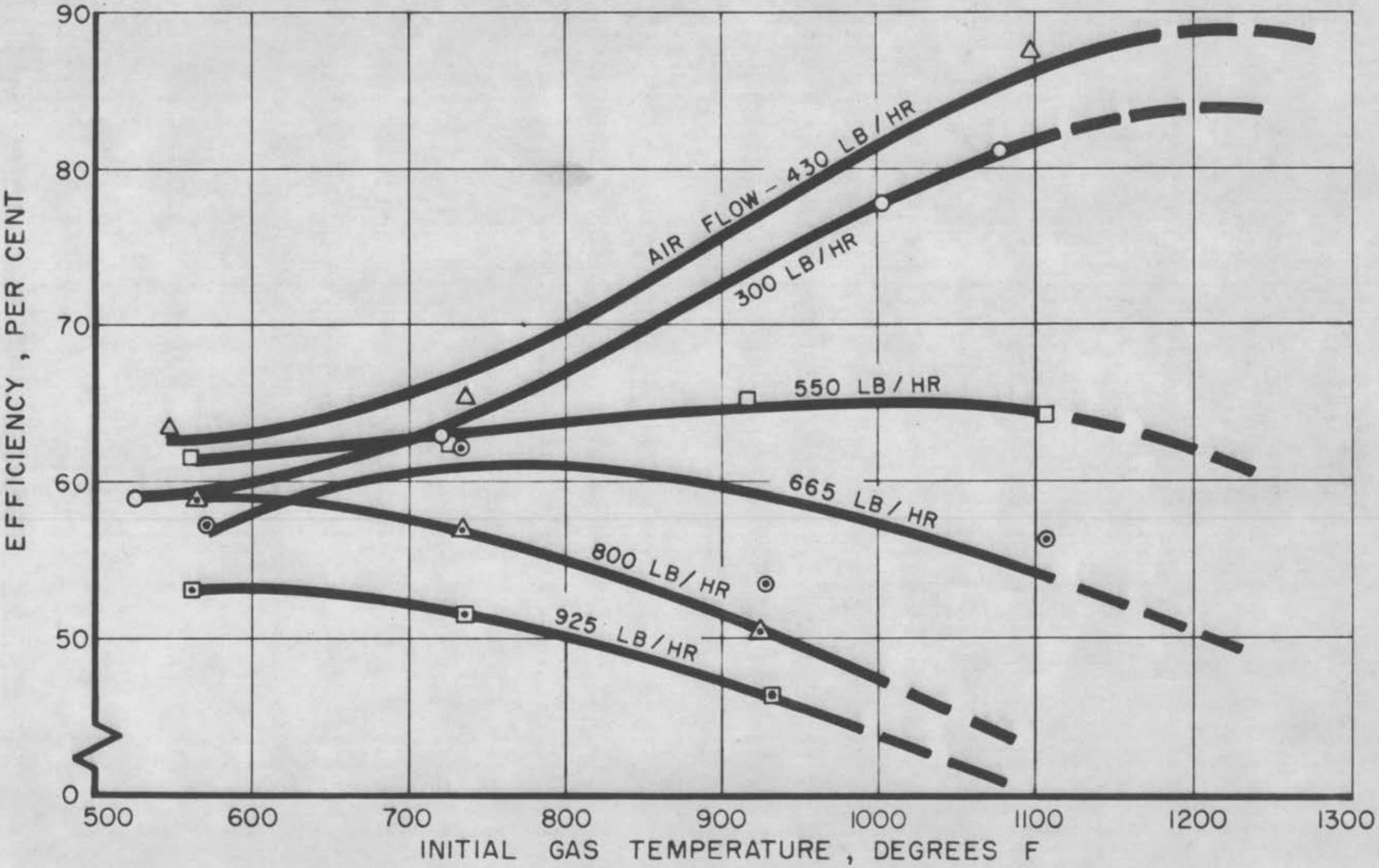

FIGURE 10. INITIAL GAS TEMPERATURE VS EFFICIENCY, CONSTANT SAWDUST FEED RATE

Figure 11 was constructed from values taken from the set of curves of Figure 10. In this way, the curves of Figure 11 corresponds more closely to the initial gas temperatures which they represent. Figure 11 merely presents the same information but in slightly different form than given in Figure 10.

The effects of varying sawdust feed rates on the rate of moisture removal and the efficiency are illustrated in Figures 12 and 13. Figure 12 is a graph of feed rate and water evaporated; the air flow remained constant at 440 lb per hour and the curves represent the different initial gas temperatures. At an initial gas temperature of 600 F, the drying rate increases with an increase in feed rate until a maximum is reached at a feed rate of 250 lb per hour. Further increase in feed rate causes a decrease in the drying rate. The same characteristic is represented by the 800 F curve but with the maximum drying rate occurring at a higher feed rate. The same tendency is shown by the curve for an initial gas temperature of 1000 F but the maximum drying rate was not reached within the feed rates investigated.

