Chapter 2
Kiln Types and Features

A lumber dry kiln consists of one or more chambers designed to provide and control the environmental conditions of heat, humidity, and air circulation necessary for the proper drying of wood. As the development of the modern dry kiln has progressed, a number of design modifications have been explored in relation to the mechanism of heat supply, arrangement and type of fans, control of relative humidity or wet-bulb temperature, and use of various materials for construction of the chamber.

The design of a kiln has an important bearing on its operation and drying efficiency. A properly designed and operated kiln will dry most species of lumber or other wood products to any specified moisture content between 3 and 19 percent in a reasonably short time without appreciable losses caused by drying defects.

Classification Systems

Dry kilns can be classified in a number of different ways. In this manual, we have chosen a system that classifies by (1) operational techniques, (2) temperatures of operation, and (3) type of heating and energy source. Other possible classifications might include fan arrangement and method of loading the kiln.

Operational Techniques

Classification by operational techniques distinguishes between the more common compartment-type kiln and the less common progressive-type kiln.

Compartment Kilns

Compartment-type kilns (figs. 2-1 to 2-8) are designed for a batch process in which the kiln is completely loaded or charged with lumber in one operation, and the lumber remains stationary during the entire drying cycle. Temperature and relative humidity are kept as uniform as possible throughout the kiln, and they can be closely controlled over a wide range of temperature and humidity. Temperature and relative humidity

---

Chapter 2 was revised by R. Sidney Boone, Research Forest Products Technologist, and William T. Simpson, Supervisory Research Forest Products Technologist.

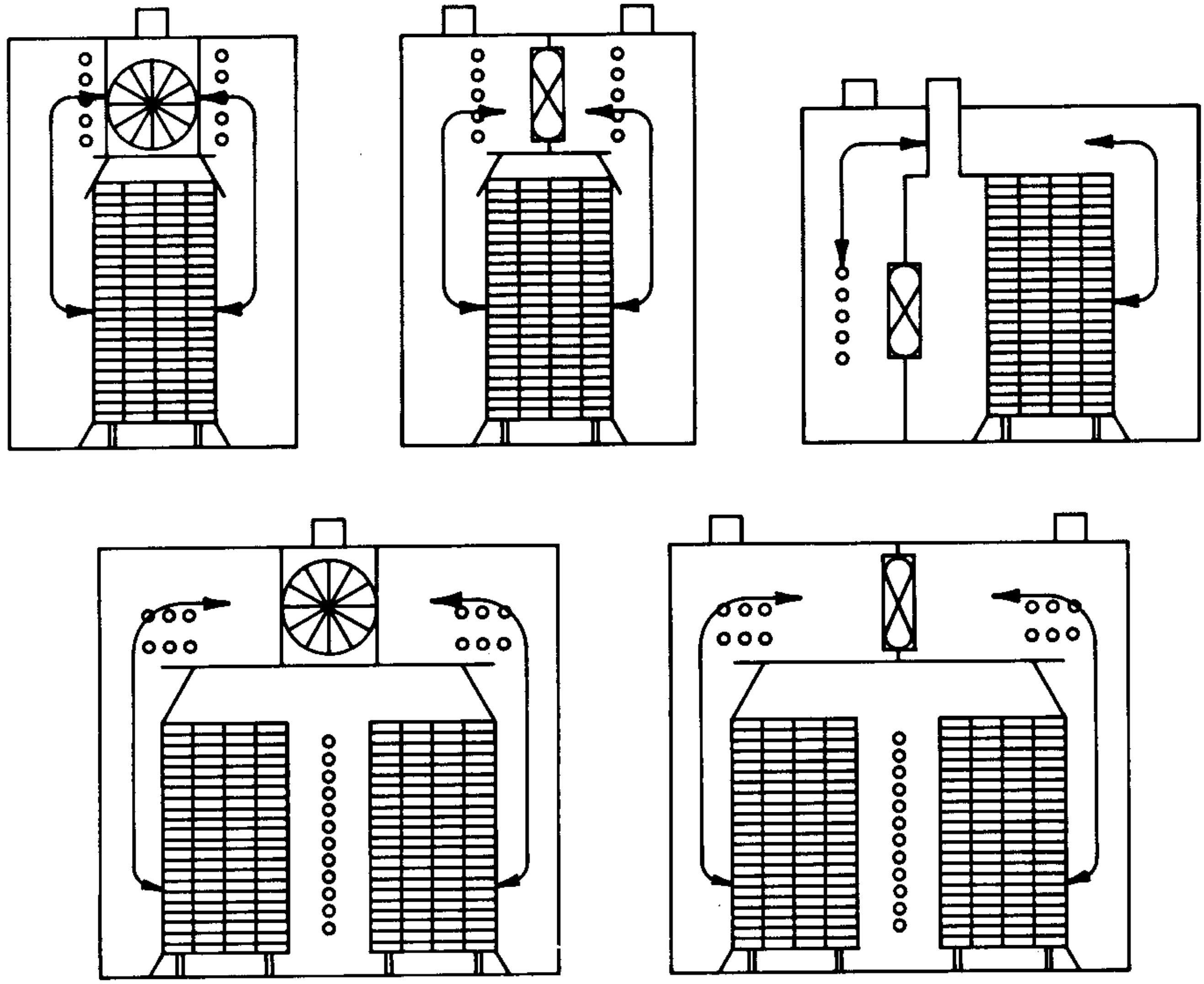


Figure 2-1—Some plans for location of fans and baffles in dry kilns. (ML88 5604)

are changed as the wood dries based on a schedule that takes into account the moisture content and/or the drying rate of the stock being dried. Drying schedules vary by species, thickness, grade, and end use of material as discussed in detail in chapter 7. All modern dry kilns use some type of forced-air circulation system, with air moving through the load perpendicular to the length of the lumber and parallel to the stickers. Although some cross-circulation kilns (airflow parallel to the length of the lumber and perpendicular to the stickers) can still be found, kilns have not been built using this technique for several decades. The natural draft circulation system, which took advantage of the principle that heated air rises, is now considered inefficient and is of historic interest only (Rasmussen 1961). A more detailed discussion of the different types of air circulation systems can be found later in this chapter under the heading General Construction Features.

Compartment kilns can be classified by the method of loading. Perhaps the largest number of kilns are of the track-loaded type. The lumber is stacked on kiln trucks that are rolled into and out of the kiln on tracks. The majority of the softwood lumber in the United States is dried in track-loaded kilns. The other method of loading involves moving stacks or packages of lumber directly into and out of the kiln with a lift truck. These are generally called package-loaded kilns, although they are frequently called side-loaded kilns in the western softwood region. The majority of the hardwood lumber in the United States is dried in package-loaded kilns.

Track-loaded kilns commonly have one or two sets of tracks and occasionally three sets, and are known as single-, double-, or triple-track kilns, respectively (figs. 2-2 to 2-5). The width of the stack of lumber per track is typically 6 to 9 feet. In kilns more than one track wide, some provision for reheating the air is made before it passses through the next stack of lumber. The length of a track kiln is usually some multiple of the lengths of the lumber being dried correlated with the amount of lumber production required. Kiln lengths vary from about 40 to 120 ft; those used for hardwood drying are typically 40 to 66 ft long and those used for

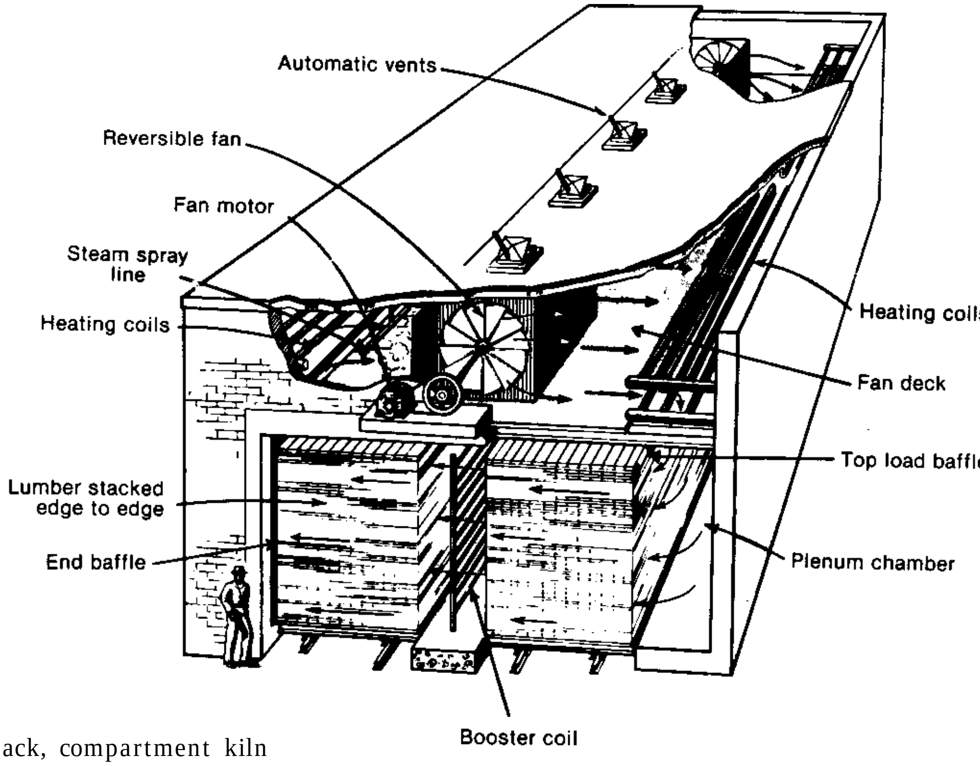


Figure 2.2—Lineshaft, double-track, compartment kiln with alternately opposing fans. Vents are over fan shaft between fans. Vent on high-pressure side of fans becomes fresh air inlet when direction of circulation is reversed. (ML88 5595)

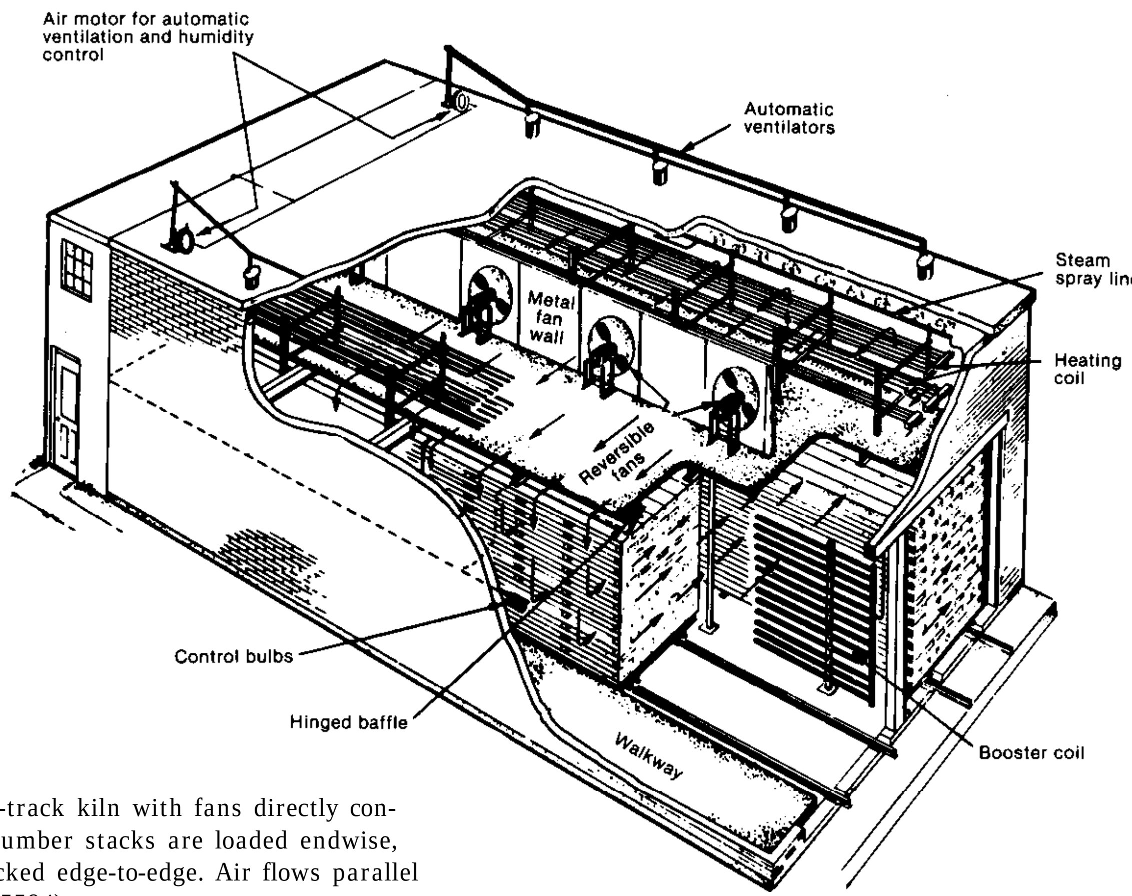


Figure 2-3—Double-track kiln with fans directly connetted to motors. Lumber stacks are loaded endwise, and boards are stacked edge-to-edge. Air flows parallel to stickers. (ML88 5594)

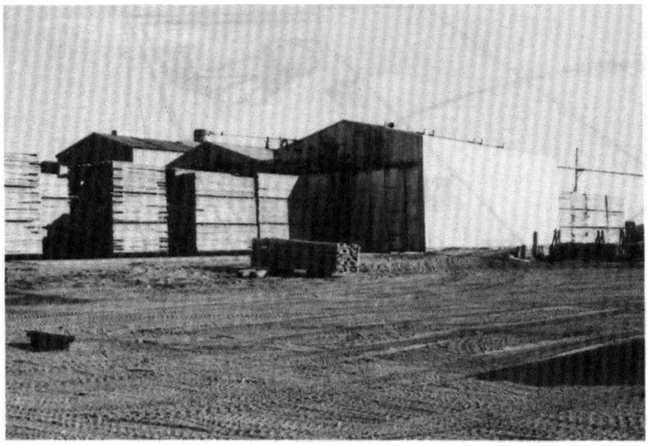


Figure 2-4—Double-tray-loaded aluminum prefabricated kiln with doors at both ends of kiln. (MC88 9017)

softwood, typically 66 to 120 ft long. Lumber-holding capacity can vary from around 25,000 fbm (4/4 basis) to 220,000 fbm (8/4 basis).

Track kilns may have doors at one end or, more commonly, at both ends so that unloading and loading the kiln require a minimum amount of time. Kiln trucks loaded with green lumber are pushed into the kiln immediately after the dried lumber is removed from the kiln. A covered shed is frequently built over the "dry" end of the kiln to protect the dried lumber from inclement weather while it is cooling and awaiting further processing. A cover over the "green" end of the kiln will protect the top courses of freshly sawn lumber from degrading in the sun as a result of uncontrolled drying and from rain or snow. Figure 2-8 shows a kiln with protective cover at both the dry and green ends. Frequently cited advantages of track kilns include short downtime for loading and unloading and more uniform drying primarily because of narrower load widths. Disadvantages include greater building cost, because track kilns require more land area than package kilns especially if kiln has tracks at both ends, and the added expense of track and kiln trucks.

