Chapter 11
Energy in Kiln Drying

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Drying of materials in general and of wood in particular is energy intensive, primarily because a high amount of energy is required to evaporate water (liquid to gas). Depending upon the type of equipment used to dry wood, the efficiency level of the operation may require one and one-half to four times the energy actually needed to evaporate the water. In addition, green wood to be dried may contain, by weight, as much as two-thirds water. Wood can be successfully dried in different types of dryers. However, even when optimally operated, the dryers may have different levels of efficiency as an inherent property of their physical design and the materials of construction, and their efficiency may also be affected by environmental factors. Certain practices or maintenance procedures may further reduce dryer efficiency. In this chapter, we discuss energy demand as related to various methods of drying, types of environmental and geographical factors, fuel, and equipment misuse.

Energy Consumption in Drying Systems

Definition of Terms

A list of symbols is provided at the end of this chapter.

Units of Thermal Energy

In English notation, the unit of energy is the British thermal unit (Btu), which is defined as the amount of energy required to heat 1 lb of liquid water 1 °F at 40 °F. Because the quantity of energy used in any one process is such a large number, the unit therm (100,000 Btu) is often substituted for Btu. Very often, energy is quoted as cost per million Btu (10^6 Btu). Some economists use an even larger unit, the quad (10^{15} Btu).

Latent Heat of Evaporation

The energy consumed at constant temperature for phase change from solid to liquid (heat of fusion) and liquid to gas (heat of evaporation) is called latent heat. For drying, the latent heat of vaporization (liquid to gas) of water is about 1,000 Btu/lb, a value that at low temperatures is a slightly decreasing function of temperature (for example, 1,054 at 70 °F to 970.3 at 212 °F). For water, the latent heat of fusion (ice to liquid) is considerably lower, 144 Btu/lb.

Heat Capacity

The heat capacity (or specific heat relative to water) of solids, liquids, and gases is by definition the amount of energy (Btu) required to heat 1 lb of material 1 °F. The actual value will differ with the physical or chemical composition of the material and again is a function of temperature. For the materials associated with drying of wood, values for heat capacity are given in table 11-1.

Heat of Adsorption

At any moisture content greater than 30 percent (fiber saturation point), the water content exists in two states: (1) water as liquid in the cellular structure of the wood and (2) adsorbed water within the wood substance--so-called hygroscopic water. The latter state represents a molecular invasion of the complex wood polymer structure. The energy associated with removing this water in drying (liquid to gas) is now greater than the latent heat of vaporization. For levels of moisture less than 20 percent, the heat of adsorption increases exponentially as the moisture content drops from 20 to 0 percent. Table 11-2 shows some values that must be added to the latent heat of vaporization. These values are sometimes referred to as the heat of wetting, so called after an experimental technique used for measurement. The values in table 11-2 are derived from an equation that approximates experimental data (Weichert 1963):

$$\Delta h_a = \exp[-14.5(M_i/100) + 6.18] \quad (1)$$

where

Ah, is the differential heat of wetting (Btu/lb) and

M_i is intermediate moisture content (percent).

Thermal Conductivity

One property of matter is that energy flows (is transferred) from a higher to a lower temperature. For the same difference in temperature (identical areas and thicknesses), various substances will transfer energy at different rates. This variation in heat transfer rate is characterized by a thermal conductivity coefficient k, defined by means of the following equation:

$$Q = \frac{kA\,\Delta t}{\ell} \quad (2)$$

where

Q is energy transferred (Btu/h),

At the temperature difference between hot and cold (°F),

A surface area (ft^2), and

ℓ thickness of substance (ft).

The units of k are then Btu/h/ft/°F. Some typical val-. ues of thermal conductivity are shown in table 11-1.

Sometimes the units of k are expressed differently. Equation (2) can be rearranged as

$$k = \frac{Q\ell}{A\,\Delta t}$$

putting the dimensions for k as

$$\frac{(\mathrm{Btu/h})(\mathrm{ft})}{(\mathrm{ft}^2)(^\circ\mathrm{F})} \text{ or } \frac{\mathrm{Btu}}{\mathrm{hr}\cdot\mathrm{ft}\cdot{}^\circ\mathrm{F}}$$

If ℓ and A are given in inches, then k' is given in

$$\frac{\mathrm{Btu}}{\mathrm{h}\cdot\mathrm{in}\cdot{}^\circ\mathrm{F}}$$

Therefore, $k = 12k'$.