Figure 13 consists of a set of efficiency curves for varying sawdust feed rates at a constant air flow of 440 lb per hour. At the lowest feed rate investigated, the lower initial gas temperature of 600 F gave the highest efficiency; whereas, at the higher feed rate the

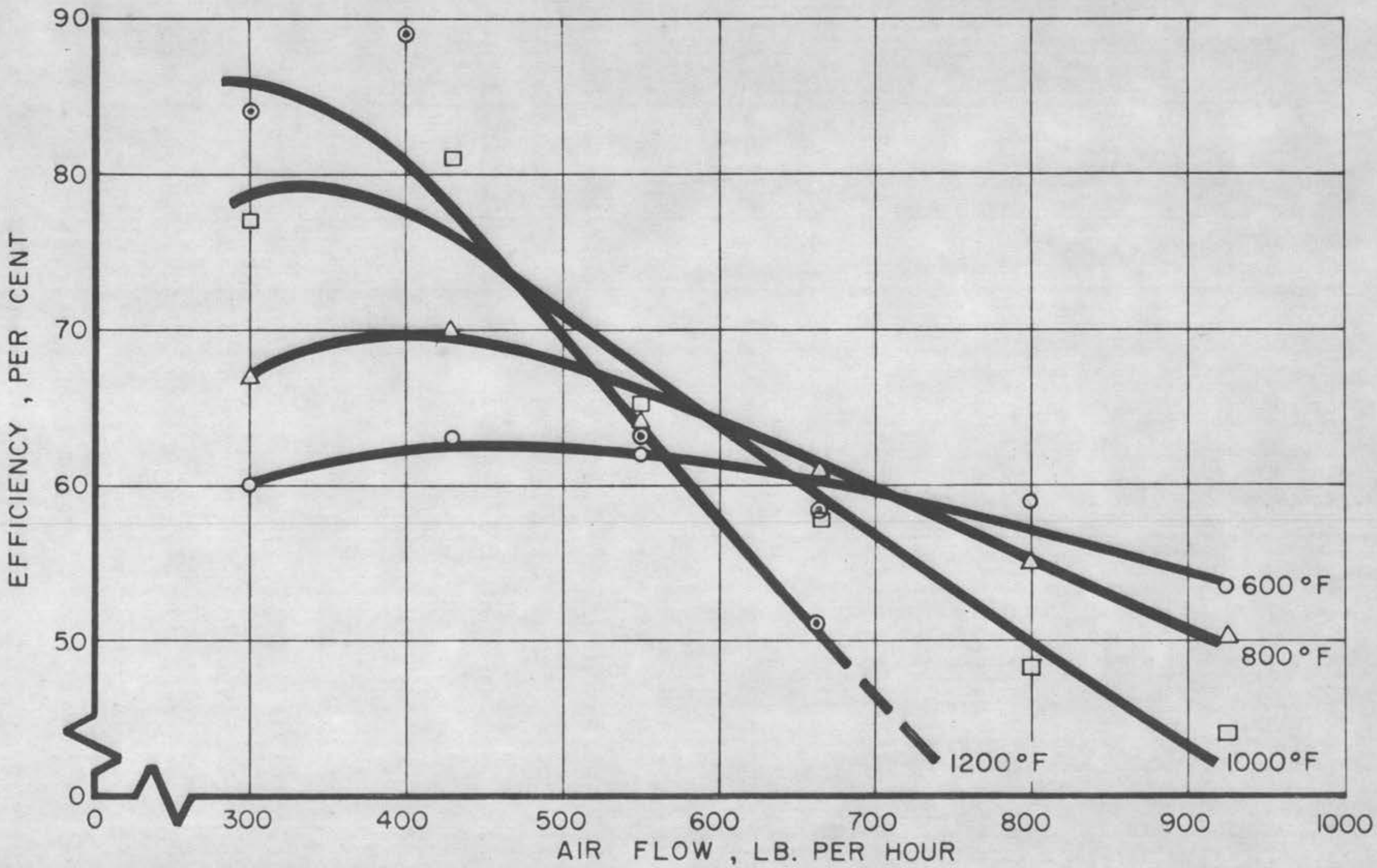

FIGURE 11. AIR FLOW VS EFFICIENCY, CONSTANT SAWDUST FEED RATE

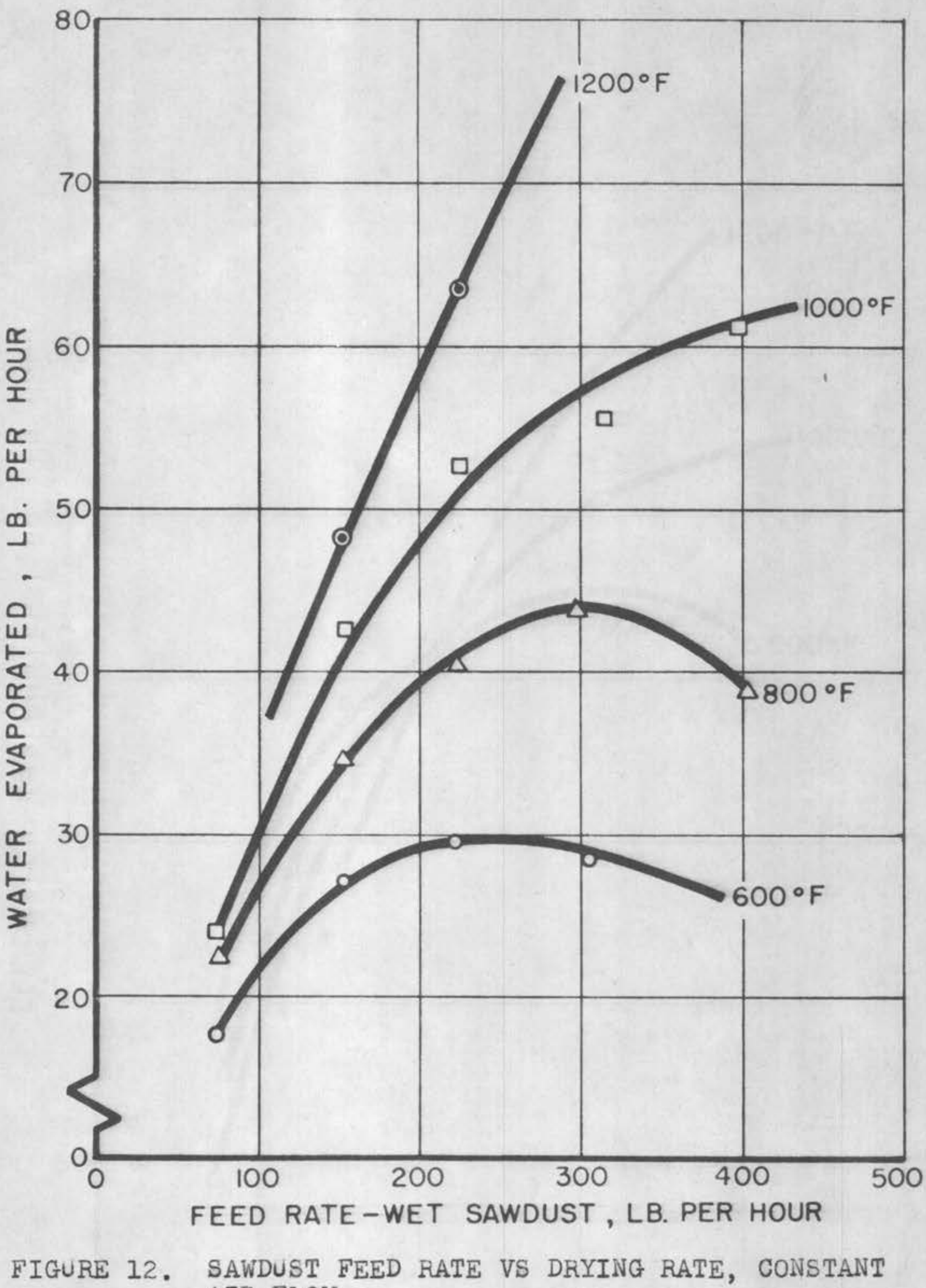

FIGURE 12. SAWDUST FEED RATE VS DRYING RATE, CONSTANT AIR FLOW

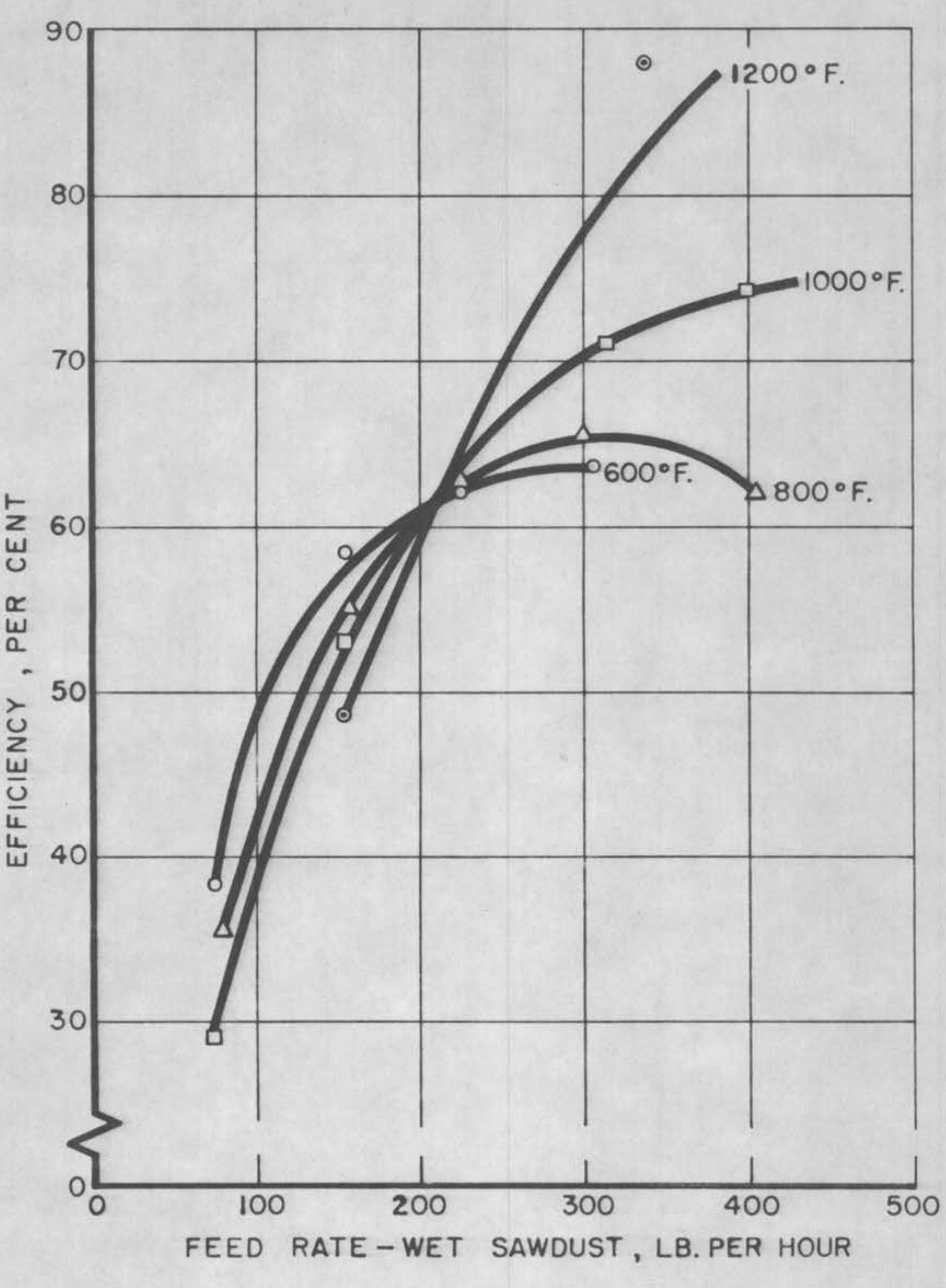

FIGURE 13. SAWDUST FEED RATE VS EFFICIENCY, CONSTANT AIR FLOW

higher initial gas temperatures proved more efficient. For a given initial gas temperature, the efficiency of the dryer increased with increased feed rate until a maximum was reached, depending upon the initial gas temperature, then decreased with further feed rate increases.

CHAPTER VI

DISCUSSION OF RESULTS

The increasing drying rates with increased air flow and initial gas temperature, as shown in Figure 9, is due to the fact that larger quantities of heat are being supplied to the system. For instance, with an increase in air flow from 300 to 420 lb per hour the heat supplied increases from 35,000 to 50,200 Btu per hour for an initial gas temperature of 600 F. In the latter case, there is more heat available to evaporate the moisture. This is true also for succeedingly higher air flows and initial gas temperatures. However, as was pointed out in the previous chapter, this additional available heat for drying is not accompanied by proportional increases in the water removal rate; this is exemplified by the set of curves in Figure 9 which have decreasing slopes. The main reason for this condition is that the succeedingly higher velocities do not allow sufficient time for heat transfer. Although the higher temperatures and velocities produce more rapid heat transfer from the drying gas to the moisture in the material, the shorter time allowed for this transfer of heat is more critical. The predominate effect of the time factor can be seen if one considers the extreme condition. For example, it is possible that the travel of the sawdust particles through a