Package-loaded kilns are generally smaller than track-loaded kilns and have a different configuration for loading the lumber (figs. 2-6, 2-7). Large doors permit the stickered and stacked lumber to be loaded into the kiln with a lift truck. Most package kilns are designed to hold 24 ft of lumber from front to back of

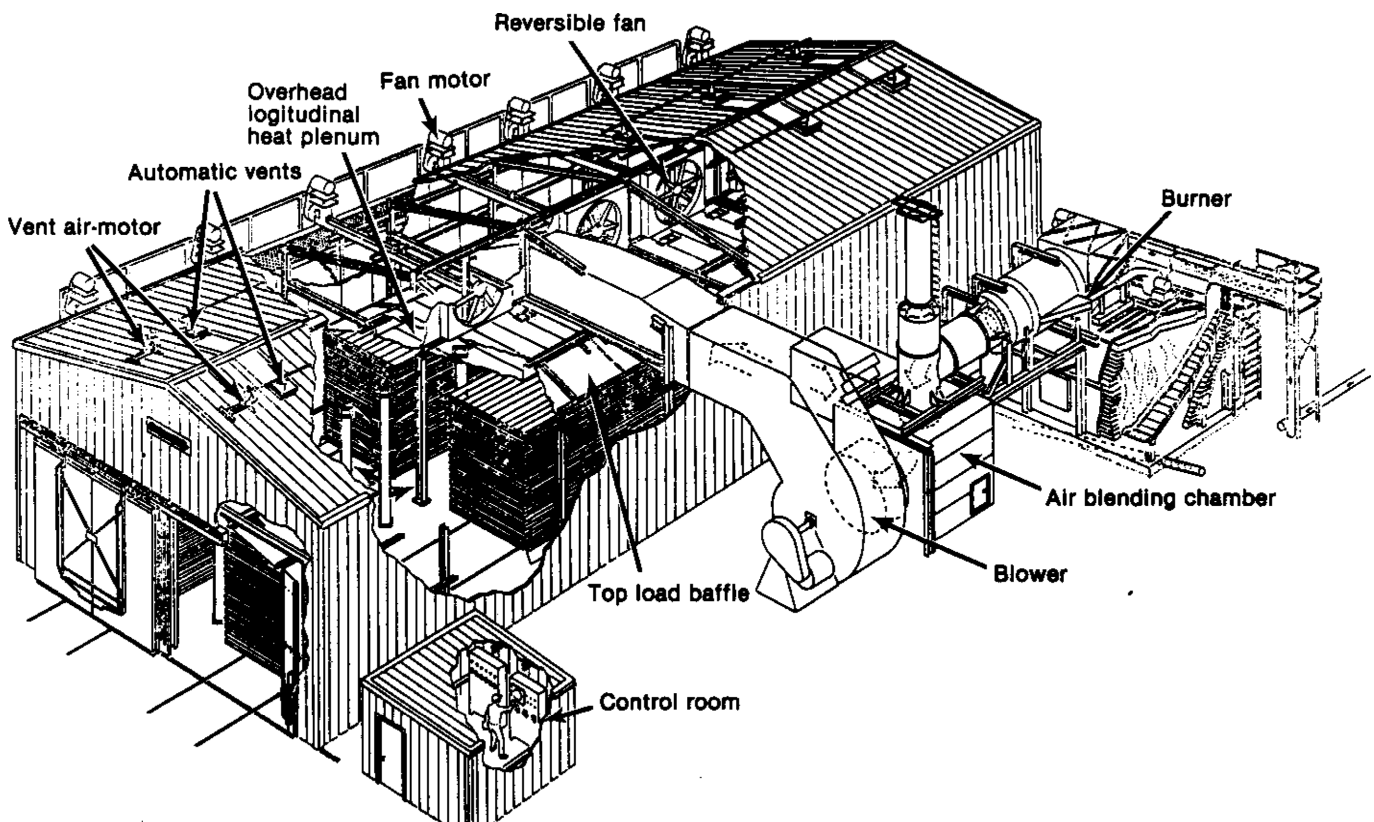


Figure 2-5—Direct-fired, double-track-loaded high temperature kiln in which hot products of combustion are discharged directly into the airstream circulating within the kiln. (ML88 5605)

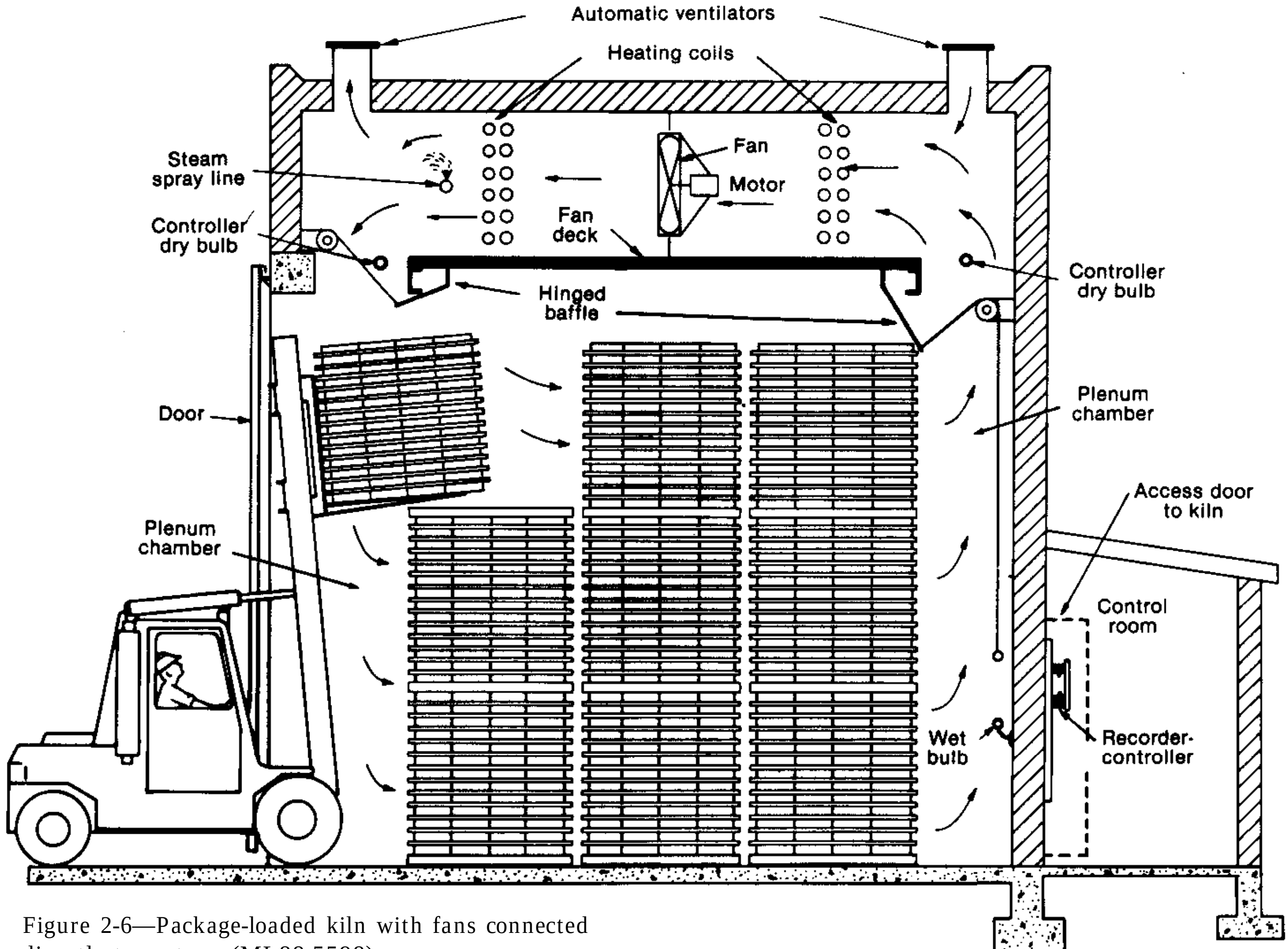


Figure 2-6—Package-loaded kiln with fans connected directly to motors. (ML88 5598)

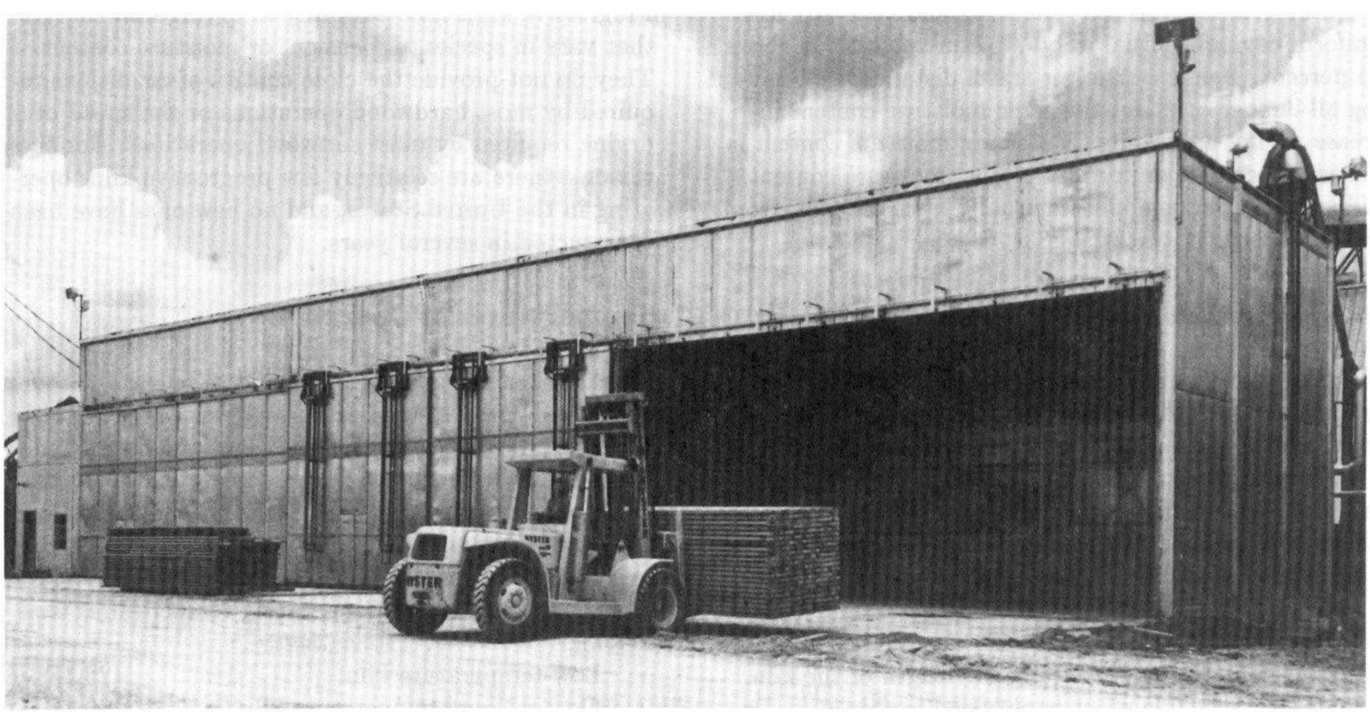


Figure 2-7—Lift truck delivering package of stickered lumber to package-loaded kiln. (MC88 9024)

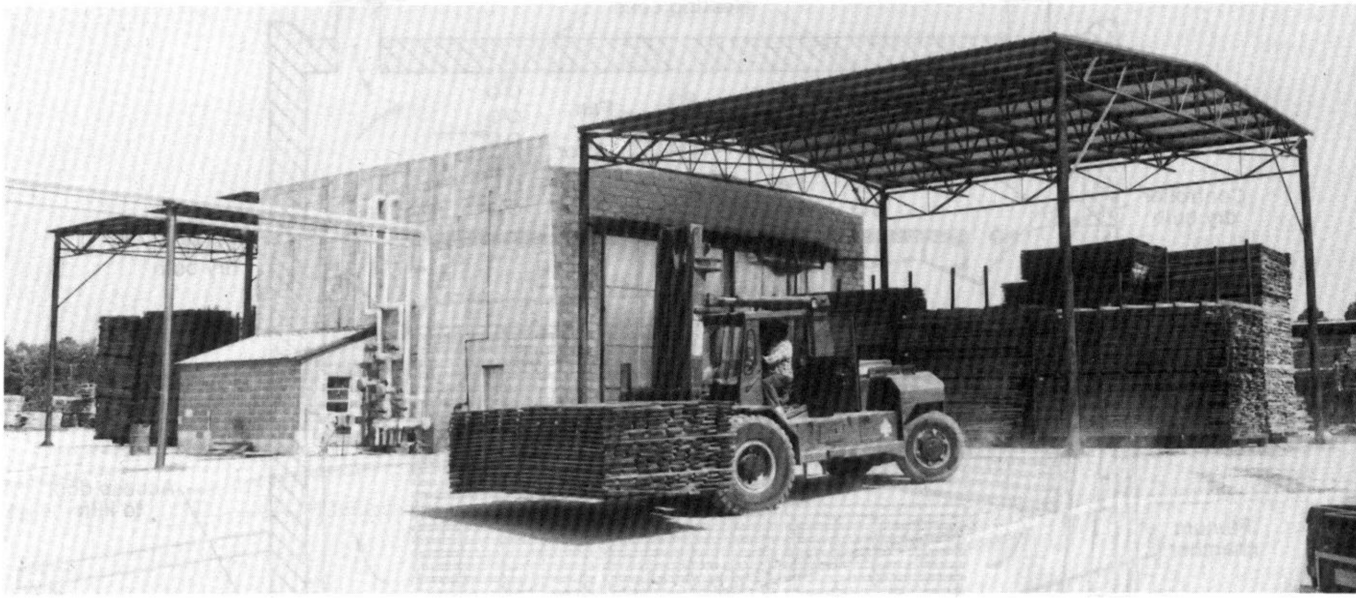


Figure 2-8—Track-loaded, concrete block kiln with doors and protective cover at both ends of kiln. (MC88 9023)

kiln, although some are designed for a depth of 16 ft of lumber. Since airflow in package kilns is from front to back, or vice versa, the length of air travel through the load is also 24 ft. No provision is generally made for reheating the air as it passes through the load. Lumber-holding capacity of package kilns varies from around 25,000 to 90,000 fbm (4/4 basis). Some frequently cited advantages of package kilns include lower building cost and use of less land area. Disadvantages include long downtime for loading and unloading and generally less uniform drying if initial wood moisture content is above 25 percent. Using shorter air-travel distances and having all lumber at about the same moisture content increase drying uniformity. If starting moisture content is below 25 percent, uniformity of final moisture content of lumber in package kilns is usually little different from that of lumber in track kilns.

Progressive Kilns

Progressive-type kilns are designed for a continuous process in which the loads of stacked lumber enter the green end of the kiln and are moved forward, usually on a daily basis, through progressively more severe drying conditions until exiting the dry end of the kiln. Each move forward is accompanied by the removal of a completed load from the dry end and the addition of a fresh green load at the green end. The temperature increases and the humidity decreases as charges move from one zone to the next along the length of the kiln. The desired schedule effect is obtained in this way. To achieve the necessary range of drying conditions, progressive kilns vary in length depending on the species and the initial and final moisture content of lumber being dried. Because of the relatively continuous movement required in this approach, progressive kilns are usually of the track-loading type. As with compartment kilns, the early models relied on natural draft circulation, but forced circulation using either internal fans or external blowers soon became the preferred method of air circulation.

Progressive kilns lack flexibility in drying kiln charges that vary in species, dimension, or moisture content. They do not provide the close control of conditions required by most hardwood operations or the speed of drying required by most softwood operations. For these reasons, there are relatively few progressive kilns operating in the United States, and no new ones have been constructed in several years.

Temperatures of Operation

Most lumber dry kilns are designed to operate within a specified range of temperatures. This range depends largely on the species to be dried and quality and end use of final products. Also considered are amount of production expected, source of energy, and limitations of certain components of the system, such as compressors and electric motors. A common classification of kilns based on maximum operating temperatures is as follows:

Low-temperature kiln . . . . 120 °F
Conventional-temperature kiln . . . 180 °F
Elevated-temperature kiln . . . . . 211 °F
High-temperature kiln . . . . above 212 °F

Regardless of the temperatures used, the basic requirements of controlled heat, humidity, and air circulation apply. Therefore, kilns of different temperature classification differ primarily in terms of the source of heat energy and the type of materials and equipment used in the kiln structure.

Low-Temperature Kilns

Low-temperature kilns typically operate in the range of 70 to 120 °F, though some may not exceed 110 °F. This classification typically includes fan dryers, predryers, shed dryers, and some types of vacuum, dehumidification, and steam-heated kilns.

Conventional-Temperature Kilns

Conventional-temperature kilns typically operate in the range of 110 to 180 °F. The majority of hardwood lumber and sizeable amounts of softwood lumber are dried to final moisture content in kilns operating in this temperature range. These include steam-heated kilns and those designs of dehumidification kilns that operate up to 160 °F. The bulk of the kiln schedules available for the various species and thicknesses are for kilns operating at "conventional temperature."

Elevated-Temperature Kilns

Elevated-temperature kilns typically operate in the range of 110 to 211 °F. The final dry-bulb temperature in a schedule for use in an elevated-temperature kiln is commonly 190 or 200 °F and occasionally as high as 210 °F. Many western softwood operations and some southern pine operations have kilns operating in this range. A few easy-to-dry hardwood species may use elevated temperatures in the final step of the schedule.

High-Temperature *Kilns*

High-temperature kilns typically operate for most of the drying schedule at temperatures above 212 °F, usually in the range of 230 to 280 °F. Perhaps the majority of southern pine lumber and increasing amounts of western softwood lumber are dried in high-temperature kilns. These kilns are more often used for drying construction-grade lumber where some surface checking and end splitting are acceptable in the grade, rather than upper-grade lumber where these defects are less acceptable. A very small amount of hardwood lumber is dried at high temperatures.

Type of Heating and Energy Source

The type of heating of lumber dry kilns and the energy source for that heat can be divided into the following categories: steam, direct fire (hot air), electricity, hot water and hot oil, and solar. Heat is required in a dry kiln for four purposes: (1) to warm the wood and the water in the wood; (2) to evaporate moisture from the wood; (3) to replace the heat lost from the kiln structure by conduction or radiation; and (4) in kilns with vents, to warm the fresh air entering the kiln.

Steam

Steam has long been the most widely used heating medium for kiln drying of lumber. Steam is moved from the boiler into the kiln by pipes, and the heat is then transferred to the circulating air in the kiln. Historically, many lumber processing operations required steam for a variety of applications, and it was therefore natural to include sufficient boiler capacity for kiln-drying operations. With the increasing popularity of electrically powered sawmills, the dry kilns are frequently the principal user of steam at an installation. In the early days of dry kilns, burning of wood waste in the boiler was the standard procedure. As oil and natural gas became more available and less expensive, most operations switched to these energy sources for their boilers. Since the "oil scare" and rising prices of the 1970's, there has been a return to burning of wood waste to generate steam. A more detailed discussion of boilers, including such items as sizing and horsepower, can be found in chapter 11. For a more complete discussion of heat transfer surfaces and how temperatures are achieved and controlled in a kiln, see Heating Systems section later in this chapter.

Direct Fire

Direct-fired heating systems differ from steam heating systems in that the heated air for the kiln originates directly from the burning of oil, natural gas, or wood waste. The heated air produced from the burning of the fuel is passed through a mixing or blending chamber to control the temperature and volume of air going into the kiln (fig. 2-5). Direct-fired systems have been used extensively for high-temperature drying of softwoods, especially southern pine. The required temperatures are easily achieved and controlled, and any discoloration of the wood caused by combustion gases is of little consequence in most softwood operations. Direct-fired systems are seldom used for drying hardwoods, primarily because these systems do not provide the close control of relative humidities generally required for proper hardwood drying.

Electricity

The use of electric power to heat a dry kiln is currently most often thought of as related to dehumidification drying systems or the type of vacuum drying systems using electric energy (radiofrequency, microwave, or electric resistance blankets). I" dehumidification systems, electricity is used to power the compressor or heat pump and the strip heaters that are frequently used to bring the kiln up to a minimum temperature for efficient operation of the compressors. For small kilns drying 500 to 1,000 fbm, designs using electric strip heaters have been suggested (Rice 1977).