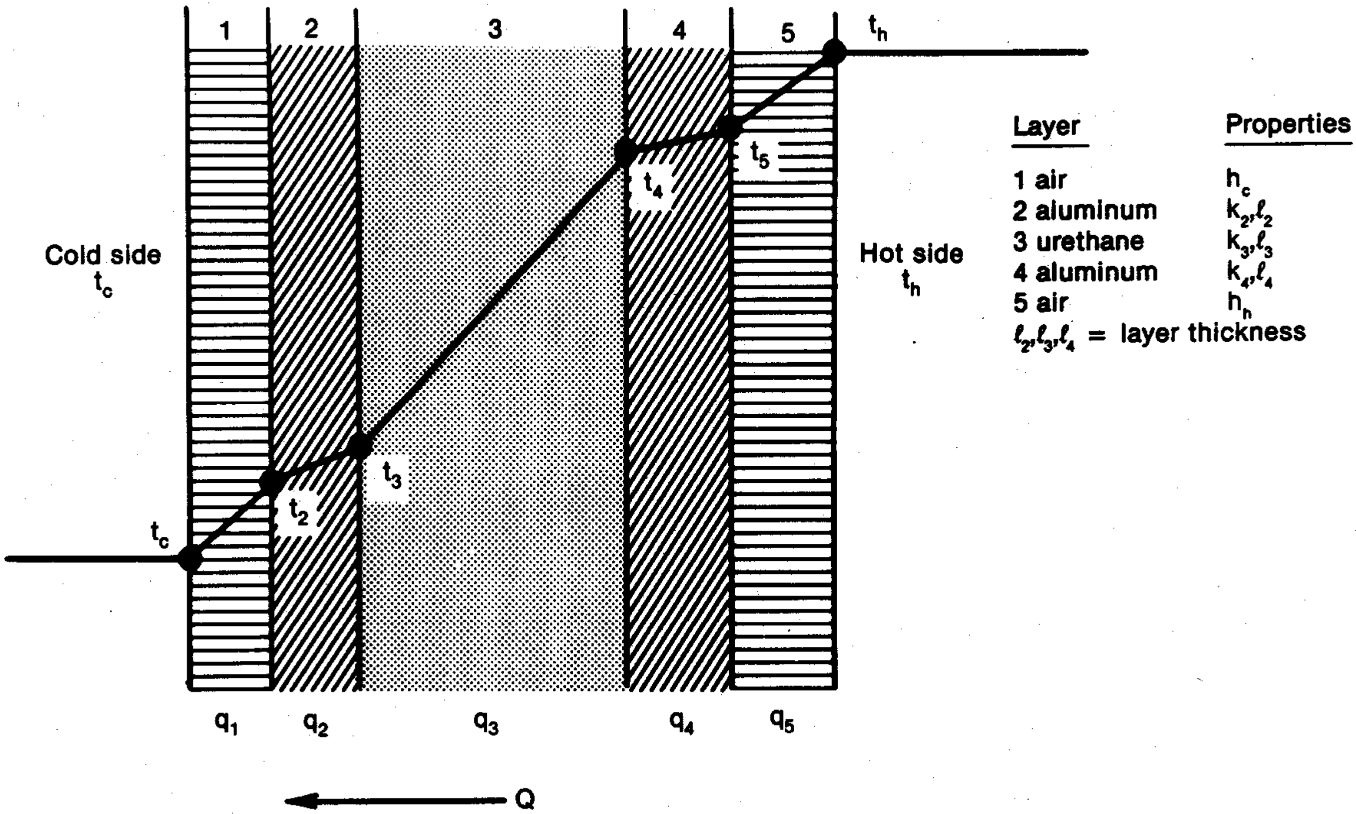

Figure 11-1—Diagram of panel construction. (ML885612)

Overall Heat Transfer Coefficient

Thermal conductivities defined by equation (2) are not directly useful in considering heat losses from dryers since in dry kiln construction, multiple layers of different materials exist in series; for example, gas, aluminum, urethane foam, aluminum, and gas. (Note: To a lesser degree, parallel layering may be used.) The more useful coefficient is the overall heat transfer coefficient U, defined by

$$Q = UA(t_h - t_c) \quad (3)$$

where

U is the overall heat transfer coefficient (Btu/h/ft^2/°F),

t_h air temperature within the dryer, and

t_c air temperature outside the dryer.

The coefficient U is very often expressed as an R value, where $R = 1/U$. The reason for expressing heat loss in this form is that when the characteristics of a given construction are known, the heat loss can be calculated simply by knowing the area and the difference in high (inside) and low (outside) temperature.