given duct could be at such a high velocity that practically no drying would occur. Even though the drying is quite rapid at these relatively high temperatures, nevertheless a finite time interval is required. In nearly all of the tests conducted, the temperature drop in the first three feet of the duct was as great or greater than the temperature drop in the remaining portion of the duct. Thus considerably longer times are required for effective drying with the lower temperature drying gas and this in turn requires a lower velocity or a longer drying duct. It is an economical requisite that the supplied drying gas be reduced to as low a temperature as possible before being exhausted.

There is an additional factor which accounts for the decreasing slopes of the curves in Figure 9. Dryer material is discharged with the higher air flows and initial gas temperatures. It is recognized that moisture removal is more difficult at lower moisture contents; especially so in wood with moisture contents below 25 per cent. Thus, the increase in drying rate diminishes at the higher air flows and initial gas temperatures.

The efficiency curves of Figure 11 are characterized by an increase in efficiency from the low air flow to the next air flow and then decrease with further increase in air flow; also the negative slopes of these curves is greater for the higher initial gas temperatures. The explanation for the above can probably better be given by considering a few particular runs. In run 53, approximately 30 per cent of the heat supplied went to heat the material and the water remaining in the material. In run 8, nearly the same quantity of heat went to the above two sources but in percentage this quantity represents only 20 per cent of the heat supplied. Referring to Table 2, the duct temperature distribution for these two runs indicates that there was sufficient time to transfer all of the available heat in the drying gas and that the drying gas was reduced to nearly the same exhaust temperature in both cases. Therefore it would be expected that a higher efficiency would occur at the higher air flow in Run 8.