Hot Water and Hot Oil

Some kilns are heated by hot water rather than steam. These systems have much lower drying efficiency and are not commonly found in typical commercial operations. However, hot water heating systems are sometimes found in smaller homemade or do-it-yourself installations where steam generation is regarded as either impractical or too expensive.

Few lumber dry kilns in the United States use the hot oil system, although interest in using this system has increased since the mid-1980's, particularly in plants that have both particleboard presses and dry kilns.

Solar

In the United States and Canada, use of solar energy to heat a lumber dry kiln is limited to small operations or hobbyists where drying large quantities of lumber on a tight production schedule is not required. Interest in totally solar-heated kilns or solar-assisted kilns is much higher in tropical countries, especially those where more traditional forms of energy are very expensive or are not readily available.

General Construction Features

Construction Materials

Dry kilns are constructed of a number of materials, including aluminum prefabricated panels, concrete block, poured concrete, brick, wood, and plywood. Various kinds of vapor barriers are used to restrict movement of water vapor from inside the kiln into the strutural members and panels and thus prevent deterioration of the structure. To have acceptable efficiency, kilns must be reasonably well insulated against loss of heat through the structure. In addition, doors and other openings must fit tightly to minimize loss of heat and humidity. The choice of building materials is frequently governed by such things as operational temperatures required for the species and thicknesses to be dried, life expectancy of the kiln, capital investment, insurance, source of energy, and type of heating system.

Aluminum

Many kilns constructed in the last decade use prefabricated aluminum panels with fiberglass or some form of rigid foam insulation. The panels are joined together and bolted to structural load-bearing members of either steel or aluminum (figs. 2-4 to 2-7). fill-length wall and roof panels are manufactured (prefabricated) in standard dimensions for rapid installation on site and to give flexibility in kiln size. All connecting joints should be designed to minimize heat losses and to allow for expansion and contraction of the metal with changing temperature. This ability to withstand expansion and contraction without damaging the structure makes aluminum the preferred construction material for kilns expected to be operated at high temperatures (above 212 °F).

Kiln doors are of similar lightweight, insulated, aluminum panel construction, mounted in a steel or aluminum frame, with additional bracing for strength and rigidity. Most doors are moved by hangers, which are connected to rollers operating on a rail over the door opening. Some type of flexible gasket is generally used around the opening to minimize air infiltration and leakage.

Because aluminum is extremely resistant to corrosion, no special vapor sealants or moisture barriers are required. However, regular inspections are needed to ensure that no leaks develop in the joints, and any punctures or tears in the skin of the panel need to be repaired to prevent moisture from the kiln atmosphere passing through to the insulation and reducing its effectiveness. If a steel supporting structure is used, usual precautions of applying a good paint or sealer must be observed to protect the steel from the corrosive atmosphere found in most kiln environments. Particular attention should be paid to locations where the steel support structure comes into contact with sources of cold temperature (where condensation will occur on the steel), such as around doors and the first 12 to 18 inches above floor level of the vertical support columns.

Concrete Block, Poured Concrete, and Brick

Concrete block, poured concrete, and brick, which are sometimes known collectively as masonry, have historically been used for construction of low-temperature, conventional-temperature, and elevated-temperature dry kilns (figs. 2-2, 2-3, 2-8). Concrete block filled with some type of insulation material, such as vermiculite or rigid foam, is currently the most common type of masonry kiln. Kilns with poured concrete walls are occasionally seen, but the use of brick has largely fallen from use. Masonry kilns may have either load-bearing or nonload-bearing walls. Where walls are nonload bearing, the block or brick is laid between structural steel members that support the roof beams or trusses. Masonry materials should be of high quality, taking into consideration such factors as durability, insulating properties, and resistance to moisture, humidity, and temperature fluctuations. A high quality mortar must also be used. To protect the masonry against humidity and condensation and to reduce heat and vapor transmissions, the interior walls and ceiling must be given one or two coats of a specially formulated heat- and vapor-resistant kiln paint or coating. Some designs suggest an inside coating of lightweight concrete to improve insulation and to retard moisture movement into the concrete block. Such designs also require a vapor-resistant coating. Expansion and contraction of these masonry materials during routine kiln operation can cause cracks, which should be sealed promptly to prevent further deterioration of the wall and roof. Largely because of this expansion and contraction, masonry materials are not usually chosen when constructing high-temperature kilns.

Roofing materials for masonry kilns are frequently prefabricated aluminum panels or a “built-up” roof consisting of a layered composite of roofers’ felt, vapor barrier, and insulation on top of wood, reinforced concrete slabs, or metal decking.

Kiln doors on newer masonry kilns are frequently the same type of aluminum prefabricated panel doors as those used on aluminum prefabricated kilns. Some older kilns may have doors constructed of insulated wood panels; however, these doors are heavy and deteriorate with time.

Wood and Plywood

The use of wood for kiln construction is usually limited to low-temperature applications where inexpensive, short-term installations are planned, and where small, possibly homemade facilities are considered adequate. Plywood interiors in metal or wooden buildings are fairly common in dehumidification kilns. Construction for dehumidification kilns requires insulation values of R-20 or more for walls and roof; higher values are needed in colder climates. Vapor barriers must be extremely tight for efficient operation, and great care must be given when installing to ensure proper joints.

Foundations and Floors

Kilns must be built on a firm foundation to prevent shifting and settlement. The structural misalignment and cracks caused by settling of the foundation are ‘more serious in kilns than in many other types of construction. Misalignment of kilns throws the track system out of line in track-loaded kilns, which creates serious problems when moving kiln trucks. Misalignment of kilns with lineshaft fan systems can also cause wear and maintenance problems in the fan system. Settling of the structure can cause cracks, which cause heat loss and problems in humidity control.

Foundation footings and walls are almost invariably made of concrete. Their width or bearing area is determined by the character of the soil and by the loads to be imposed upon them.

Most kiln floors are made of poured concrete, usually 6 in thick. Placing some form of insulation under the concrete floor is an increasingly common practice. This reduces heat loss and helps to prevent condensation of water on the kiln floor in the early part of the kiln run when the relative humidity of the air is high and the floor may be cold.

In some cases, a thick layer of crushed stone may be used. In package-loaded kilns, which use lift trucks to load and unload lumber, floors made of crushed stone are difficult to maintain. Uneven floors can cause lumber stacks to lean, resulting in poor drying, or to fall, damaging the structure or injuring workers. Another disadvantage of crushed stone is that heat is more readily lost to the soil or, alternatively, moisture from the soil enters the kiln when kiln humidity is low. However, crushed stone does permit rapid drainage when condensation and water from melting snow or ice accumulate in the kiln during warmup.

Heating Systems

The drying of lumber requires the removal of large quantities of water from the wood. For example, drying southern pine dimension stock green from the saw to 15 percent moisture content requires the removal of 1.92 lb (0.23 gal) of water per board foot (24.9 lb/ft^3). Drying l-in-thick red oak lumber green from the saw to 7 percent moisture content requires the removal of 1.83 lb (0.22 gal) of water per board foot (22 lb/ft^3). Since the heat of evaporation of water is approximately 1,000 Btu/lb, great quantities of heat energy must be generated and transferred to the circulating air and to the wood in the drying process. This section discusses the mechanism of heat energy transfer from the generating source into the kiln and types of heat transfer surfaces.

The principal methods of conducting heat into the kiln are (1) indirect, where a hot fluid (commonly steam) flows into the kiln through pipes and radiates heat to the kiln atmosphere through a suitable radiating surface, and (2) direct, where hot gases are discharged directly into the kiln atmosphere.

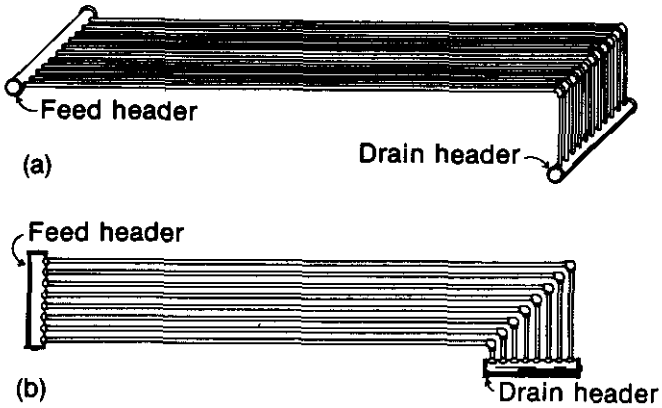


Figure 2-9—Headers with heating coils. (ML88 5599)

Indirect Heating

Perhaps the best examples of hot fluids used in indirect heating systems are steam, hot water, and hot oil. Steam systems are by far the most common in lumber drying, though systems using hot water or hot oil are occasionally found.

Steam.-Steam is used at various pressures. Since the temperature of steam varies with different levels of pressure, more radiating surface is required to maintain a given heat transfer rate or operating temperature with low-pressure steam than with high-pressure steam (see ch. 11 for a more detailed discussion of energy).

Steam is transported from the boiler to one or more kilns through large insulated pipes, often called the main feedline. At the kiln, steam enters one or more distribution header pipes, from which each bank of heating pipes originates (fig. 2-9). A condensate header is located at the opposite end of the bank of pipes. Plain iron pipes were the standard material for radiating surfaces for many years, but now finned pipe heating coils are used almost exclusively (figs. 2-10, 2-11). Depending on diameter and other factors, finned pipes are considered to have from four to eight times the radiating capacity of conventional black iron pipes. Finned pipes are made of iron, aluminum, or copper piping, which are wound with thin metal strips or attached to discs by welding or pressing to increase the heat transfer surface. Fins are made of various materials. Heavy gauge steel is the most rigid and serviceable but is subject to corrosion, and aluminum is an excellent heat conductor but much more subject to damage. The heat transfer rate of aluminum fins is twice as great as that of steel fins. Copper is an excellent conductor but is generally considered too expensive for extensive use in lumber dry kilns and is easily damaged because of its softness.

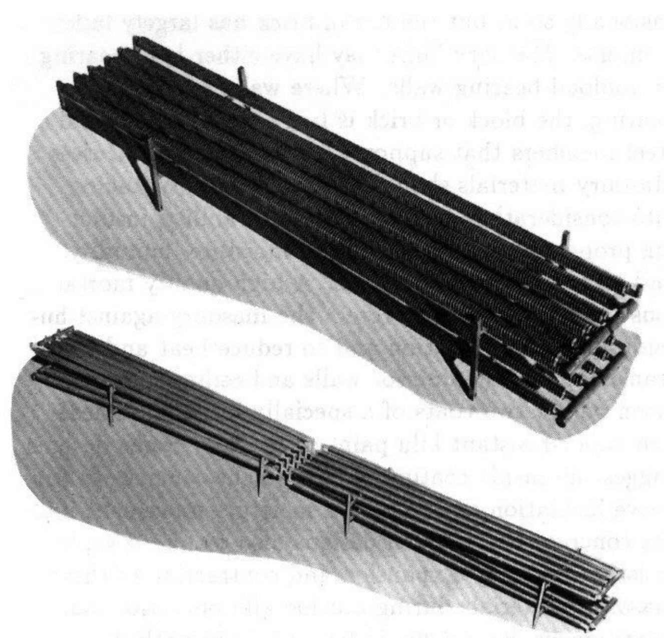


Figure 2-10—Return-bend heating coil made with fin pipe. (M 106142)

The return-bend heating system has historically been the most common arrangement of steam pipes within a kiln (fig. 2-10). In this system, the banks of pipes leave the distributing header, extend the length of shorter kilns, and return to a discharge (condensate) header. In longer kilns (over 66 ft), a return-bend header is at each end of the kiln, such that returns meet in the middle of the kiln (fig. 2-10, bottom).

It is now considered better practice to divide the heating coils into banks of shorter length, single-pass coils (fig. 2-11) rather than return-bend coils. These short banks can be separately valved and thus produce more uniform temperatures along their length than do long coils.

As heat is transferred from steam through the coils to the kiln atmosphere, the temperature of the steam drops. It cools to the point of condensation, and water (condensate) begins to gather along the length of the coil, providing the opportunity for uneven heating in the kiln. Thus, all horizontal coils should be installed with a downward pitch varying from 1/8 to 1/4 in per foot of coil length to allow for drainage of condensate.

In multiple-track kilns where the circulating air passes through more than one truckload of lumber, it is good practice to install booster or reheat coils between the tracks (figs. 2-1 to 2-3, 2-12). The coils may be arranged either vertically or horizontally and serve to maintain a more uniform temperature within the kiln.

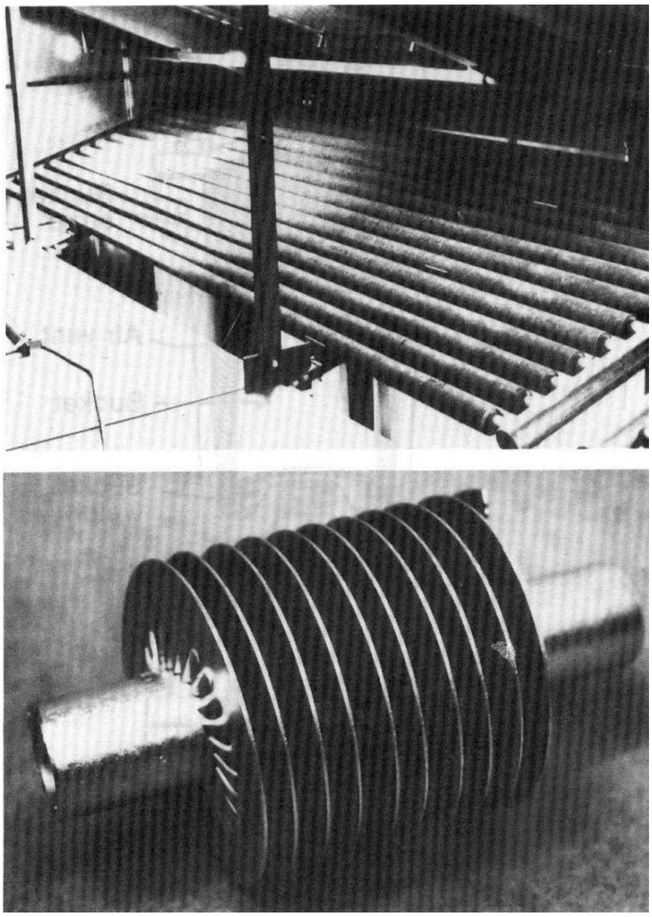


Figure 2-11—Horizontal single-pass header coils and enlarged view of coils. (MC88 9027)

Hot water and hot oil—In hot water and hot oil systems, the liquid is circulated by pumps through heating coils similar to those used in a steam kiln. The lower amount of heat available from hot water (where no latent heat is present) in comparison with steam requires a greater radiating surface. Maximum temperature attainable in the kiln is about 180 °F, which is adequate for many operations. However, few of these systems are currently in use in the United States. Hot oil systems work on the principle of pumping heated oil through the heating coils in the kiln, though temperatures considerably higher than hot water can be attained.

Direct Heating

In direct-heated kilns, the hot gases produced by burning gas, oil, or wood waste are discharged directly into the kiln. These hot gases frequently pass through a mixing or blending chamber to control temperature and volume of air entering the kiln.

Burners commonly have electrically or pneumatically modulated fuel valves, which operate in connection with the recorder-controller. The fuel and air supply

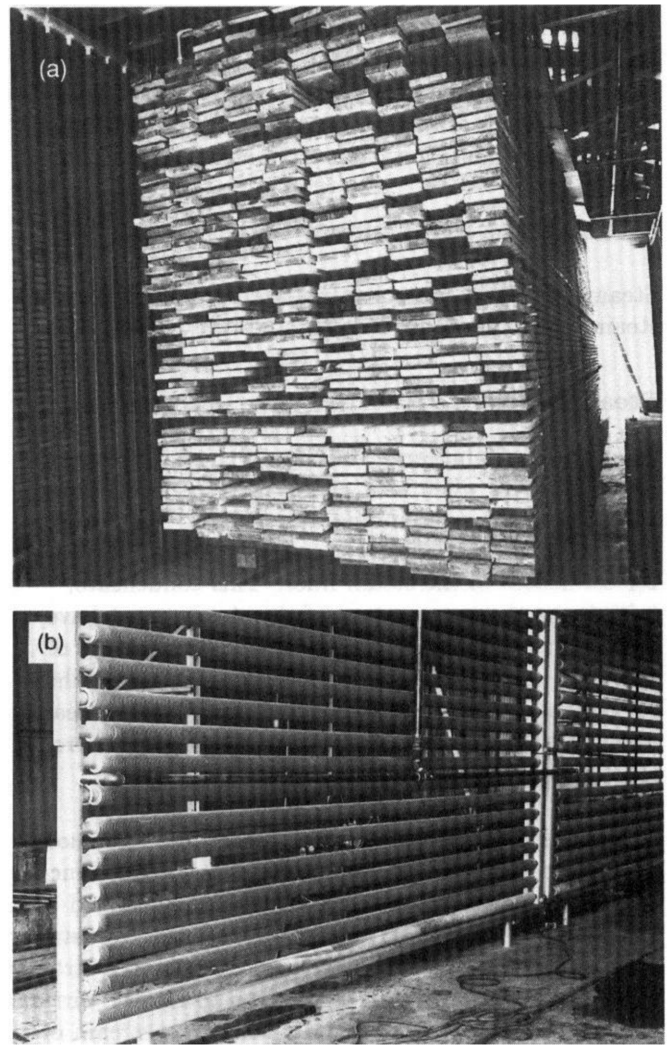


Figure 2-12—Booster coils. (a) Vertical booster or reheat coils between loads in track-loaded kiln. (b) Booster coils in horizontal position. (MC88 9032, MC88 9033)

for combustion is regulated to maintain the desired kiln temperature. Some designs use several burner nozzles, which can be operated individually or the series modulated over a wide turndown range. Many burners are designed to utilize wood waste and oil or gas interchangeably.