When manufacturer specifications (U or R values) for multilayer walls are not known, it is possible to estimate U from known thermal conductance (table 11-1) and heat transfer coefficients. In a steady-state operation (fig. 11-1),

$$Q = q_1 = q_2 = q_3 = q_4 = q_5$$

The heat flow through each layer can be expressed in the form of equation (2):

$$q_2 = \frac{k_2 A}{\ell_2}(t_3 - t_2)$$

or

$$t_3 - t_2 = \frac{q_2 \ell_2}{k_2 A}$$

and

$$q_1 = h_c A(t_2 - t_c)$$

or

$$t_2 - t_c = \frac{q_1}{h_c A} \qquad t_h - t_5 = \frac{q_5}{h_h A}$$

where h_c is heat transfer coefficient of the surface air layer outside the kiln, h_h is the heat transfer coefficient of the surface air layer inside the kiln, and

$$t_h - t_c = (t_h - t_5) + (t_5 - t_4) + (t_4 - t_3) + (t_3 - t_2) + (t_2 - t_c)$$

Substituting for temperature drops in each layer,

$$t_h - t_c = \frac{q_1}{h_c A} + \frac{q_2 \ell_2}{k_2 A} + \frac{q_3 \ell_3}{k_3 A} + \frac{q_4 \ell_4}{k_4 A} + \frac{q_5}{h_h A} = \frac{Q}{AU} = \frac{Q}{A}\left(\frac{1}{h_c} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3} + \frac{\ell_4}{k_4} + \frac{1}{h_h}\right)$$

or

$$U = \frac{1}{1/h_c + \ell_2/k_2 + \ell_3/k_3 + \ell_4/k_4 + 1/h_h} = \frac{1}{R_1 + R_2 + R_3 + R_4 + R_5} \qquad (4)$$

For the panel shown in figure 11-1, which is made of aluminum, urethane foam, and aluminum, an *R* value for the composite can be estimated with the properties given in table 11-1. It is important that consistent units for k and ℓ be used. An example of the method for calculating an *R* value using equation (4) is shown in table 11-3. It should be cautioned that this calculated *R* value may be too high when the panel has metal ends and joints (parallel layering). Under these circumstances, the walls and roofs of an assembled kiln may have greater heat losses than predicted.

Heat Transfer Concepts

Heat is transferred from one body to another by conduction, convection, and radiation.

Conduction is the energy transfer from a high to a low temperature through a medium (solid, liquid, or gas, alone or in combination).

Convection is a complex combination of heat conduction and mass flow; it is the most important form of heat transfer between solid surfaces and liquids or gases (Kreith 1965). Convection can be subclassified as free or natural convection (the physical displacement of energy by movement of material (gas and liquid) induced by density differences) or forced convection (displacement and mixing induced by fans and pumps). Free and forced convection can take place independently or in combination.

Radiation is energy transfer across transparent spaces by electromagnetic means such as infrared wavelengths. The amount of energy transferred will be controlled in conduction by temperature difference (t_2 - t_1); in convection within a medium by density differences or forced means, or both; and in radiation by the difference in the fourth power of absolute temperature $(T_2^4 - T_1^4)$.

In any system exhibiting energy transfer, any of these mechanisms may occur singly or in combination. For practical considerations of energy losses in dry kiln operation, the overall heat transfer coefficient *U* is sufficient for describing heat losses. Inside the kiln, radiation may be a factor in operating performance. Natural circulation (convection) kilns are no longer of commercial importance.

Identification of Energy Consumed in Wood Drying

Even though each individual dryer will consume different combinations and quantities of energy per unit of water evaporated, it is useful to consider energy consumption for the general case, which will help one to understand the limitations and advantages of different drying systems.

In general, all the possible elements of energy consumption and supply in wood drying that appear in various combinations in specific drying systems can be listed as follows:

1. Latent heat required to evaporate water (also heat of adsorption and possibly heat of fusion)
2. Heat loss from dryer structures by conduction from the high-temperature interior through the walls, ceiling, and floor to lower temperature regions outside

3. Heat loss associated with vent air used to remove water vapor from the dryer (and air loss from leaky dryer structures in excess of necessary venting)
4. Sensible heat (heat capacity) required to heat the lumber and building structure to drying temperature
5. Electrical energy needed for air movement
6. Energy source and delivery system

Each of these items is discussed in the following sections.