Now in run 51, there is a further increase of air flow over that of run 8, but the efficiency is lower. Here, the time factor comes into play and reference to Table 2 shows that there was insufficient time for heat transfer and consequently a greater percentage of heat was lost to the exhaust gas. Thus, with further increase in air flow, the time for heat transfer becomes less and although there is more drying occuring at the higher air flow, the percentage of the heat supplied for this purpose decreases.

The same reasoning applies to explain the more rapid decrease in efficiency with increasing air flow for the high initial gas temperatures. The gas velocity is a function of both air flow and temperature.

With a low sawdust feed rate, there is a relatively low surface area exposed to the drying gas and, therefore, the quantity of heat transferred to evaporate moisture is low. Conversely, if the feed rate is extremely high relative to the quantity of drying gas, there will be a high heat transfer but all of the heat will go merely to heat the material with little moisture being evaporated. Thus, it is expected that a curve of drying rate and feed rate would follow a positive slope, reach a maximum, and then drop off. This is the case for the curves of Figure 12. The maximum drying rate for the higher gas temperature occurs at a higher feed rate because of the greater quantity of heat supplied.

CHAPTER VII

CONCLUSIONS

It should be recognized that the scope of this thesis does not encompass a complete evaluation of the suspension drying process as applied to sawdust. It has been confined to the investigation and evaluation of the effects of the initial gas temperature, the air flow or drying gas flow, and the sawdust feed rate on the moisture removal rate in this drying process for Douglas fir sawdust. The test results that were obtained seems to justify the following conclusions:

1. For a given air flow, the drying rate increases with increased initial gas temperature.

2. For a given initial gas temperature, the drying rate increases with increased air flow. Therefore, the highest rate of water removal occurs at the highest initial gas temperature and air flow.