In the blending chamber the hot products of combustion are mixed with the circulating air, raising its temperature to the point where subsequent mixing in the kiln will produce the required temperature as governed by the dry-bulb control mechanism. Temperature-limit switches on the inlet and discharge ends of the combustion chamber shut down burners if they overheat. The discharge air is usually limited to a maximum of 425 to 450 °F. A centrifugal blower forces the heated air from the burner through ducts to a plenum chamber, which distributes the air to the circulation fans (fig. 2-5). Most kiln air makes repeated circuits through the lumber piles, and only a portion is returned to the heating chamber, usually by means of a collecting plenum running the full length of the kiln. As mentioned earlier, in some designs the heat energy is transmitted from the burner through a heat exchanger to the circulating air to prevent combustion gases from entering the kiln.

Steam Traps and Control Valves

Steam traps and control valves are used to conserve steam and regulate its flow through the heating coils.

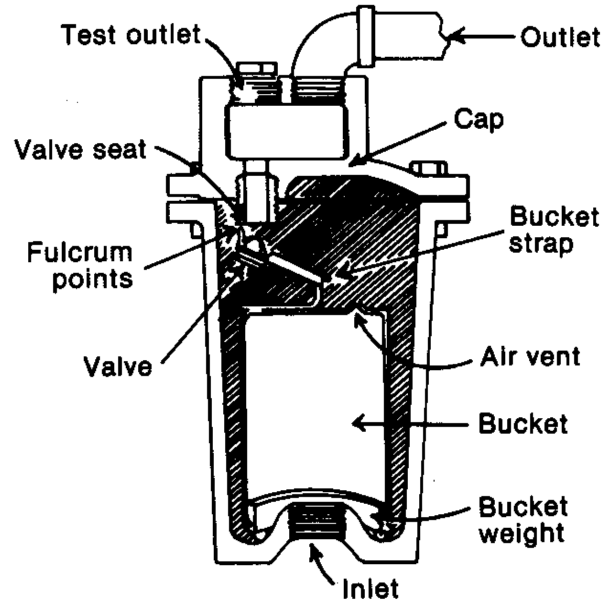
Steam Traps

In any steam kiln, large volumes of condensate form as steam cools when heat energy is transferred from the coils to the surrounding atmosphere. For every 1,000 Btu of heat delivered, approximately 1 lb of water condenses in the steam lines. This condensate, initially at the temperature of the steam, must have a controlled discharge, otherwise the temperature of the coils would drop as they fill with condensate thus preventing the entry of the higher temperature steam. Steam traps operate like automatic valves to control the flow and discharge of steam.

Steam traps are installed in the drain lines to remove condensate without the loss of steam. Another function of steam traps is to release trapped air mixed with the steam. Steam traps should be installed downstream from and below the coils. For best operation, a strainer must be placed upstream of the trap to remove dirt and oil, and a check valve must be placed downstream of the trap to prevent back pressure or reverse condensate flow. A blowdown valve should be provided to periodically clean out scale and debris from the line. All heating coils should be individually trapped to prevent the condensate from short circuiting from one coil to another. The return line to the boiler must be large enough to handle peak loads of condensate.

Proper sizing of steam traps for dry kilns is extremely important and is more difficult in a dry kiln operation than in many other applications of steam traps. It is just as harmful to oversize a trap as it is to undersize. Undersizing a trap retards the discharge of condensate, which results in a slow and waterlogged heating system. Oversizing a trap causes a discharge of some steam with each discharge of condensate, which interferes with efficient operation of the heating system and wastes energy.

Steam traps generally used on dry kilns are of three types: mechanical or gravity, thermostatic, and thermodynamic.



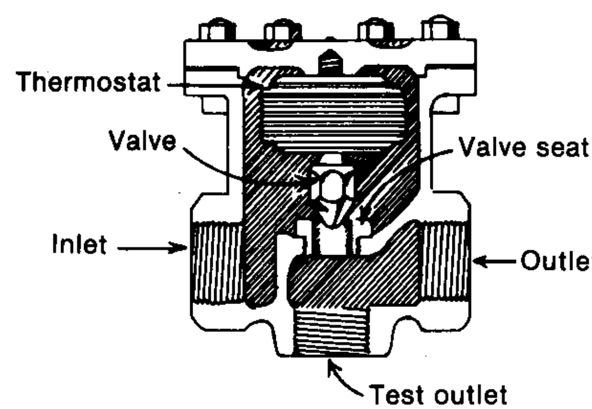


Figure 2-14—Thermostatically controlled steam trap. (ML88 5596)

The mechanical or gravity-type traps often used on dry kiln heating systems are of the inverted bucket or open-bucket design. The inverted bucket design (fig. 2-13) has generally superseded the open-bucket type and is the most commonly used mechanical trap. As steam condenses in the heating system, the condensate flows into the trap. When the trap is filled, the condensate discharges through the outlet pipe. As soon as the system is free of condensate, steam enters the inverted bucket. The pressure of steam causes the bucket to rise against the valve arm until the valve closes the discharge port. Air trapped in the bucket escapes through a vent in the top of the trap. Condensate again begins to flow into the trap, displacing the steam in the bucket. This reduces the buoyancy of the bucket until it again rests on the bottom of the trap. The discharge valve then opens and allows the condensate to be discharged. Since the air in the top of the trap es capes before the condensate does, air binding is kept to

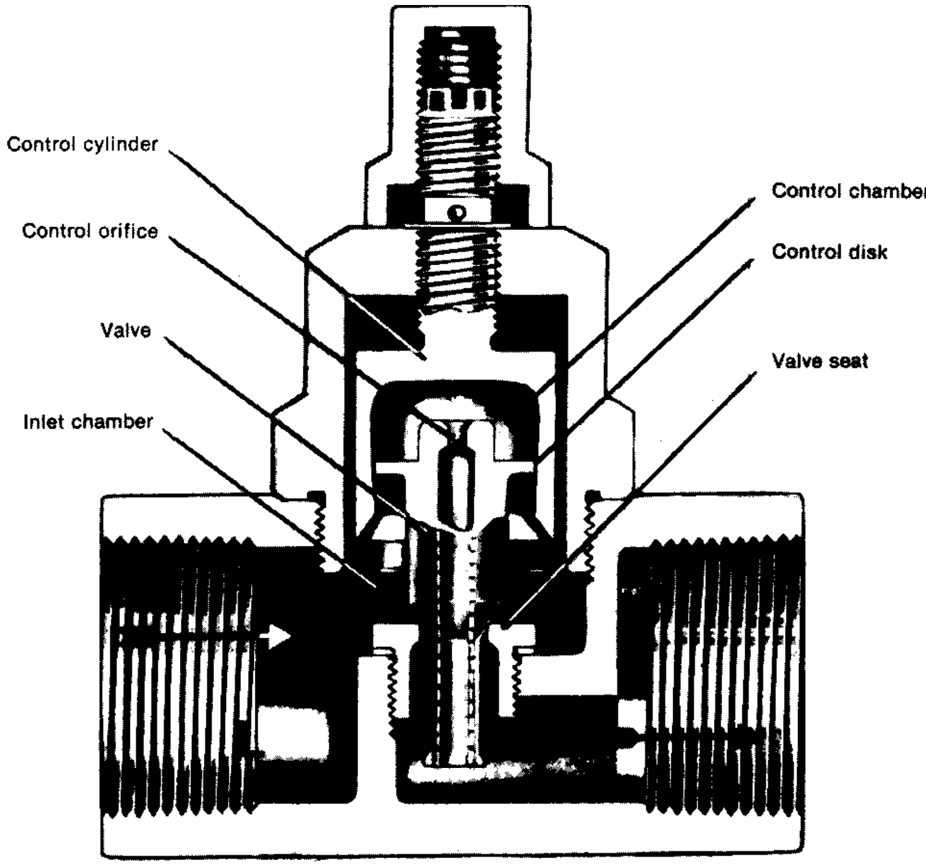


Figure 2-15—Impulse steam trap. (MC88 9038)

a minimum. Because bucket-type traps contain liquid condensate or water, it is important to provide adequate insulation in colder climates to prevent freezing of the water and damage to the trap.

In a typical thermostatic trap (fig. 2-14), a bellows that expands or contracts with changes in temperature is attached to a valve stem and valve. As the bellows expands or contracts, it closes or opens the valve. When the heating system is first turned on, the coils and trap are cold and contain air and water. At this point, the bellows are contracted and the valve is open. As steam enters the heating system, it displaces the water and air and forces them through the open valve. When all the air and water have been discharged, the trap is filled with live steam. By then the trap temperature has increased enough to cause the bellows to expand, closing the valve and preventing loss of steam through the trap outlet. After the valve is closed, condensate again begins to accumulate and cool the bellows. This contracts the bellows enough to open the discharge valve, and the cycle is repeated.

The third type of trap is the thermodynamic or impulse design (fig. 2-15). The flow of condensate through this trap is controlled by differences in pressure between the inlet chamber and the control chamber. When the steam is off and the trap is filled with air, the pressure is the same in the inlet as in the control chamber, and the control valve rests firmly against the valve seat. When condensate enters the trap, the pressure in the inlet chamber becomes greater than that in the control chamber. The pressure on the underside of the control disk lifts the control valve free of the valve seat, and air and condensate pass through the valve opening into the discharge line.

The control cylinder has a reverse taper that adjusts the flow of condensate around the control disk and into the control chamber, until the pressures above and below the disk are balanced. The temperature of the condensate then increases because of the hot steam behind it. The hot condensate entering the lower pressure control chamber flashes into steam, which increases in volume and retards the flow of condensate through the control-valve orifice. When the downward pressure on the upper surface of the valve and valve disk exceeds the upward pressure on the rim of the valve disk, the valve is forced downward, shutting off the flow of condensate through the main orifice. The temperature in the control chamber then drops, and the cycle is repeated.

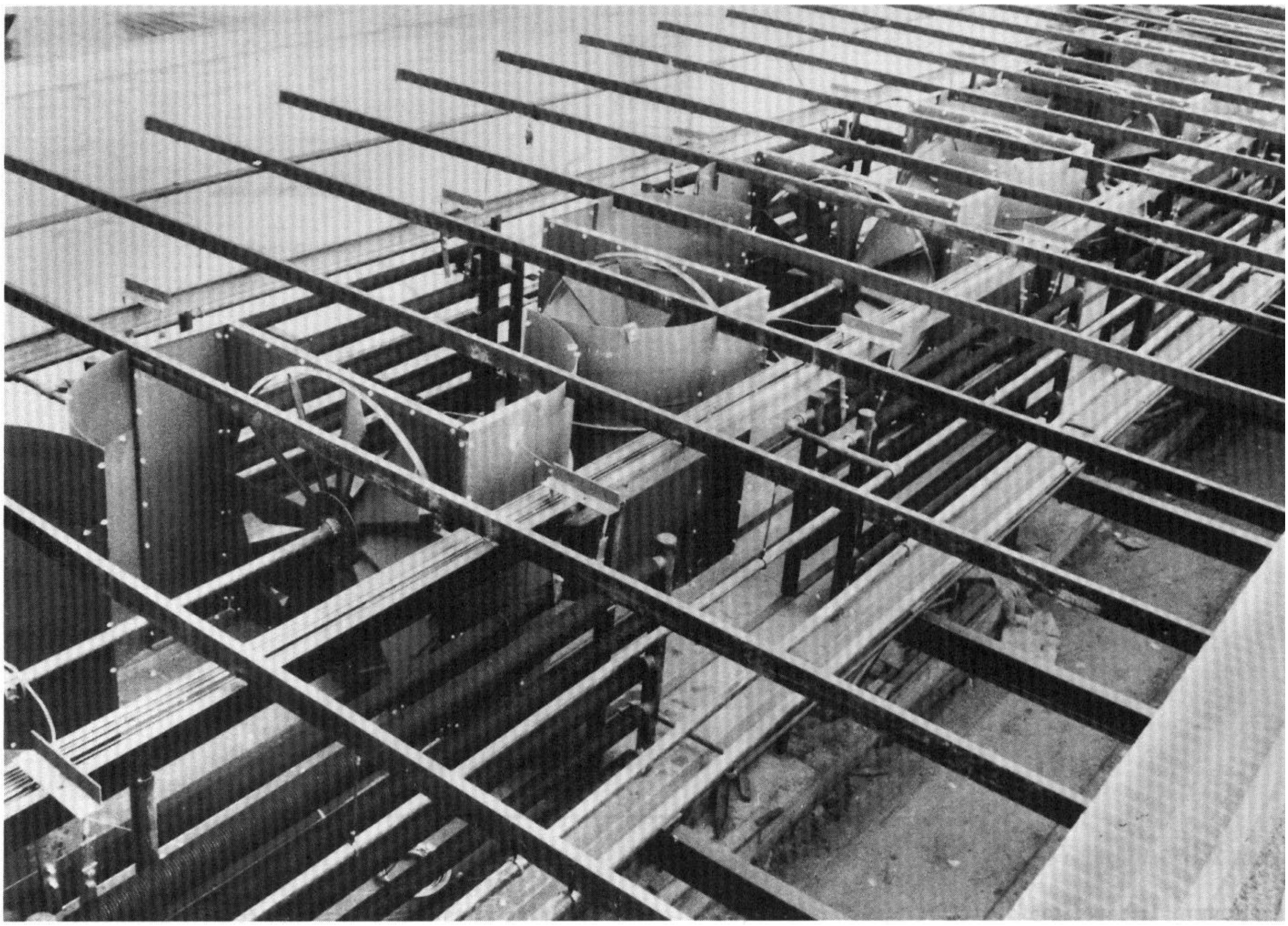


Figure 2-16—Fans in lineshaft arrangement showing disc fans and zig-zag baffle-shroud system, which directs the air through the lumber in either direction depending on fan and motor rotation. (MC88 9022)

Control Valves

Both manually and automatically operated valves are used to control the flow of steam into the coils. Pressure regulators and reducing valves are also used to control the pressure of the steam.

Steam flow is regulated by automatically controlled air-operated or electrically operated control valves coupled to the recorder-controller (see section on Equipment to Control Drying Conditions). Hand-operated gate valves are usually installed upstream of the control valves for "on-off" control of the steam supply. Hand valves are also advantageous on the feed and drain lines of individual heating-coil banks, especially in hardwood drying operations. These hand valves enable operators to close certain banks for better control at lower temperatures, thereby reducing excessive fluctuations in temperature due to overshoot of the dry bulb when all banks are open. The ability to isolate banks of coils also permits damaged or leaking ones to be removed and repaired without disturbing the remainder of the heating system.

Air-Circulation Systems

To dry lumber, air of controlled temperature and humidity must be passed uniformly over its surface. This circulating air is the "workhorse" of the dry kiln. As such, the air performs two functions: it carries heat to the wood to effect evaporation, and it removes the evaporated water vapor. Effective and uniform circulation of air involves several factors: the size, location, and speed of the fans to drive the air; provision for reversal of air circulation; installation and use of baffles to direct the air through the load; and placement of stickers within the load to facilitate the movement of air across each piece of lumber.

Kiln Fans

In modern kilns, fans can be classified in two broad categories: internal fan kilns, that is, fans located inside the kiln itself; and external blower kilns, a system where the fan or blower is located outside the kiln and the air is conducted into the kiln through ducts.

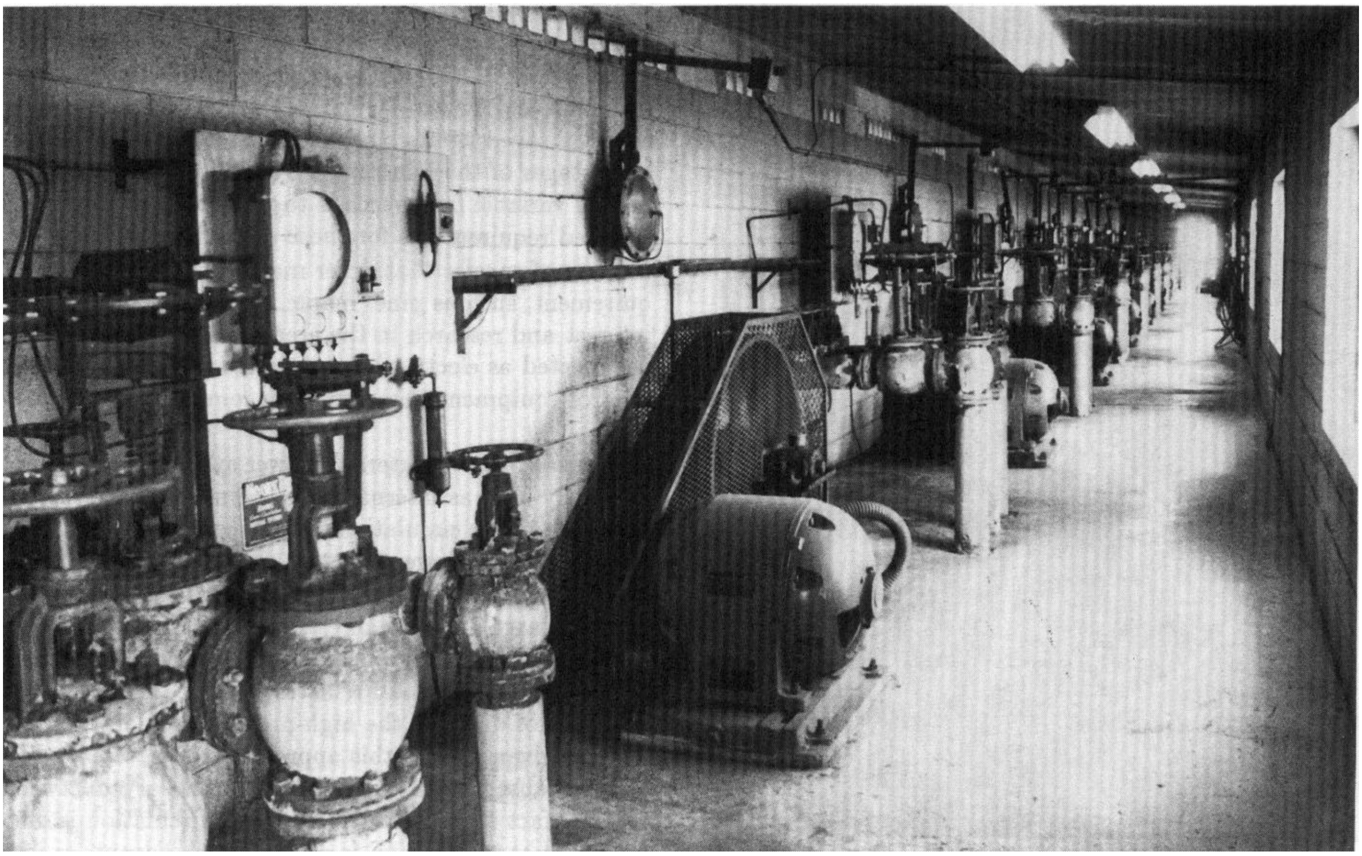


Figure 2-17—Control room for battery of lineshaft kilns, showing motor and pulley on lineshaft, recorder-controller, air-operated control valves to headers, hand-operated valves, and air-motor controlling vents. (MC88 9021)

Before discussing different types of fans in these two categories, it may be helpful to review the following laws regarding fans: (1) the volume of air moved varies directly with the fan speed in revolutions per minute (rpm), (2) the static pressure varies with the square of the fan speed, and (3) the horsepower varies as the cube of the fan speed and directly as the air density. For more detailed discussion of fan engineering and power consumption, see chapter 11.