3. The maximum drying rate, assuming a constant air flow, occurs at a higher feed rate for increased initial gas temperatures.

4. Contact time or the time allowed for heat transfer has a considerable influence on the efficiency of the dryer. To effectively utilize the heat supplied to the dryer, the duct length required varies with the feed rate.

5. Assuming a constant feed rate, a lower final moisture content occurs with increased air flow and initial gas temperature. However, the feed rate and air flow limit the permissible gas temperature. It was found that with a feed rate of 300 lb per hour and at the highest air flow (925 lb per hour), the initial gas temperature was limited to 1000 F. With this feed rate, 1200 F gas temperature at air flows exceeding 700 lb per hour caused considerable burning and charring of the sawdust particles.

6. As the ratio of the material to gas increases the required duct length decreases; for a constant ratio of material to gas, higher initial gas temperatures required longer drying ducts.

7. With a fixed air flow, a definite material-gas ratio gives a maximum drying rate and efficiency. Therefore, if a given drying problem has a fixed air flow and feed rate, it would be advantageous to recirculate a portion of the material to increase the ratio of material to gas.

8. To obtain low final moisture contents, the ratio of material to gas must be low--1/3 to 1/5 depending upon initial gas temperature.

9. Suspension drying is an effective process for drying wood particles and allows for very close control over the final moisture content.

10. Within the range of desirable application of this type of dryer, expected efficiencies would range from 60 to 85 per cent.

11. This type of dryer is relatively inexpensive to construct and simple to operate. The efficiencies obtained in the tests indicate that not only is suspension drying an effective way of reducing moisture in wood particles, but also that it is one of the most economical processes available for this means.

12. The results obtained form, at least, a partial bases for dryer design. To illustrate this, the results will be applied to the design of a dryer for a hypothetical drying problem.

Assume that a certain saw mill operates a boiler which has a fuel rate of 20,000 lb of wet sawdust per hour at 40 per cent moisture content and that there was 100,000 lb of stack gas at 600 F. Thus to estimate the possible moisture reduction in the fuel by suspension drying with the stack gas, and to determine the sizes of the dryer required to effect this moisture removal (both solutions being on the basis of the results obtained in this investigation), the procedure would be as follows:

The ratio of material to gas is 1 to 5. Utilizing the 600 F initial gas temperature curve in Figure 12, it is possible to determine the water evaporated for the same material-gas ratio as the above. The curves in Figure 12 were established with an air flow of 440 lb per hour; therefore, a feed rate of 88 lb per hour gives a material-gas ratio of 1 to 5. Before proceeding, it might be well to make explicit the necessary assumption before the test results can be used to solve the stated drying problem. It is assumed that if two dryers have the same duct length, initial gas temperature, and mass velocity (lb of gas per sq ft per hour), then directly proportional drying rates will occur with similar material-gas ratios. The curve in Figure 12 shows that water is evaporated at the rate of 19.5 lb per hour and, therefore, in the larger scale dryer 4430 lb of moisture would be removed per hour.

Total moisture in the wet material equals 8000 lb per hour, therefore,

8000 - 4430 = 3570 lb per hour, moisture left in dried material and

$$\text{Per cent moisture content} = \frac{3570}{12{,}000 + 3570} = 22.9\%$$

Mass velocity for this condition equals 6160 lb per sq ft per hour therefore duct area required equals

$$100{,}000/6160 = 16.25 \text{ sq ft}$$

and duct diameter = 54.7 inches. Duct length = 47 feet.

The designed dryer would have an exhaust temperature equal to that obtained in the test results

(253 F, Table 2). If a slightly longer duct were used, the exhaust temperature would be lowered and a higher drying rate and efficiency would be obtained.

CHAPTER VIII

RECOMMENDATIONS

On the basis of the experience that has been obtained in conducting the tests and evaluating the results for this thesis, the following recommendations are made:

1. Tests should be conducted with varying sawdust feed rates for several additional rates of air flow. It is suggested that the feed rates which give the maximum drying rate for the initial gas temperatures of 1000 and 1200 F be established. It is believed that this can be accomplished with the present dryer arrangement.

2. Tests to determine the effects of varying initial moisture contents should be conducted. This information would be valuable in evaluating multi-stage drying and the possibilities of employing partial recirculation of the material.

3. Tests should be conducted with various particle sizes. Determination of the effects of particle size is important in evaluating the application of suspension drying of wood particles used in the various types of pressed-board production.

4. Investigation of the improved drying rates which might be possible with better agitation of the gas-particle mixture is highly recommended. More than

likely this would necessitate considerable expense in providing additional component parts for the present dryer unit as well as making different arrangements. However, it is felt that this is a highly important factor and that the investigation would be rewarding.

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APPENDIX

(A) SAMPLE CALCULATIONS (For Run No. 8)

I AIR FLOW

$$w = 61.5\ k \sqrt{\frac{\Delta P_n\ P_B}{T}}$$

Eckman, "Industrial Instrumentation" Page 272

where w = wt. of air, lb per min
k = flow coefficient
ΔP_n = orifice pressure differential, in. of water
P_B = barometric pressure, psi
T = temperature of air at orifice, F abs.

$$w = (61.5)\ (0.63) \sqrt{\frac{(1.24)\ (14.7)}{524}}$$

w = 7.22 lb per min

II WATER EVAPORATED

$$Ww = W_1 - W_2$$

where Ww = water evaporated, lb
W_1 = sawdust in, lb
W_2 = sawdust out, lb

$Ww = 300 - 271$
Ww = 29 lb

or

$$Ww = (W_1)\ (IMC) - (W_2)\ (FMC)$$

where IMC = initial moisture content, per cent
FMC = final moisture content, per cent

$Ww = (300)\ (41.1) - (271)\ (35.1)$
Ww = 28 lb

III CONSTITUENTS OF DRYING GAS

Propane - C_3H_8

$$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$$

for each lb of propane burned

$$5\,\frac{(32)}{44} = 3.64 \text{ lb } O_2 \text{ required}$$

products of combustion for each lb of propane

$$3\,\frac{44}{44} = 3 \text{ lb } CO_2$$

$$4\,\frac{18}{44} = 1.64 \text{ lb } H_2O$$

Air Flow = 7.22 lb per min or 432 lb per hr
Propane Rate = 2.95 lb per hr

Therefore

$$\frac{432}{2.95} = 146.5 \text{ lb air per lb of propane}$$

and

$$(146.5)\,(0.23) = 33.7 \text{ lb } O_2 \text{ per lb propane}$$

$$(146.5)\,(0.77) = 112.8 \text{ lb } N_2 \text{ per lb propane}$$

$$33.7 - 3.64 = 30.06 \text{ lb excess } O_2 \text{ per lb propane}$$

(wt of product per lb propane) (wt propane per hr) = wt product per hr

Therefore

$$(3)\,(2.95) = 8.84 \text{ lb } CO_2 \text{ per hr}$$

$$(30.06)\,(2.95) = 88.8 \text{ lb } O_2 \text{ per hr}$$

$$(112.8)\,(2.95) = 332 \text{ lb } N_2 \text{ per hr}$$

$$(1.64)\,(2.95) = 4.84 \text{ lb } H_2O \text{ per hr}$$

Dry bulb temperature of air = 64 F
Wet bulb temperature of air = 53 F
41 grains of moisture per lb of air

Therefore

$$\frac{(432)\ (41)}{7000} = 2.53 \text{ lb } H_2O \text{ per hr (from air)}$$

IV HEAT BALANCE

Mean specific heats used in following taken from Spiers, "Technical Data on Fuels", page 158

1. Heat supplied (measured above 70 F)

$$H = w\ c_p\ (t_7 - 70)$$

where w = wt of gas constituent per hour
c_p = specific heat of gas
t_7 = temperature of gas in, F

For N_2

$$H = (332)\ (0.248)\ (479) = 39,400 \text{ Btu/hour}$$

For O_2

$$H = (88.8)\ (.220)\ (479) = 9,350 \text{ Btu/hour}$$

For CO_2

$$H = (8.82)\ (0.198)\ (479) = 835 \text{ Btu/hour}$$

For H_2O

$$H = (7.37)\ (0.446)\ (479) = 1,570 \text{ Btu/hour}$$

Total heat supplied = 50,155 Btu/hour

2. Heat to evaporate water (data from Keenan & Keyes "Thermo. Prop. of Steam".)

$$H = (Ww)\ (1150 - (t_9 - 32))$$

where Ww = water evaporated, lb per hour
t_9 = temperature of sawdust in, F

$$H = (28.5)\ (1150 - (59 - 32))$$
$$H = 32,000 \text{ Btu/hour}$$

3. Heat to material

$$H = (Fs)\ (c_p)\ (t_g - t_9)$$

where Fs = wt of dry sawdust, lb per hour
c_p = specific heat of wood, 0.65 Btu/lb-F (Marks Handbook for M.E.)
t_8 = temperature of sawdust in, F
t_9 = temperature of sawdust out, F

$$H = (179)\ (0.65)\ (108 - 59)$$
$$H = 5700 \text{ Btu/hour}$$

4. Heat to water left in material

$$H = (Wf)\ (c_p)\ (t_8 - t_9)$$

where Wf = wt of water left in sawdust, lb per hour
c_p = specific heat of water, /lb - F

$$H = (96.5)\ (1)\ (108 - 59)$$
$$H = 4720 \text{ Btu/hour}$$

5. Heat to exhaust gas

$$H = w\ c_p\ (t_1 - 70)$$

where w = wt of gas constituent, lb per hour
c_p = specific heat of gas
t_1 = temperature of exhaust gas, F

For N_2

$$H = (332)\ (0.248)\ (125 - 70)$$
$$H = 4530 \text{ Btu/hour}$$

For O_2

$$H = (88.8)\ (0.219)\ (125 - 70)$$
$$H = 1070 \text{ Btu/hour}$$

For CO_2

$$H = (8.81)\ (0.201)\ (125 - 70)$$
$$H = 97.5 \text{ Btu/hour}$$

For H_2O

$$H = (7.37)\ (0.444)\ (125 - 70)$$
$$H = 262 \text{ Btu/hour}$$

Total loss to exhaust gas = 5950 Btu/hour

6. Heat to radiation and unaccounted for

$$H = H_s - \Sigma H$$

where H_s = heat supplied, Btu/hour
ΣH = summation of Item Nos. 2, 3, 4, and 5, Btu/hour

$$H = 50{,}155 - 48{,}370$$
$$H = 1785 \text{ Btu/hour} = 3.55\% \text{ of heat supplied}$$