Internal fans.-For internal fan kilns, there are two principal arrangements of the fans: lineshaft and cross-shaft. In both of these arrangements, the fans are typically placed overhead, with a false ceiling or deck between the fans and the load of lumber but not extending beyond the edge of the lumber (figs. 2-1 to 2-3, 2-5, 2-6).

In the traditional lineshaft arrangement, a series of multibladed disc fans (up to 84 in. in diameter in some large softwood kilns) is mounted on a single shaft running the full length of the kiln. The fans are alternately a left- and right-hand design. They are housed in a zigzag baffle-shroud system that directs the air across the kiln (figs. 2-2, 2-16). So that air circulation may be reversed efficiently, the fans are designed to operate in either direction. The motor, usually 50 to 75 horsepower, is generally located in the operating room or control room at the end of the kiln (fig. 2-17). This type of lineshaft arrangement provides for moving large volumes of air at low speeds (up to 400 ft/min through the load) with a minimum of power, and it is particularly suited to drying lumber with low initial moisture content or a species that needs to be dried slowly.

In a more recent adaptation to the lineshaft arrangement, propeller-type fans are mounted on the lineshaft (fig. 2-18). This modification can deliver upwards of 800 ft/min through the load, and the propeller-type fans are considerably more efficient per motor horsepower than disc fans. When changing from disc to propeller-type fans in retrofit operations, it may be necessary to change the type of bearings used for the shaft.

In the cross-shaft arrangement, fans are mounted on individual shafts aligned across the width of the kiln (figs. 2-3, 2-5). Each fan is driven by an individual motor (usually about 7.5 hp) either belt driven or direct connected. The motor may be mounted inside or outside the kiln. Motors mounted inside the kiln must be of special construction to withstand high temperatures, especially in kilns operating above 200 °F. With externally mounted motors, consideration should be given to offering some protection from the weather, particu-

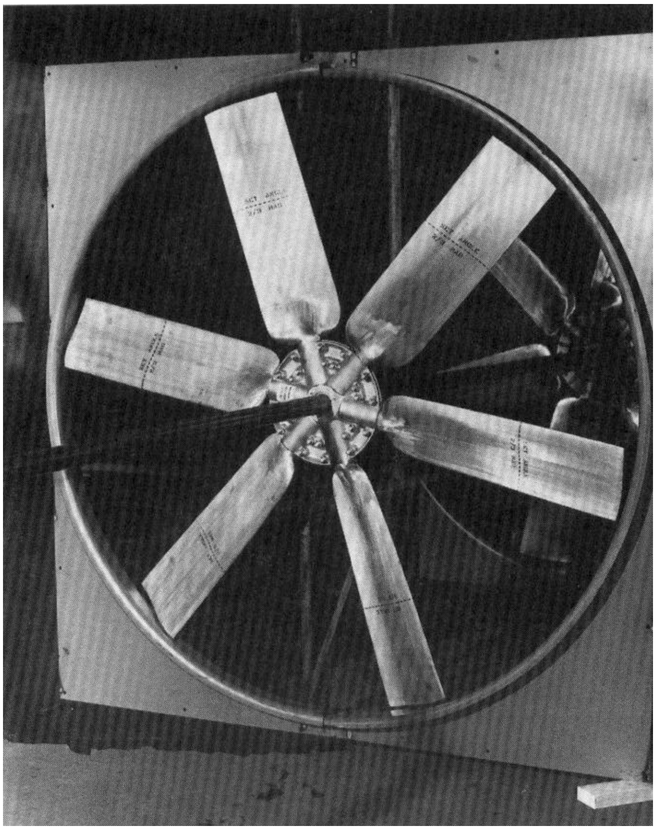


Figure 2-18—Propeller-type fans mounted on lineshaft. (MC88 9020)

larly in colder climates where freezing of condensed water vapor on the motor or shaft may present problems. Either multiblade-disc or propeller-type fans are commonly used for cross-shaft kilns. They can deliver large volumes of air at speeds considerably higher than the fans found in the traditional lineshaft kilns. With the modern trend to higher air velocities, especially desirable in the high-temperature kilns, propeller-type fans are becoming increasingly popular. These fans have two to six blades, some of which have adjustable pitch; are made of cast aluminum; operate at high revolutions per minute; and are capable of producing air velocities of 1,500 ft/min or more (fig. 2-19).

Traditionally, kilns have been designed such that fan speeds and thus the velocity of air through the load of lumber do not change during the time of the kiln run. However, for the most efficient drying, higher airspeeds are needed during the early stages of drying when the wood is wet and large quantities of water need to be evaporated. Later in the drying schedule, lower airspeeds are adequate as the wood becomes drier and less moisture needs to be evaporated. As electrical energy costs have increased over the last decade, there has been increasing interest in installing control equipment on fan motors so that fan speeds can be adjusted during the run, thus saving on energy costs. The amount of savings appears to be higher in softwood drying, which generally starts with relatively high moisture content woods that can be dried rapidly with minimal drying degrade. In hardwood drying, which uses milder schedules and slower drying, less energy costs are apparently saved through reduction in fan speeds in the later stages of the kiln run. Perhaps the greater advantage of variable fan speeds is to provide flexibility in airspeed requirements for those operations that dry a number of species that differ markedly in airspeed requirement, such as pine, maple, and oak. Continuing interest and research in the area of variable speed fans is expected as electrical energy costs rise and cost of control equipment becomes more competitive.

External fans.—External blower systems, though not as widely used as internal fan systems, offer another approach to air circulation. These commonly use only one motor and blower to move air into the kiln. In this system, air is drawn from the discharge side of the load through large ducts to an external centrifugal blower, from which the air is passed over the heater, humidified to the proper level, and redistributed in the kiln by another set of ducts to the high-pressure side of the load. The disadvantages of this approach are the low air velocities caused by the length of the necessary ductwork and the fact that the direction of air circulation is difficult, if not impossible, to reverse. The advantage of this approach is that the air circulation system (the major moving parts of a kiln) is concentrated in an easily accessible place and can be readily serviced.

Baffles

To achieve uniform and, where desired, rapid drying, the properly heated and humidified air must be uniformly directed to and through the lumber. To do this effectively, all alternate flow paths must be blocked so that airflow over, under, and around the load is prevented. The best practical way to do this is by using hinged baffles. The lack of effective use of baffling is one of the major causes of uneven or too slow drying. Airflow under the load in a track-loaded kiln may be prevented by having baffles hinged to the floor that can be turned up against the kiln trucks to prevent air bypassing under the load. An alternative is to construct the floor of the kiln with a trough just wide enough to accommodate the rails and trucks and high enough so that the lowest course of lumber just clears the level of the floor (fig. 2-2). The use of ceiling-hinged baffles arranged so their lower free edge rests on the top of the load is an effective way of preventing airflow over the top of the load. As the load shrinks during drying, the baffles must have the ability to move down to keep contact with the load (fig. 2-6). Airflow around the ends of the load can be prevented by mounting bifold-hinged baffles in or near kiln corners, ensuring contact with the ends or corners of the load. A real effort should be made to construct all kiln loads so that no holes or

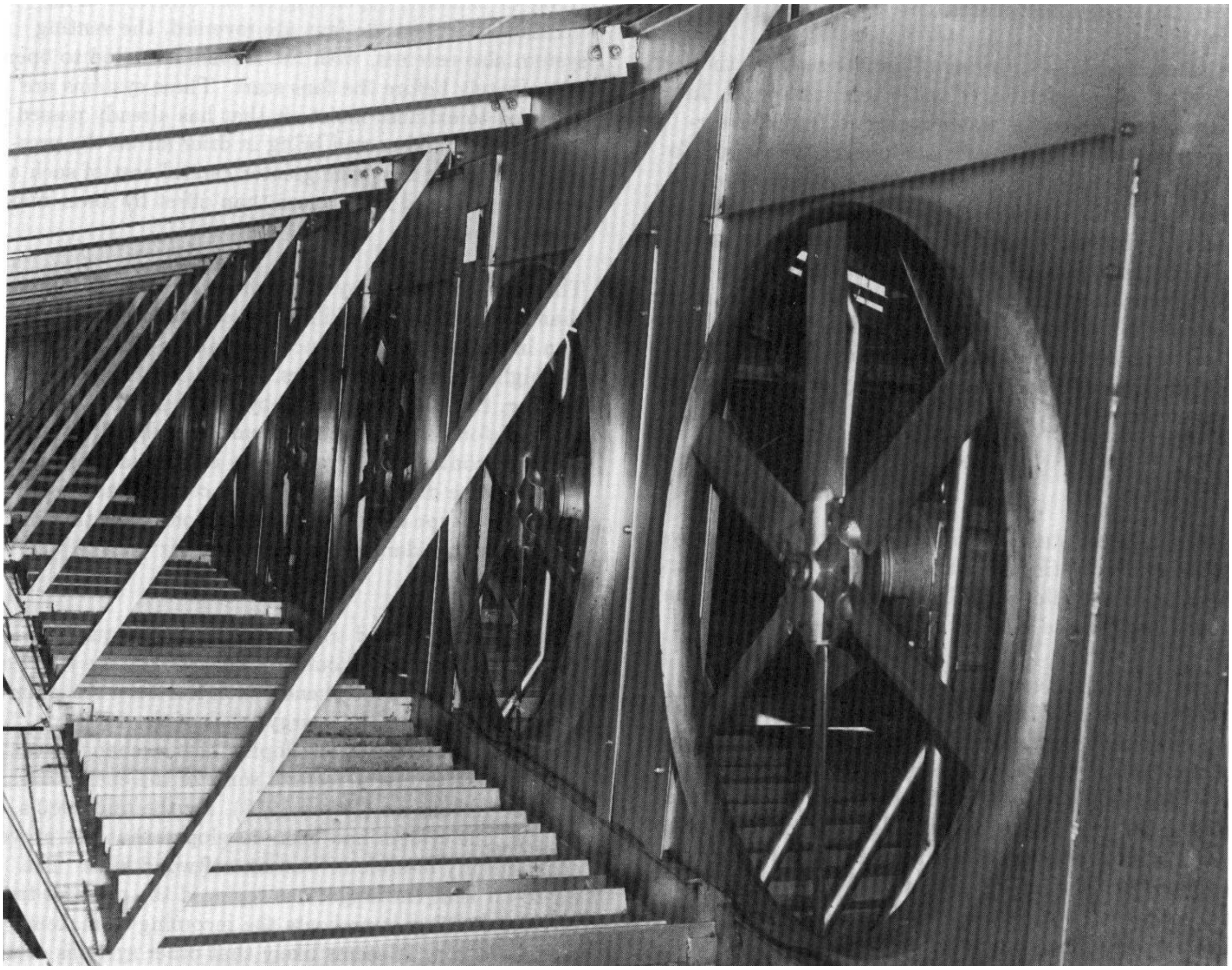


Figure 2-19—Propeller-type fans of cast aluminum in cross-shaft arrangement. (MC88 9019)

gaps occur between stacks because of mixed lumber lengths or stacks of uneven height.

Considerable care must be taken by personnel unloading the kiln to make sure all hinged baffles (floor, ceiling, and end) have been moved away from load before starting to move the load out of the kiln. Failure to do so results in baffles being ripped off or damaged. If baffles are damaged, they should be replaced immediately so that uniform air circulation can be maintained.

Plenum Chamber

The proper design and use of the plenum chamber or plenum space are necessary for adequate and uniform air circulation in a kiln. The plenum chamber is the space between the lumber and the wall on either side of a track-loaded kiln or between the lumber and the door or wall in a package-loaded kiln (figs. 2-2, 2-6). This area provides space for the fans to build up slight air pressure before passing through the courses of lumber, thereby improving the uniformity of air distribution through the load. When the fans reverse direction, the positive pressure reverses sides; the other side is always under slightly negative pressure. The plenum chambers should be wide enough so that the static pressure built up in them is sufficient to ensure uniform air flow across the loads from bottom to top. A frequently heard rule-of-thumb for estimating plenum width is that the width of the plenum should be equal to the sum of the sticker openings. Thus, if the sum of the sticker openings from top to bottom on one side of the load is 60 in, the plenum on that side should be about 60 in wide. A properly designed and loaded kiln will have adequate plenum space.

It would be a mistake in loading package kilns to put an extra row of packages in what should be the plenum space on the door side. This results in improper and nonuniform air circulation, and it is a practice to be strongly discouraged.

Venting and Humidification Systems

As mentioned before, drying of lumber requires the removal of large quantities of water from the wood. In conventional kilns, the water is carried from the surface of the wood by the air passing over the wood. To achieve proper drying of lumber, the amount of moisture in the kiln atmosphere (humidity) must be precisely controlled. When the humidity inside the kiln is higher than desired, the excess moisture is vented to the outside atmosphere and replaced with air from the outside. When the humidity inside the kiln is lower than desired, additional moisture is added to the kiln atmosphere by a steam spray or water spray-atomization.

Venting

Excess kiln moisture can be vented in one of two ways: (1) by static venting with the fans required for air circulation in the kiln or (2) by pressure venting with an additional fan and ductwork.

In static venting, vents are placed in the roof on the intake and exhaust sides of the fans. When the vents are opened, fresh air is drawn in on the suction side of the fan and moist air forced out on the pressure side (figs. 2-1 to 2-3, 2-5). When the direction of rotation of the fans is reversed, the flow of air through the vents is also reversed. The size and number of vents required depend on the species to be dried, that is, the amount of water to be removed from the wood. Species with large quantities of water, such as most pines and poplars, require more ventilation than species with lower initial moisture content, such as oak or hard maple or woods that have been air dried or partially dried in a predryer. Kilns may have one or two lines of vents running the length of the kiln depending on the fan arrangement (lineshaft (fig. 2-2) or cross-shaft (figs. 2-3, 2-5, 2-6)). Each line is automatically opened and closed by pneumatically or electrically powered motors activated by the recorder-controller system. In some cases, an additional row or two of manually operated vents are located on the roof. Opening these vents can provide additional venting when drying species that require large venting capacities (such as sugar pine or white pine). Static venting is the most common method of venting currently used in dry kilns.

In the pressure or powered venting systems, roof openings are replaced with two identical metal ducts placed inside the kiln, running the full length in the zone above the fan deck. These ducts vent to the atmosphere through louvered openings. Adjustable openings along the length of each duct regulate the volume of air discharged into or withdrawn from the kiln; thus air is distributed uniformly throughout the kiln. A fan unit at the end of each duct acts interchangeably as intake or exhaust, depending on the direction of air circulation. When the fans are reversed, the venting system also reverses, with the louvers actuated to open immediately before the fans start. These systems are designed to exhaust moist air that has already passed through the lumber and bring in drier air on the pressure side of the fan. The greater capital cost of such a system is claimed to be more than offset by lower maintenance costs.

The vent system in any kiln exhausts more air volume than it draws into the kiln to accommodate the expansion in volume of cooler incoming air as it is heated to the higher kiln temperatures. In the case of powered venting, this is accomplished by the design of the fan blade airfoil. The venting system is regulated by the recorder-controller mechanism as in normal roof venting. In some direct-fired kilns, the centrifugal blower produces a type of powered ventilation by venting moisture through a damper in the return-air duct to the blower.

When venting is used to control excess moisture in the air, substantial amounts of heat energy are thrown away or wasted. This phenomenon has been recognized for some time, but the energy crisis of the 1970's increased the interest in developing heat exchangers or economizers to use or reclaim some of the energy exhausted in vent air (Rosen 1979). By the mid-1980's, at least one system had been developed that has proven economically feasible in western softwood kilns. The air-to-air heat exchanger has replaced the need for traditional venting; it preheats the incoming or makeup air to the kiln. It seems likely that other systems or improvements to this system will be forthcoming, and the effectiveness and savings in energy costs to heat kilns will increase over the next decade.

Humidification

Control of the wet-bulb temperature or humidity in the kiln is important during the drying, equalizing, and conditioning stages of the drying operation. Close control of wet-bulb temperatures is especially important in the early stages of drying hardwood species that are prone to surface checks, such as oak and beech, and to minimize surface and end checking in the upper grades of softwood species. Close control of wet-bulb temperatures is also important during the conditioning phase at the conclusion of the kiln run of any species requiring this stress-relief treatment.