TABLE I INITIAL GAS TEMPERATURE CORRECTION

Run No.	Initial Gas Temp (original)	Initial Gas Temp (corrected)	Run No.	Initial Gas Temp (original)	Initial Gas Temp (corrected)
53	595	525	26	1197	1077
8	601	549	27	1199	1094
51	600	560	28	1199	1103
10	606	570	29	1194	1104
55	597	563	33	598	549
11	593	560	36	601	552
54	800	720	41	612	563
45	808	734	34	798	724
22	797	726	37	791	717
23	799	730	40	799	725
24	800	733	49	800	726
25	800	735	35	1002	913
46	1000	900	38	1000	911
50	1006	912	42	999	910
52	1002	915	13	987	898
19	1006	927	48	997	908
17	1000	924	39	1195	1091
18	1003	933	43	1201	1097

TABLE 2 DUCT TEMPERATURE DISTRIBUTION

Run No.	Initial Moisture Content %	Final Moisture Content %	Initial Gas Temp (uncorr) F	Duct Temperatures, F T_2	T_3	T_4	T_5	T_6	T_{11}	Exhaust Gas Temp F	Sawdust In Temp F	Sawdust Out Temp F
53	38.1	33.1	595	121	121	123	129	151	226	120	70	116
8	41.1	35.1	601	130	135	147	177	209	293	125	59	108
51	33.5	22.3	600	176	183	217	251	269	342	161	70	131
10	40.5	30.7	606	198	208	235	275	304	382	166	61	120
55	41.2	28.6	597	225	230	260	290	308	396	193	67	126
11	39.9	27.7	593	265	277	300	335	352	424	217	61	128
54	41.9	35.6	800	133	133	136	151	176	295	133	65	132
45	38.0	27.5	808	189	202	236	275	308	385	172	63	135
22	37.6	24.5	797	234	245	286	343	385	510	198	67	133
23	43.1	29.1	799	246	258	299	342	370	525	212	64	139
24	43.7	28.1	800	301	316	350	385	394	549	258	62	151
25	41.3	22.2	800	361	385	415	453	464	563	308	62	139
46	41.1	32.3	1000	146	146	152	172	223	358	144	70	137
50	35.7	23.2	1006	186	204	247	297	340	463	171	66	176
52	33.9	13.7	1002	313	338	399	446	496	628	272	71	162
19	40.7	22.7	1006	399	413	457	531	576	720	325	58	190
17	40.9	20.2	1000	456	474	522	586	611	718	371	62	198
18	40.1	15.9	1003	528	553	598	660	693	774	433	64	203
26	43.3	31.7	1197	160	164	185	212	255	440	152	65	139
27	45.9	27.6	1199	255	266	324	378	422	630	225	63	150
28	41.4	17.7	1199	454	489	559	625	692	804	377	67	195
29	36.6	10.5	1194	593	645	725	758	817	914	489	74	270

TABLE 2 DUCT TEMPERATURE DISTRIBUTION (con't)

Run No.	Initial Moisture Content %	Final Moisture Content %	Initial Gas Temp (uncorr) F	Duct Temperatures, F T_2	T_3	T_4	T_5	T_6	T_{11}	Exhaust Gas Temp F	Sawdust In Temp F	Sawdust Out Temp F
33	39.2	18.4	598	284	304	339	364	372	418	253	68	146
36	38.2	25.1	601	220	229	261	287	310	370	197	64	132
41	40.3	30.3	612	159	168	201	228	257	307	145	64	120
34	39.2	13.5	798	412	439	496	529	550	606	358	68	174
37	39.1	18.8	791	310	326	389	434	462	550	272	60	150
40	40.6	25.5	799	222	233	285	324	360	445	196	62	135
49	36.1	27.7	800	153	161	188	228	258	348	145	67	133
35	36.6	6.2	1002	590	620	684	727	750	813	524	62	257
38	39.1	14.7	1000	421	445	512	570	608	711	363	60	175
42	38.0	17.7	999	321	336	407	459	508	636	278	58	151
13	42.6	29.2	987	206	223	264	316	360	520	182	63	140
48	36.6	23.8	997	195	206	255	298	347	456	178	68	145
39	38.0	9.1	1195	546	573	648	713	758	880	475	63	239
43	37.7	14.3	1201	421	444	522	581	636	792	359	60	165

TABLE 3 AIR, SAWDUST FEED, AND MOISTURE REMOVAL RATES

Run No.	Initial Gas Temp (corrected) F	Air Flow lb/hr	Mass Velocity lb/hr/sq ft	Air Velocity Duct Inlet ft/min	Feed Rate Wet Sawdust lb/hr	Water Evaporated lb/hr
53	529	317	4430	1810	305	18.6
8	549	432	6050	2530	305	28.5
51	560	555	7770	3280	299	36.5
10	570	665	9300	3980	294	41.2
55	563	790	11000	4680	311	49.8
11	560	922	12900	5450	283	51.5
54	720	310	4340	2120	316	27.8
45	734	440	6160	3450	311	42.0
22	726	575	8050	4000	299	51.8
23	730	665	9300	4640	317	63.2
24	733	797	11120	5560	312	67.0
25	735	925	12900	6400	295	69.0
46	900	296	4140	2330	324	32.1
50	912	370	5180	2940	309	47.1
52	915	503	7040	4000	298	61.7
19	927	675	9450	5420	296	67.9
17	924	797	11120	6400	291	75.7
18	933	925	12900	7460	282	81.2
26	1077	293	4100	2610	318	53.5
27	1094	430	6020	3880	337	86.4
28	1103	575	8050	5200	301	85.6
29	1104	660	9240	5980	288	86.4