As mentioned earlier, when the humidity or the wet-bulb temperature of the kiln atmosphere is lower than desired, additional moisture is added. In steam-heated kilns, humidity is usually supplied as steam spray from the same source that supplies the heating coils. Steam is ejected through special nozzles on a steam spray line located in the airstream adjacent to the circulation fans, so the spray is mixed with the circulating air before it reaches the lumber (figs. 2-2, 2-6). As with the heating system, steam spray is regulated by the recorder-controller.

If high-pressure steam is used for heating the kiln and is available for humidification, it should not be used directly to humidify the kiln. Use of high-pressure steam adds a considerable amount of heat to the kiln in addition to increasing the humidity. This may cause fluctuation or overshoot of the dry-bulb temperature such that it is difficult or impossible to maintain the wet-bulb depression desired. This may be especially troublesome during conditioning when controlling wet-bulb depression is critical and adding large quantities of steam is necessary to increase the wet-bulb temperature. Steam pressure for the steam spray line should, therefore, be reduced to about 15 lb/in^2-gauge by a pressure regulator some distance before the line enters the kiln. If permitted by safety regulations, the portion of the line between the regulator and the kiln should be left uninsulated so that the superheat in the steam can dissipate, and the steam for humidification will be cooled to near saturation (250-260 °F). Another alternative is to install a desuperheater in the spray line. This device injects water as a fine spray or mist into the steam spray line, thereby removing the superheat and reducing the temperature of the steam to near saturation.

In some installations that do not have a source of steam for humidification, water sprays are sometimes used. The water should be injected into the kiln in the form of a fine mist. It is highly desirable to heat the spray water since cold water has an appreciable cooling effect in the kiln and can cause fluctuation of the dry-bulb temperature and poor control of drying conditions. In some kilns, water sprays are used in conjunction with steam sprays, but extra care must be taken to prevent water droplets from falling on the lumber and creating stains.

For close control of wet-bulb temperatures in direct-fired kilns where no steam is available from the central boiler, a small boiler may need to be installed to generate the large volumes of low-pressure steam required for proper conditioning of the lumber.

Equipment to Control Drying Conditions

While drying conditions in most commercial dry kilns are controlled by automatic or semiautomatic controllers, manual control is sometimes used in smaller installations or home-designed equipment.

Automatic Control Equipment

Automatic systems can be further divided into semiautomatic and fully automatic. Semiautomatic systems record and control on set points that are changed from time to time during the kiln run by an operator. In fully automatic systems, process control information is entered at the start of the kiln run, and any needed changes are made automatically by the equipment during the kiln run.

Several process control techniques, some using specialized equipment, are available for use with either the semiautomatic or the fully automatic control equipment. They include zone control (see Zone Control section), variable frequency speed control for fans (see Kiln Fans section), and in-kiln moisture meters. In-kiln moisture meters are generally of two types: (1) the resistance meter, in which electrodes (pins) are driven or screwed into boards in the charge of lumber, and (2) the capacitive admittance meter, in which the electrode (a strip of metal) lies flat on the surface of the lumber. The electrode is slipped into the load parallel to the stickers. Electric signals on both systems are converted to moisture content values and read on a meter. Both types of meters are subject to temperature corrections and are not considered very reliable at moisture contents above 30 percent. In-kiln resistance meters are frequently used to monitor moisture content of drying lumber below 30 percent and may be used to control kiln schedules. Capacitive admittance meters are most commonly used in softwood kilns to monitor moisture content of drying lumber below 30 percent and are frequently used to determine when a charge is finished. Some capacitive admittance meters are connected to the controller to shut the kiln down when a predetermined moisture content is achieved.

Semiautomatic Control Systems

Semiautomatic dry kiln control systems are typically characterized by having a recorder-controller. This instrument continuously measures and records on a chart the conditions prevailing in the kiln and controls the heat and humidity to conform to the conditions preset by the kiln operator. As drying progresses, the operator changes the instrument set-points to the desired conditions in the kiln. This may be done based on time elapsed since the start of the run or on the current moisture content of the wood as measured by a sampling technique such as weighing sample boards. The first is more typical of a softwood drying operation, and the latter is more commonly used in drying hardwoods. Once a dry-bulb and a wet-bulb temperature have been set, the instrument automatically controls the conditions until they are reset.

Signals indicating the current conditions in the kiln are received at the recorder-controller from sensors located in the kiln. There is typically only one wet-bulb temperature sensor in a kiln but multiple dry-bulb temperature sensors. This is because the wet-bulb temperature is essentially the same throughout the kiln, but the dry-bulb temperature may vary considerably over the length and height of the kiln. The instrument compares these kiln conditions to the instrument set-point conditions, Changes in the kiln conditions are made through signals to air-operated valves that open or close heating systems, valves that open or close vents electrically, and humidification systems as necessary to bring the kiln to set-point conditions.

For many years, the recorder-controller and its companion valve systems worked in an on-off mode; that is, the controller told the valve to be completely open or completely closed. This method often wastes energy and does not offer as close control of kiln conditions as may be desired. More recently the use of proportional valves and controllers has become the accepted practice in most kiln operations. In this approach valves are open to varying degrees depending on how far the kiln environment deviates from set-point conditions, thus offering more precise control and saving energy.

Sensors currently used in lumber dry kilns are of three types. The traditional sensor used for over 50 years is the gas-filled or liquid-vapor system. A more recent introduction is an electric system using a resistance temperature detector (RTD). A third type of sensor is used to measure equilibrium moisture content (EMC) of the kiln atmosphere. This sensor measures EMC directly by electric resistance measurements across electrodes clamped to a small wood specimen or cellulose pad (EMC wafer) mounted in the kiln.

Liquid-vapor or gas-filled systems consist of four main parts: (1) the temperature-sensing bulbs inside the kiln, (2) the armor-protected capillary tubes connecting the bulbs with the recorder-controller, (3) the helical movement (Bourdon tubes) inside the recorder-controller that provides the mechanical force to move the pens on the recorder chart and the air relay portion of the controller, and (4) the clock movement that turns the recording chart.

The dry-bulb and wet-bulb temperature-sensing units are connected individually by long capillary tubes to the Bourdon tubes inside the recorder-controller

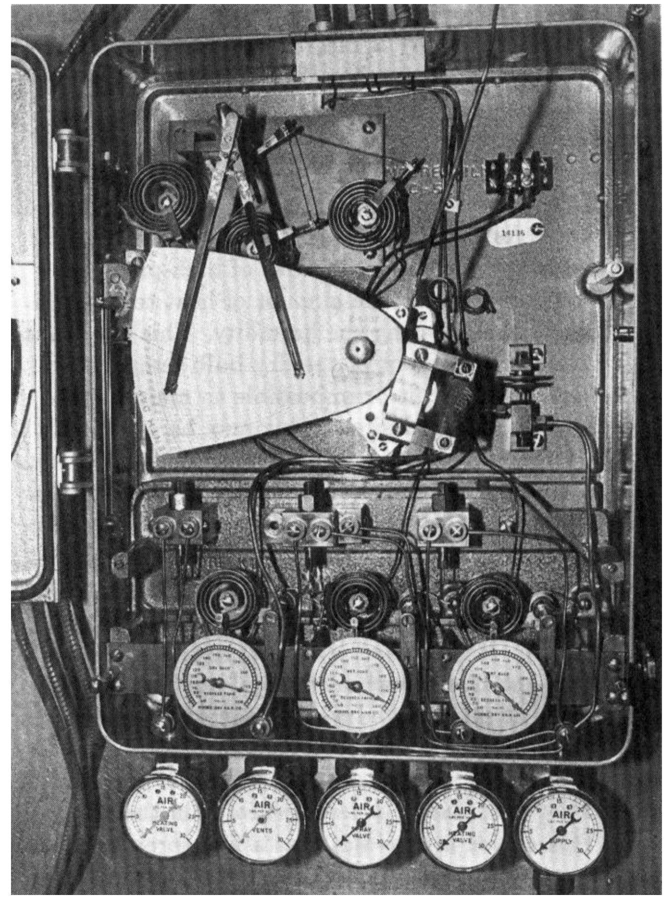


Figure 2-20—Internal view of three-pen, gas-filled recorder-controller (Moore type) showing Bourdon tubes, air relays, clock, gauges, and dials. (MC88 9018)

(fig. 2-20), which is normally located in the kiln control room. The bulbs and capillary and Bourdon tubes are sealed with a volatile liquid (butane) and its vapor. Increasing kiln temperature causes an increase of pressure in the liquid-vapor system; the capillary tube transmits the pressure change into the helical or Bourdon tube, causing it to expand. This movement is transmitted to the pen arm, which moves radially outward on the recording chart to indicate the increase in temperature. When the temperature in the dry kiln decreases, the reverse process takes place.

A typical dry kiln is usually equipped with one wet bulb and two or more pairs of dry bulbs. The wet bulb measures the wet-bulb temperature in the kiln resulting from the cooling effect of evaporation on the moist wick and controls the humidity in the kiln through the instrument. The paired or dual dry-bulb system (two bulbs connected to a common capillary tube) measures and controls the temperature of the kiln environment on the entering-air side of the lumber load in the kiln. The entering-air side of the load will always be the hotter side. When the air circulation reverses, the opposite side becomes hotter, and the bulb on the opposite side of the load becomes the controlling bulb. Larger kilns have two or more pairs of dual-control bulbs to better control the temperature in different zones of the kiln.

The controlling function of the liquid-vapor instrument is a pneumatic system of operating valves that control the amount of steam entering the dry kiln. Inside the recorder-controller case of a Moore instrument, the capillary tube from each bulb system is divided, with one lead going to the recording function and the other to a second Bourdon tube. Foxboro and Honeywell liquid-vapor instruments do not split this capillary but achieve the same results using mechanical linkages. As pressure changes within the system, needle-type air valves are brought into play, thereby accurately controlling heat input into the kiln and also controlling venting and spray or humidification.

Although the gas-filled or liquid-vapor control system has been time proven to be very dependable and adequately accurate, it does have some disadvantages when compared to the newer electronic recorder-controllers.

Electronic recorder-controllers use platinum RTD-type bulbs for sensors of both dry-bulb and wet-bulb temperatures and are connected to the instrument by 16-gauge, three-conductor lead wire. The recording function of the RTD control system contains an electronic servo module that measures resistance changes of a RTD and positions the pen accordingly on the chart. The instrument contains a separate servo module for each measuring system (fig. 2-21). For example, a three-pen RTD electronic control system will have three servo module units, one for the wet bulb and two for the dry bulbs.

The principal element of the controlling system is either a modulating or an off-on pneumatic control unit, which tracks the measured variable through movement of the pen linkage. When the measured variable crosses the set point, the control unit actuates a pneumatic or electrical relay, which in turn sends an air signal to the control valves, activating them as required.

The heart of the RTD electronic system is the servo module assembly, which contains an electronic bridge circuit, balancing amplifier, slide wire, and direct-current balance motor. One of the elements of the electronic bridge circuit is a resistance bulb that senses the dry-bulb or wet-bulb temperature. An external relay switches in the appropriate resistance bulb when fans reverse, thus assuring measurement of entering air temperature.

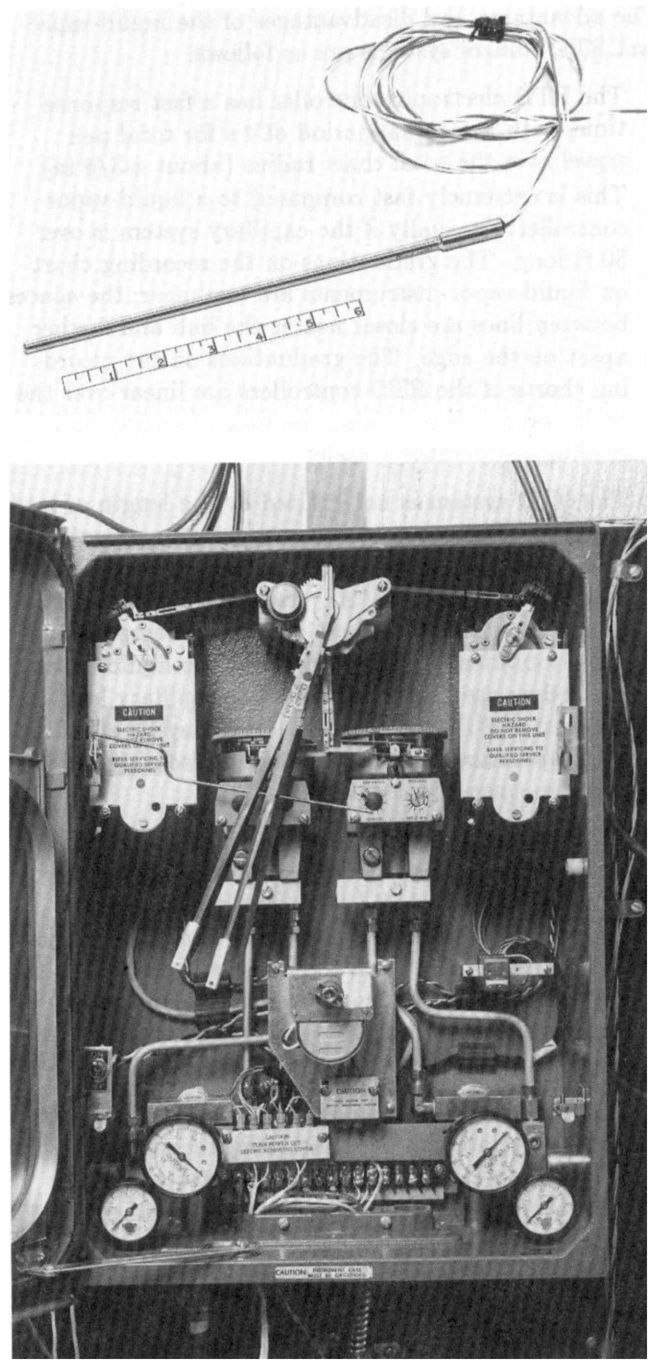


Figure 2-21—RTD sensor and instrument. (M87 0167, M88 132-4)

The advantages and disadvantages of the liquid-vapor and RTD control systems are as follows:

1. The RTD electronic controller has a fast response time, with a nominal period of 4 s for total pen travel over the total chart radius (about 4-3/8 in). This is extremely fast compared to a liquid-vapor controller, especially if the capillary system is over 50 ft long. The graduations on the recording chart on liquid-vapor instruments are nonlinear; the spaces between lines are closer nearer the hub and farther apart on the edge. The graduations on the recording charts of the RTD controllers are linear over the entire range, thus making the task of setting and reading temperatures easier.
2. The RTD system is not limited by the length of lead required. The control instrument can be mounted at distances of up to 2,000 ft with no loss of accuracy or response time. Any temperature changes caused by variation in lead length are compensated for automatically. By comparison, the liquid-vapor controllers are generally limited to capillary lengths of about 100 ft, and the capillaries may be affected by temperature changes between the sensing bulbs and the control instrument.
3. Temperature ranges can be easily changed on the RTD electronic controller by simply removing the existing range card and replacing it with a new range card. The liquid-vapor system requires removing the instrument from the kiln and returning it to the manufacturer or repair facility, where the system has to be refilled and recalibrated with special equipment.
4. The liquid-vapor instruments are sensitive to bulb locations related to the instrument mounting (higher or lower). If these distances change for any reason, calibration is affected. The RTD system is not affected by bulb location, and sensing bulbs can be moved at any time without affecting the calibration of the instrument.
5. If any damage occurs to the sensing system of the RTD controller, it can be repaired at the site. Sensing bulbs can be replaced in a matter of minutes, and damage to lead wires can be repaired without any change in calibration or accuracy of the instrument. Liquid-vapor systems require removing the instrument from the kiln with all capillary lines and bulbs intact and returning the instrument to the manufacturer or repair facility.
6. Perhaps the biggest advantage of the RTD electronic controller is the ease of calibration. Unlike the time-consuming two-person operation of using buckets of hot water or hot oil and an etched stem thermometer required for calibrating the liquid-vapor system (see ch. 4), the calibration of the RTD controller is a very simple one-man operation using a decade box. A given amount of electrical resistance can be applied to the instrument for various temperature ranges, and a direct readout on the chart indicates either proper or improper calibration. Adjustments are done very easily at the front of the instrument by simply adjusting the appropriate linkage. Note that this technique calibrates only the instrument, not the RTD sensor. The sensor is generally assumed to be accurate. Proper resistance in the RTD sensor can be checked against an electronic bridge. To check the total system, sensors and instrument, it is suggested that the sensor(s) be placed in an ice-water slurry (32 °F) and then boiling water (212 °F) and the respective values read on the instrument chart.

Fully Automatic Control Systems

In this manual, fully automatic control means the process control information or other drying schedule information is entered at the start of the kiln run. Any changes in temperature or humidity are made automatically by the controller during the kiln run. These changes may also include determination of final target moisture content and shutdown of the kiln. Override changes are possible with these systems, but seldom used. This procedure differs from semiautomatic control in which the recorder-controller effectively maintains preset conditions but does not change set points, which must be changed by the operator. Fully automatic systems range from cam-operated controllers, used in some regions for several decades, to controllers based on load cells that weigh the load or part of it, to the rather recently introduced computerized controllers that measure or infer changing lumber moisture content in the kiln.

Cam controllers represent the earliest attempt at fully automatic control. They are a form of time-based schedule and depend on the assumption that for a given species, thickness, and grade of lumber, the load moisture content and hence the conditions in the kiln will depend on the length of time drying has been in progress. Two specially cut cams are required, one to control the dry-bulb temperature, the other to control the wet-bulb temperature. Different cams have to be cut for different species and thicknesses.

The advantages of cam controllers include the following: (1) schedules are predetermined and monitoring is minimal; (2) schedules can be ramped or moved smoothly from one set of conditions to the next rather than arranged in steps, which cause abrupt changes in conditions and which may waste energy or put extra loads on the boiler; and (3) cams can be cut to give very predictable, reproducible results, based on experience in drying a given thickness(es) of given species starting at similar initial moisture contents.

The disadvantages of cam controllers include the following: (1) there is no direct link between the controller and the moisture content of the lumber at any given time during the kiln run—a load drying more slowly than usual could easily be shut down while at a moisture content higher than desired; conversely, a load drying more rapidly than usual could easily be overdried; (2) a recorder-controller rigged for following cams is not readily converted to other forms of set-point determination; (3) care and experience are necessary to cut accurate cams; and (4) failure to monitor at frequent intervals may result in not implementing necessary changes in response to unforeseen factors such as boiler shutdown, steam leak, or loss of water to the wet bulb.

Load-cell systems are available that weigh the load or a portion of it and make changes in the schedule as the lumber dries. Selected boards are sampled to determine initial or "green" weight in the usual way by cutting, weighing, ovendrying, and reweighing moisture sections (ch. 6); these values are averaged or weighted. This information together with details of the schedule to be followed are preprogrammed into the controller at the start of the run, and the system takes complete control of the drying operation. The main disadvantages of this approach are the problems of sampling and determining reliable initial moisture content values, drying on the average moisture content of the load or portion sampled, and lacking an indication of board-to-board variation in moisture content in the load during drying. A preferred approach would be to use very small load cells to follow the weight loss of individual sample boards and to make these data available to the control system by board or in groups of boards.

Since about the middle 1980's, computerized controllers have been introduced in both softwood and hardwood operations. The introduction of desk-top-sized personal computers has provided a big boost to computerized control systems. Computerized control systems can range from those that are little more than electric cam time-based systems to those that measure the moisture content of the wood in certain ranges and infer the moisture content of the wood in other moisture content ranges. Since there is currently no reliably accurate method of measuring wood moisture content above the fiber saturation point (about 30 percent) except by weighing, values above 30 percent are inferred from controlled temperature and relative humidity conditions in the kiln. Moisture values below fiber saturation point are determined by measuring the electrical resistance between metal pins or electrodes driven into the board. Pins may be of different lengths so that moisture contents in the core and near the surface may be monitored and some idea of gradient may be determined. Some systems not only closely monitor and control temperature and humidity conditions in the kiln but also make changes in fan speeds and monitor or control energy consumption. One computer may control from 1 to as many as 8 to 10 dry kilns.

Computerized kiln controllers will likely find wider acceptance in the lumber industry in the future. Many current installations have shown that computerization can make the operation of dry kilns easier and can reduce the cost of producing high-quality lumber. The technology is advancing rapidly, and as we learn to sense more variables such as shrinkage, stress, wood temperature, and moisture content, we will add to the precision with which computer controllers can dry lumber.

Zone Control

Zone control is a process control technique for equalizing dry-bulb temperatures throughout the kiln and can be used with either semiautomatic or fully automatic control systems. Cool spots in the kiln have long been noted for uneven drying, producing lumber that is higher in moisture content than desired. Hot spots tend to produce lumber that is drier than desired. In zone control, the kiln is divided into several zones, with temperature sensors coupled to control valves or dampers in the heating system. Zones typically run along the length of the kiln; some designs have vertical zones as well. The number of independently controlled zones can vary from 2 up to 24. Historically, zone control with gas-filled recorder-controllers meant that long (66 ft or longer) kilns were divided into two zones: one zone for each end, or one zone control for operating the reheat coils in a double-track kiln and another zone control for operating the overhead heating coils. Computerized control with electronic RTD sensors has made it possible to control a much larger number of zones. With computerized control, paired sensors measure the, temperature drop across the load (TDAL or ΔT) and seek, through their circuits with control equipment, to keep the drying rate at the same level in all zones. This technique is successful and rather widespread in newer high-temperature softwood kilns in both the southern and western United States. It is expected to become more common in older remodeled or retrofitted softwood kilns and some hardwood operations. However, in conventional-temperature hardwood kilns, the TDAL is usually so small that trying to control using this variable is not very promising.

Manual Control Equipment

Some form of automatic kiln control is commonly used on commercial kilns in the United States and Canada. However, manual control is possible and is generally of interest to very small operations, often using home designed equipment, and to operations in which a person monitors the kiln on nearly a full-time basis. For successful manual control of drying conditions, the dry- and wet-bulb temperatures must be known. If these temperatures differ from those desired, the valves that regulate the flow of steam (heat) and spray (humidity) into the kiln must be adjusted until the desired temperature readings are obtained. The appropriate amount of venting must also be watched and adjusted. To keep the temperature or temperatures reasonably close to those desired requires considerable operator time for monitoring and making minor adjustments to valves.

Temperature-Measuring Devices

The temperature-measuring devices commonly used for manual control are of two classes, indicating and recording. Glass-stemmed indicating thermometers are frequently used. The most satisfactory glass-stemmed thermometers have the graduations etched on the stem. Thermometers with separate scales stamped on an attached metal strip are not very satisfactory, since any shifting of the strip with relation to the thermometer tube will result in incorrect readings. Indicating digital thermometers have largely replaced the pressure-spring type mentioned in the earlier edition of this manual. The sensor for these digital thermometers may be either a thermocouple or a RTD. Type–T (copper-constantan) thermocouple wire is suggested for most dry kiln use.

Glass-stemmed indicating thermometers of the maximum type are also used to obtain dry-bulb temperatures. Maximum thermometers show the highest temperature to which they have been exposed. After each reading, they must be shaken down like clinical thermometers. Care should be taken in using maximum thermometers to allow enough time for the mercury to reach a peak temperature.

Digital thermometers with the capability to be coupled to a printer are also available when written records of the temperature are desired over a period of time. As with indicating-type thermometers, the sensor of recording thermometers can be either a thermocouple or an RTD.

Humidity-Measuring Devices

To follow standardized kiln schedules with manual control requires a knowledge of the wet-bulb temperature or the relative humidity of the air circulating in the kiln. This can be done by using an instrument that reads relative humidity directly or with wet-bulb thermometry, which reads the wet-bulb temperature. The difference between the dry-bulb temperature and the wet-bulb temperature is the wet-bulb depression. By knowing these values and by using a psychrometric chart, relative humidity can be calculated (see appendix to ch. 1). As discussed in some detail in the appendix to chapter 1, wet-bulb sensors must be continuously wetted and located in a position in the kiln where sufficient airflow over the sock or wick will provide adequate evaporation of the water and thereby cooling so that accurate wet-bulb temperatures can be determined. The wet-bulb wick should be changed after every kiln charge or more frequently if it becomes hard or crusty and is not wicking properly. If kiln conditions are to be controlled by monitoring relative humidity and dry-bulb temperatures, then a high-quality relative humidity sensor should be obtained. Inexpensive sensors or meters of the type commonly found in hardware stores are not recommended as they do not stay in calibration well and can rather quickly give misleading or erroneous readings. Wet- and dry-bulb hygrometers are sometimes used for manual control. These provide wet- and dry-bulb temperatures from the same instrument and are illustrated in chapter 3 under Equipment for Determining Temperatures.

Specialized Drying Approaches and Kiln Types

Dehumidification Kilns

Dehumidification kilns have been mentioned in several places in this chapter. In many respects, these kilns are similar to steam-heated or direct-fired kilns, but they differ enough to warrant a separate description. Dehumidification kilns have several advantages: a boiler may not be required (except as required for stress relief or desired for warmup); they are more energy efficient, offering good control in drying refractory species that require a low initial dry-bulb temperature as well as high relative humidity; and a low-cost kiln structure is adequate for some applications. Disadvantages are that dehumidification kilns operate primarily on electrical energy, which in some regions may be more expensive than gas, oil, or wood residue (even though these kilns are more energy efficient than other types of kilns); maximum temperatures are limited to about 160 °F and in some units to about 120 °F; and, in some cases, there may be concern over chemicals in the condensate.

Air-circulation systems are essentially the same as those used in steam or direct-fired kilns. The entire dehumidification unit may be located outside the kiln in an equipment room and blowers used to circulate air between the dehumidifier and the kiln. Another common arrangement is a split system with the compres-

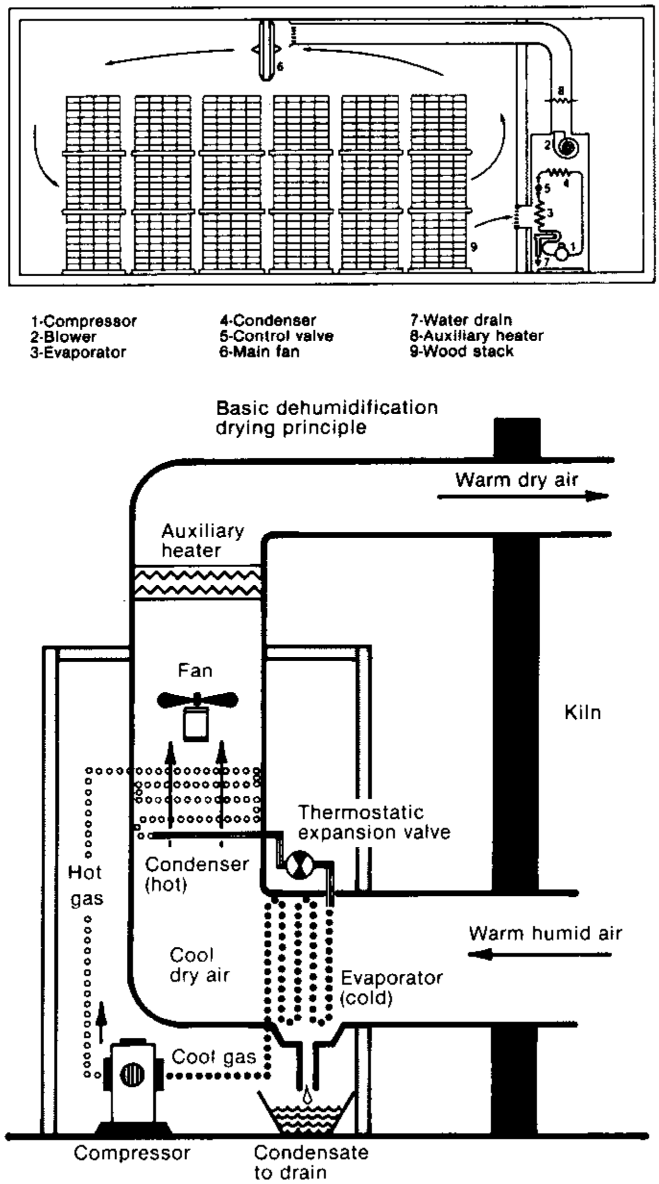


Figure 2-22—View of a typical dehumidification kiln and schematic of typical dehumidification drying system. (ML88 5625)

sor and control panel in a separate equipment room and the blower and coil cabinet inside the kiln. In some smaller systems (less than 10,000 fbm), the entire dehumidification unit may be inside the kiln. Air circulation within the drying compartment is provided as in the other types of kilns. While earlier designs typically had air velocities in the lower range, the industry has gradually increased the air velocity to a level comparable to that used in a conventional-temperature hardwood kiln. A typical dehumidification kiln is shown in figure 2-22.

The major difference between dehumidification kilns and other types of kilns is the method by which water is removed from the kiln air. The majority of the water is condensed on the coils of the dehumidifier and removed as liquid, rather than being vented to the outside atmosphere. Many larger dehumidification systems have provisions for periodically venting excess heat, and some moisture is vented in the process of venting heat, but only a small part of the total moisture in the air is vented. These two characteristics account for the greater energy efficiency of dehumidification kilns. First, since little moist air is vented to the outside of the kiln, the energy contained in the warm, moist air is not lost. Second, when the moisture in the air condenses on the cold coils of the dehumidifier, the heat of vaporization is recovered. Most dehumidification kilns are built so that this recovered energy is used in drying the lumber. The same approximately 1,000 Btu of energy per pound of water required to evaporate the water from the lumber in the first place is recovered in this condensation.

Kiln control systems on dehumidification kilns of about 5,000 fbm and larger are similar to those of other kilns. They typically use RTD dry- and wet-bulb sensors and recorder-controllers. Controllers for smaller systems may use a timer to control the percentage of time the compressor operates or a humidistat to activate the compressor. Most large systems (over 10,000 fbm) used for drying hardwood lumber are installed with a boiler for warmup and conditioning or stress relief. Smaller systems often have electrical resistance heating elements that are used to bring the kiln up to operating temperature to the point where the compressor can supply enough energy to maintain the desired drying conditions. These heating elements can also be used to attain the higher temperatures often called for near the end of the drying schedule.

Materials of construction vary from wood to masonry to prefabricated aluminum panels. The main criteria are that the drying compartment be well insulated so that maximum benefit can be derived from the energy efficiency and that the compartment be both airtight and moisture resistant. For medium to large kilns, insulation values of R-20 for walls and R-30 for roofs are recommended. Slightly lower values may be acceptable in warmer climates. For smaller kilns (10,000 fbm capacity or less) with less compression-generated heat, higher R values are required. Very serviceable and low-cost kilns can be built with simple wood-frame construction, in both large and small sizes.

In general, one can expect that drying stresses will be present after dehumidification kiln drying, as they are after drying in other type kilns. When drying lumber for uses where drying stress must be relieved, special provisions must be made if the system is not equipped with a boiler. A small-capacity electric or gas-fired boiler can be incorporated in the kiln for this purpose.

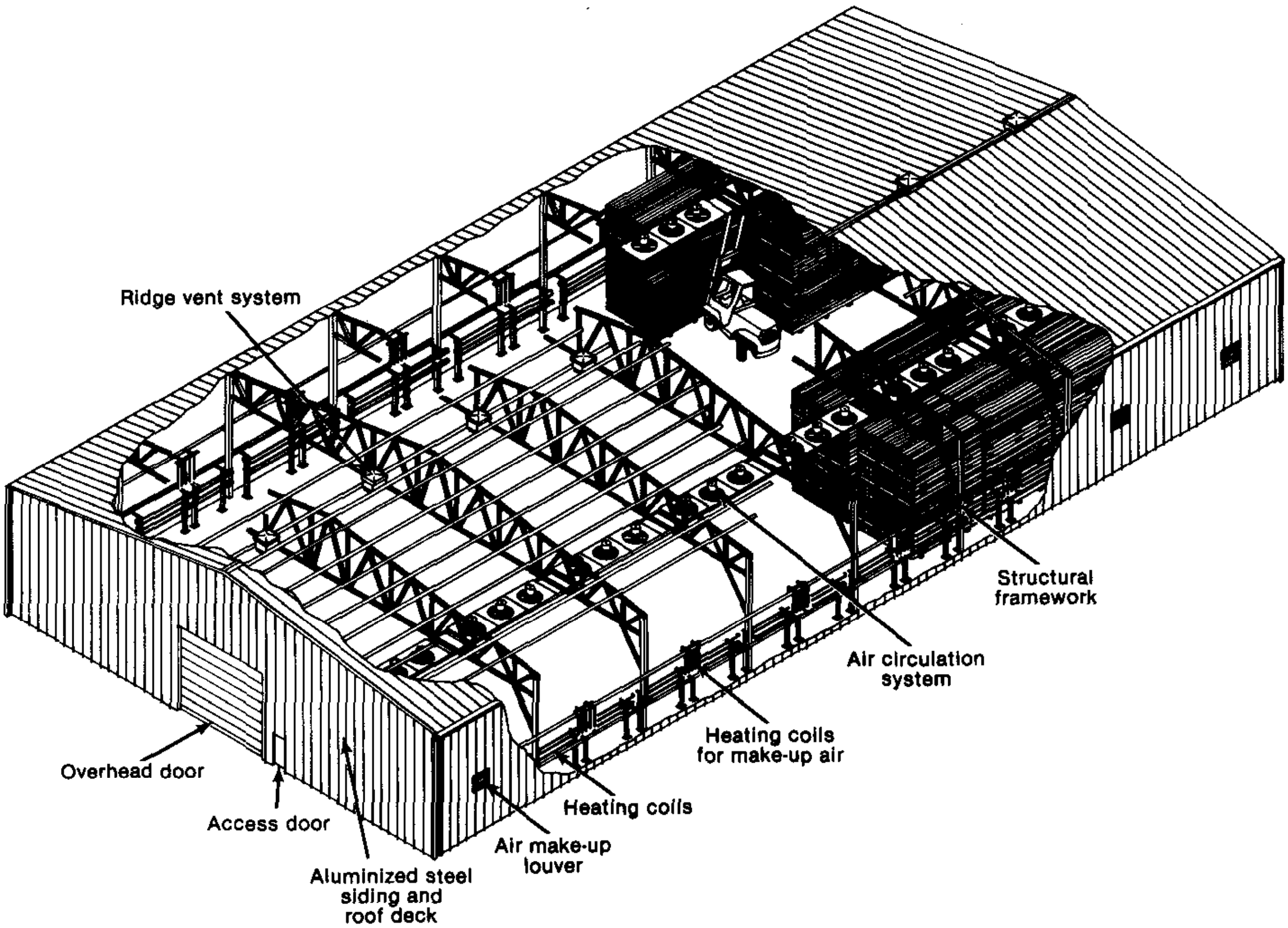


Figure 2-23—Typical predryer. (ML88 5600)

It is very important to properly size the compressor for the thickness and species to be dried in the dehumidifier. If the compressor is too small, there is a risk of stain, increased warp, and checking. If the compressor is too large, humidities in the kiln can cycle excessively, possibly resulting in a lack of heat.