TABLE 3 AIR, SAWDUST FEED, AND MOISTURE REMOVAL RATES (con't)

Run No.	Initial Gas Temp (corrected) F	Air Flow lb/hr	Mass Velocity lb/hr/sq ft	Air Velocity Duct Inlet ft/min	Feed Rate Wet Sawdust lb/hr	Water Evaporated lb/hr
33	549	440	6160	2570	76.4	17.6
36	552	444	6200	2600	153.8	27.0
41	563	446	6240	2640	224.0	29.6
34	724	440	6160	3020	78.0	22.4
37	717	446	6240	3040	153.8	34.7
40	725	448	6270	3080	225.0	40.3
49	726	443	6200	3040	402.0	38.8
35	913	445	6220	3540	73.8	24.0
38	911	440	6160	3510	152.5	42.7
42	910	447	6250	3550	224.0	52.7
13	898	428	6000	3370	311.0	61.5
48	908	443	6200	3520	398.0	61.2
39	1091	438	6150	3960	151.0	48.3
43	1097	445	6220	4010	224.0	63.4

TABLE 4 HEAT BALANCE

Run No.	Heat Supplied Btu/hr (100%)	Heat To Evap. Water Btu/hr	%	Heat To Material Btu/hr	%	Heat To Water Left In Mat. Btu/hr	%	Heat To Exhaust Gas Btu/hr	%	Heat To Radiation Btu/hr	%
53	35,000	20,700	59.0	5750	16.4	4370	12.5	3800	10.8	400	1.3
8	50,200	32,000	63.7	5700	11.4	4720	9.4	5700	11.3	1180	4.2
51	66,000	40,600	61.5	8100	12.2	3580	5.4	12100	18.3	1620	2.6
10	80,600	46,200	57.3	6630	8.2	4510	5.6	15300	19.0	7960	9.9
55	94,500	55,600	59.0	7100	7.5	4390	4.7	23300	24.6	4110	4.2
11	109,800	58,000	52.8	7450	6.8	4480	4.1	36600	33.3	7170	3.0
54	49,500	31,200	63.0	7600	15.3	6460	13.0	4690	9.5	-450	-0.8
45	72,000	47,200	65.5	9100	12.6	5320	7.4	10780	15.0	-400	-0.5
22	92,800	57,700	62.2	8250	8.9	4150	4.5	17650	19.0	5150	5.4
23	108,000	70,600	65.4	8150	7.6	5150	4.8	22650	21.0	1450	1.2
24	129,500	75,000	58.0	8890	6.9	5390	4.2	36000	27.8	4220	3.1
25	151,000	78,000	51.6	10150	6.7	4510	3.0	52800	35.0	5540	3.7
46	61,000	35,800	58.8	8840	14.5	6500	10.6	5250	8.6	4610	7.5
50	77,200	52,500	68.0	9250	12.0	4300	5.6	8960	11.6	2200	2.8
52	105,000	68,700	65.5	13900	13.2	3420	3.3	11000	10.5	7980	7.5
19	143,000	76,300	53.4	11700	8.2	5300	3.7	41300	28.8	8400	5.9
17	168,000	84,900	50.5	14300	8.5	5520	3.3	56700	34.3	5700	3.4
18	197,000	91,000	46.3	14600	7.4	4240	2.2	81600	41.0	6560	3.1
26	73,500	59,700	81.2	8200	11.2	6220	8.5	5770	7.8	-6790	-8.7
27	109,500	96,500	88.0	10450	9.6	6100	5.6	15950	14.6	-19500	-17.8
28	148,000	95,500	64.5	14500	9.8	4780	3.2	42400	28.6	-9180	-6.1
29	170,000	96,000	56.5	21050	12.4	3660	2.2	66400	39.0	-17100	-10.1

TABLE 4 HEAT BALANCE (con't)

Run No.	Heat Supplied Btu/hr (100%)	Heat To Evap. Water Btu/hr	%	Heat To Material Btu/hr	%	Heat To Water Left in Mat. Btu/hr	%	Heat To Exhaust Gas Btu/hr	%	Heat To Radiation Btu/hr
33	51,300	19,600	38.2	2425	4.7	8200	16.0	19300	38.0	1175
36	51,800	30,200	58.2	4200	8.1	2180	4.2	13500	26.0	1720
41	53,400	33,100	62.0	5080	9.6	3380	6.3	8030	15.0	3810
34	70,600	25,000	35.4	3340	4.7	825	1.7	30400	43.0	11035
37	71,000	39,000	55.0	5620	7.9	2000	2.8	21600	30.4	2780
40	72,200	45,200	62.6	6550	9.1	3450	4.8	13600	18.8	3400
49	71,500	44,400	62.0	11200	15.7	6610	9.3	7950	11.1	1340
35	92,800	26,900	29.0	5900	6.4	605	0.7	48500	52.3	10895
38	91,800	48,000	53.0	7180	7.8	1865	2.0	31000	33.8	3750
42	93,000	58,900	63.2	8500	9.1	2820	3.0	22300	24.0	480
13	88,000	62,300	71.0	9360	10.6	5950	6.8	11500	13.1	-1110
48	92,200	68,300	74.1	13100	14.2	6300	6.8	11500	12.4	-7000
39	111,500	54,000	48.5	10700	9.6	1640	1.5	42500	38.2	2660
43	113,500	71,000	62.5	9400	8.3	2420	2.1	30800	27.1	-120