Predryers

Predryers are large low-temperature dryers used to dry green lumber to a moisture content of around 25 percent prior to drying to a lower final moisture content in a kiln. Also called warehouse dryers, these large free span buildings range in lumber-holding capacity from 50,000 to over 1,000,000 fbm and are typically sized at four times kiln capacity (fig. 2-23). Generally, predryers are forklift loaded, although track loading may be preferred in some cases. Most predryers are preengineered buildings of structural steel with 1 to 2 in of rigid foam insulation between painted steel or aluminum sheathing. They commonly have concrete floors. Temperature and relative humidity are controlled with temperature set-points typically ranging from 75 to 100 °F and with relative humidity maintained between 60 and 90 percent.

Predryers for controlling air-drying conditions have been used successfully for over 25 years by some companies in the northern latitudes of the United States where natural air-drying conditions are unfavorable for many months, from both the standpoint of defect development and length of air-drying time. However, in recent years high lumber prices and high interest rates have produced financial incentives strong enough to interest lumber producers in other areas, especially hardwood producers who had typically air dried their lumber 60 to 90 days or longer before final drying in the kiln.

The advantages of predrying over air drying in the yard are brighter lumber, more uniform moisture content of dried lumber, and reduction of drying defects, all in about one-third less time. Inventory can be reduced by one-third to one-half, freeing capital and yard space. Several species and thicknesses can be mixed in these dryers. Thus, lumber of different moisture contents, species, and thicknesses may be in the predryer at the same time; drier lumber can be moved frequently out to the kilns and newly acquired green lumber can be moved in. The lumber is usually arranged by blocks in a zone to group similar species, thicknesses, and levels of moisture content. Disadvantages of predrying over air drying are largely associated with costs of building, energy, and maintenance.

Predryers are typically heated with steam and finned coils. Humidity is controlled by external venting when humidities are too high and by using moisture released from the lumber to maintain humidities as high as required. Larger predryers are divided into two and sometimes three zones; conditions are controlled separately in each zone by a recorder-controller similar to those described earlier in this chapter. In some installations, temperature and humidity conditions are maintained with dehumidification units.

Temperatures are usually sensed by electronic RTDs, and humidity is sensed by wet-bulb thermometry or with relative humidity sensors using the cellulose pad or similar sensor. Placement of the sensors above the load in the rafters is often criticized because the sampled air is not as representative of the air entering the stacks as one would like. However, the free-span construction of the structure does not provide much choice in where to place the sensors.

Air circulation is usually provided by overhead fans arranged in a row horizontally over the plenum between the two rows of lumber (fig. 2-22). The air is directed down into the plenum by belt-driven or directly driven fans, and then it is passed through the stacks of lumber. One criticism of predryers has been uneven air distribution, resulting in uneven drying from top to bottom of the stacks. Various forms of baffle systems have been suggested to improve distribution and uniformity of airflow. Exhaust ventilation should be designed so that it does not direct the humid exhaust air down onto the roof; this has been reported to cause localized deterioration of the roof. Rather, exhaust ventilation should consist of "upblast" units that direct vented air straight up and way from the building. The makeup air enters through louvers in the walls and can be preheated if needed.

The concept of using predryers rather than air drying has gained wide acceptance in the hardwood industry, though it may not be a technique that works well and is profitable for all operations and installations. The techniques are still evolving, and many changes are likely to be seen in the next few years.

Solar Dry Kilns

Interest in solar dry kilns was low until the energy concerns of the mid-1970's. The advantage of solar kilns is the free and often abundant energy available, but the disadvantage is that there is a cost to collecting free energy. Free energy is also low-intensity energy, which often limits the operating temperature of a kiln to approximately 130 °F unless prohibitively expensive special solar collectors are used. Despite the cost of collecting the energy, another advantage of solar kilns is that relatively small, simple, and inexpensive kilns are possible, and this level of technology is often well suited for small operations.

The average annual solar energy available on a horizontal surface in the United States ranges from 1,000 to 2,000 Btu per day per square foot of collector area. Average amounts for several locations are given in table 2-1. Tilting the collector surface perpendicular to the sun maximizes the intensity of the direct solar radiation and minimize losses caused by the reflection of the direct radiation. The general rule for maximizing solar radiation on a year-round basis is to tilt the collector at an angle to the ground equal to the latitude. If solar radiation is to be maximized in the summer months in locations where latitude and ambient temperature make winter drying impractical, direct radiation can be maximized by reducing the tilt angle to about 15° less than the latitude. In the northern hemisphere, the collector should face directly south.

Solar kilns can operate by direct solar collection (greenhouse type) or by indirect solar collection where the collector is isolated in some way from the drying compartment. They can also operate with solar energy alone or with supplemental energy. The four types of solar kilns are as follows:

1. Direct collection (greenhouse)
   a. Solar only, which is characterized by wide diurnal and day-to-day changes in temperature and relative humidity
   b. Solar with supplemental energy, which is characterized by the ability to follow a drying schedule and has large nighttime heat losses because of the low insulating ability of the transparent cover
2. Indirect collection (isolated drying compartment)
   a. Solar only, where the diurnal change in temperature and relative humidity can be reduced by energy storage and reduced heat losses at night
   b. Solar with supplemental energy, where scheduled drying is possible and nighttime losses are minimized

Generalized solar kiln designs are shown in figure 2-24. Possible collector surfaces are south-facing walls, east and west walls, and a roof. Solar collection is either direct (fig. 2-24a,c) or indirect (fig. 2-24b,d). The collector surface is either uninsulated (fig. 2-24a,b) or insulated at night (fig. 2-24c,d).

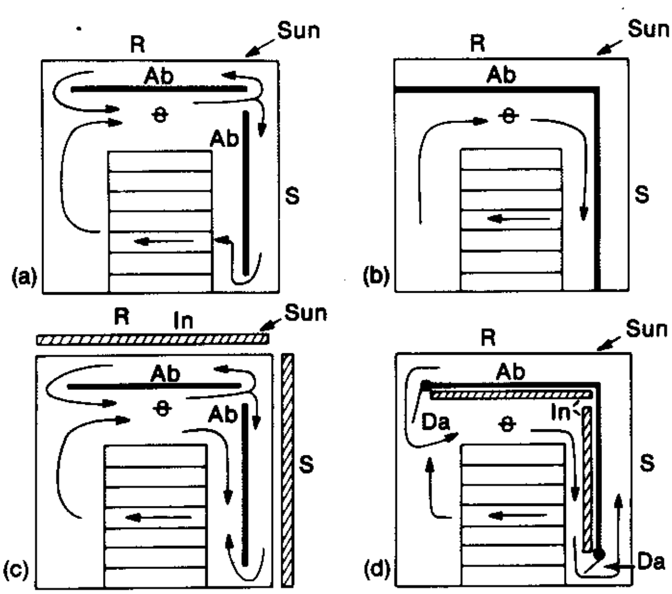


Figure 2-24—Generalized solar kiln design types. (a) Uninsulated dryer and collector are one unit. Airflow mixes on both sides of absorber panel (Ab). (b) Uninsulated, improved design. Airflow mixes within chamber. (c) Insulated (ln) externally. Airflow mixes on both sides of Ab, day and night. (d) Insulated (ln) internally. Air flows over the front of the absorber panel (Ab) when damper (Da) is open. (ML88 5603)

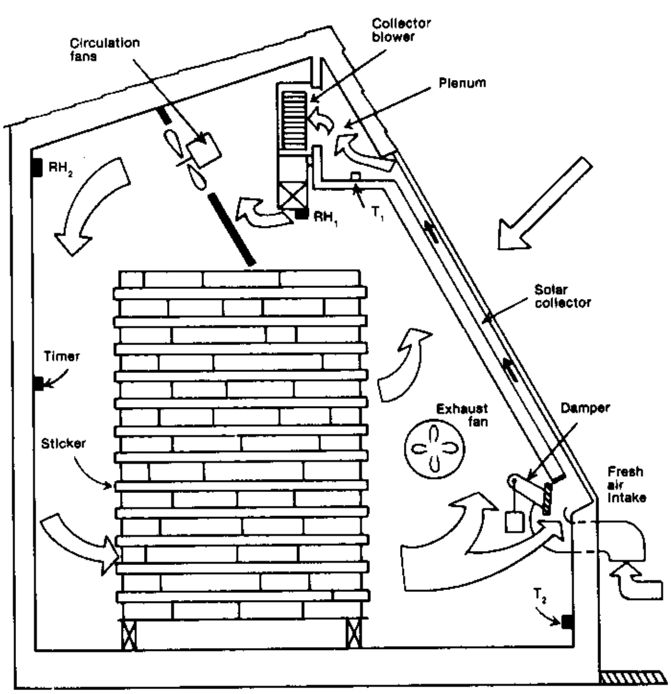


Figure 2-25—Solar kiln design for northern latitudes, showing inexpensive control system. (ML88 5602)

In the simplest uninsulated form (fig. 2-24a), air flows on both sides of the absorber surfaces (Ab). The drying chamber and collector surfaces are one unit as in a true greenhouse structure. A somewhat improved design (fig. 2-24h) isolates the collector surfaces (R and S) and the outer absorber surface (Ab) from the drying chamber. The energy absorbed on the absorber surface flows through the absorber to its inner surface where it is transferred to the circulating kiln air. Both of these systems suffer large nighttime heat losses.

For the insulated designs, two variations are possible. In the simpler of these designs (fig. 2-24c), airflow is similar to that in figure 2-24a except that diurnal insulation (ln) is accomplished by external means such as shutters or blankets. Collector and absorber surfaces are also isolated in the design shown in figure 2-24d, with the drying air acting as the medium for heat transfer. When the dampers (Da) are open, the air flows over the black absorber surface (Ab) and back into the dryer chamber. When the dampers are closed, nighttime airflow is interrupted, thereby reducing nighttime (and cloudy day) heat losses because the absorber has an insulated back (ln). A more detailed schematic of this type of solar kiln is shown in figure 2-25. In another common variation of this insulated-type solar kiln, the solar collector is detached from the drying compartment, and blowers transfer the heated air from the collector to the drying compartment (fig. 2-26).

At present, solar drying is not widely used in the United States. The main uses are hobbyists or small woodworking shops that do not require large drying capacity and that do not wish to make large capital investments in drying equipment.

Vacuum Drying

Vacuum drying of lumber is not a new idea, and, in fact, it has been considered since the turn of the century. However, vacuum drying did not come into use until the 1970's because it was considered uneconomical. The principal attraction of vacuum drying is that the lowered boiling temperature of water in a partial vacuum allows free water to be vaporized and removed at temperatures below 212 °F almost as fast as it can at high-temperature drying at above 212 °F at atmospheric pressure. Drying rate is therefore increased without the dangers of defects that would surely develop in some species during drying above 212 °F. Vacuum drying is essentially high-temperature drying at low temperatures. During the early 1970's, the economic outlook for vacuum drying became more favorable, largely because of the increased costs of holding large inventories of lumber during long drying processes. This is particularly true in the drying of thick, refractory, high-

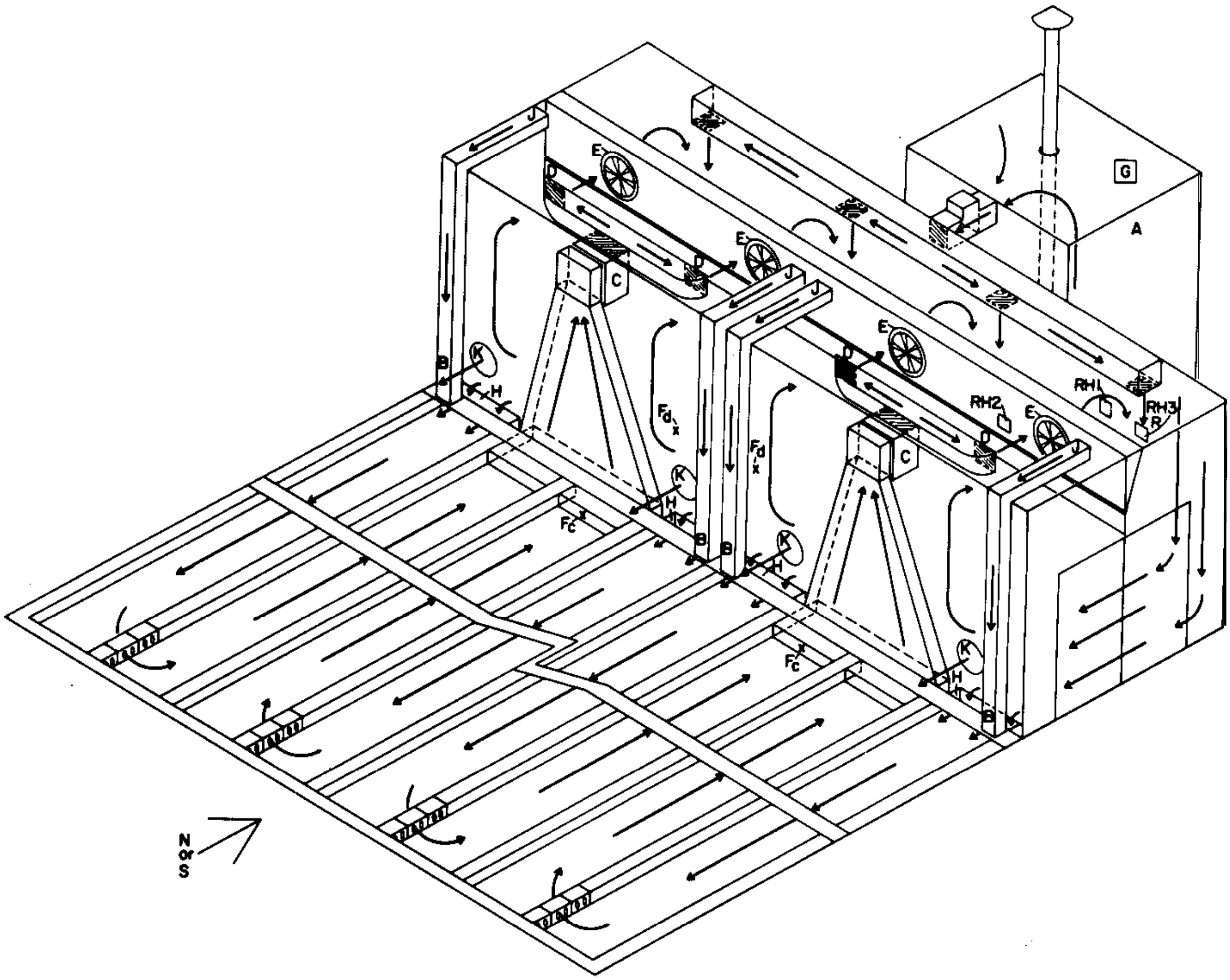


Figure 2-26—Schematic diagram of solar wood-residue dry kiln. A, furnace room; B, intake air enters collector; C, solar blower; D, manifold ducts for solar-heated air; E, internal fans; F_c, differential temperature sensor-collector; F_d, differential temperature sensor–dryer; G, humidifier; H, return-air duct from dryer to collector (dampered at night); J, entry point of intake air; K, exhaust vents; RH1, humidistat for exhaust vents K: RH2, humidistat for shutting kiln off at high humidity; RH3, humidistats for humidifier G. (ML88 5601)

value species, which can be safely dried in a vacuum kiln in a small fraction of the time required in a conventional kiln.

The main difference between the several types of vacuum kilns currently on the market is the way in which heat is transferred to the lumber. Convective heat transfer in a partial vacuum is almost nonexistent. In one common type of vacuum kiln, there are alternate vacuum and atmospheric pressure cycles. Heat is applied to the lumber convectively at atmospheric pressure, and then a vacuum cycle is applied to remove water at low temperature. These cycles are alternated throughout the drying. Another common type of vacuum kiln maintains a vacuum throughout the entire drying process, and the heat is transferred to the lumber by direct contact with steam-heated platens or by electrically heated conductive blankets that contact the lumber (fig. 2-27). A third type employs high-frequency electrical energy to heat the lumber. In all types, water is removed from the drying chamber by pumps.

Figure 2-27—Vacuum-kiln type in which heat is supplied to the lumber by contact with electrically heated blankets. (M85 0351-10)

Literature Cited

Rasmussen, E. F. 1961. Dry kiln operator's manual. Agric. Handb. No. 188. Washington, DC: U.S. Department of Agriculture. 197 p,

Rice, W. W. 1977. Dry kiln: A design to season 500 board feet. Fine Woodworking. Spring: 39-43,

Rosen, H. N. 1979. Potential for energy recovery from humid air streams. Res. Pap. NC-170. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

Sources of Additional Information

Branhell, G.; Wellwood, R. W. 1976. Kiln drying of western Canadian lumber. Western Forest Products Laboratory Information Report VP-X-159. Vancouver. 112 p.

Cech, M. Y.; Pfaff, F. 1977. Kiln operator's manual for eastern Canada. Eastern Forest Products Laboratory Report OPX192E. Ottawa. 189 p.

Knight, E. 1970. Kiln drying western softwoods. Moore-Oregon, Portland. (Out of print.) 77 p.

McMillen, J. M.; Wengert, E. M. 1978. Drying eastern hardwood lumber. Agric. Handb. No. 528. Washington, DC: U.S. Department of Agriculture. 104 p.

Tschernitz, J. L. 1986. Solar energy for wood drying using direct or indirect collection with supplemental heating. Res. Pap. FPL-477. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 81 p.

Wengert, E. M.; Oliveira, L. C. 1985. Solar heated, lumber dry kiln designs. Blacksburg, VA: Department of Forest Products, Virginia Polytechnic Institute and State University. 91 p.

Table 2-1—Annual average of daily solar radiation available at various locations in the United States

City	Solar radiation (Btu/ft^2-day)
Albuquerque, NM	1,915
Ames, IA	1,273
Atlanta, GA	1,454
Boise, ID	1,456
Boston, MA	1,148
Corvallis, OR	1,255
Davis. CA	1,598
Fort Worth, TX	1,638
Grand Junction, CO	1,675
Greensboro, NC	1,410
Indianapolis, IN	1,273
Lexington, KY	1,506
Little Rock, AR	1,432
Shreveport, LA	1,458