Latent Heat of Evaporation

Latent heat is directly and invariably determined by the wood volume, specific gravity, and expected percentage of moisture change (expressed on a dry basis).

$$q_a = \text{Volume} \times \text{Specific gravity} \times \rho_{H_2O} \times \lambda \times (M_o - M_f)/100 \quad (5)$$

where

q_a is total heat (Btu) required to evaporate water from wood substance,

λ latent heat of vaporization (Btu/lb H_2O) (moisture content >20 percent),

M_o original moisture content (percent), and

M_f final moisture content (percent).

Let

$$q_a = q_f + q_b$$

where

q_f is energy (Btu) needed to evaporate free water per drying run and

q_b is energy (Btu) needed to evaporate bound water per drying run.

For final moisture contents greater than 20 percent,

$$q_b = 0$$
$$q_a = q_f$$

For final moisture contents less than 20 percent, q_b can be calculated from equation (5), substituting

where volume is total green volume charged to the kiln (ft^3), specific gravity is based on ovendry–green volume of wood (lb/ft^3), r_{H_2O} is the density of water (62.4 lb/ft^3), and

$$\lambda' = \lambda + \Delta h_a \quad (6)$$

(see table 11-1). See table 11-2 for definition of $\bar{\lambda}'$. The variable λ is a function of temperature that can be expressed by the following equation (Keenan et al. 1969):

$$\lambda = 1,075.4 - 0.58(t - 32) \text{ Btu/lb } H_2O$$

where evaporation occurs at temperature t (°F)

Heat Loss From Dryer

The magnitude of the quantity of heat loss from the dryer will depend upon the difference in temperature between the inside and the outside of the dryer, the area of the dryer surfaces, the materials of construction, and the time of dryer operation for any batch run. Heat loss can be expressed as the sum of heat loss through various kiln surfaces at different times in the drying schedule:

$$q = \sum U_i A_i (t_2 - t_1) \theta_i \quad (7)$$

where

q is heat loss through walls (Btu),

U_i overall heat transfer coefficient of individual dryer structural components ($Btu/h/ft^2/°F$),

A_i surface area of walls, ceiling, floors, and doors (ft^2),

t_2 dry-bulb temperature (°F),

t_1 exterior or ambient temperature (°F), and

q_i drying time (h).

Since the temperature of the dryer will vary with time, as by schedule, the time q will be broken into time steps: q_1, q_2, . . ., q_i. Also, the U values of walls, ceiling, and floors will differ: U_1, U_2, . . ., U_i. The outside surface temperature t_1 will vary night to day and the ground (floor) temperature will be higher than the outside air, as will the third wall common in tandem installations. The value t_1 will have seasonal variation for any one location and will vary according to the local climate. Wind may be a factor.

Heat Loss Associated With Vent Air

The kiln most used in wood drying is a forced convection dryer wherein air is the means used to supply heat to evaporate water as well as to remove water from the dryer as water vapor-air mixture. For operations below 212 °F, air will always be needed to vent the dryer. The energy required to heat this vent air from an ambient temperature to dryer exhaust temperature represents a big part of the energy required to dry wood; it is the reason why more than 1,000 Btu are needed per pound of water evaporated in convective dryer operation. Because air will hold more water vapor at higher temperatures, less vent air is needed at higher operating temperatures (for equal relative humidity in the vent exhaust). It is an easy task to calculate necessary venting under various conditions of operation. This is more clearly understood by looking at the psychrometric chart in chapter 1, appendix 1-A, figure 1-A-1. For any given temperature (dry bulb) and relative humidity (wet bulb or wet-bulb depression), one can define a very useful quantity, the absolute humidity H (also called the humidity ratio). The units of this term are pounds water per pound dry air. The vent air needs (volume of vent air per pound of water evaporated) can be calculated as follows:

$$V = V_{\mathrm{air}} + V_{\mathrm{H_2O}}$$

where

V is vented moisture air volume at STP (ft^3),

V_{air} vented dry air volume at STP (ft^3), and

$V_{\mathrm{H_2O}}$ vented H_2O vapor volume at STP (ft^3).

(STP is standard temperature and pressure: 32 °F, 1 atm.)

For the following derivation, let the basis be 1 lb of evaporated water, where the following definitions apply:

H_2 is pounds of H_2O per pound dry air in vent air,

H_1 is pounds of H_2O per pound dry air in ambient air,

m_a, is pounds of air needed to vent 1 lb of evaporated water, and

$$m_a = \frac{1}{\Delta H}$$
$$\Delta H = H_2 - H_1$$
$$V_{\mathrm{air}} = \frac{m_a}{\rho_{\mathrm{air}}}$$
$$V_{\mathrm{H_2O}} = \left(\frac{H_2 m_a}{\rho'_{\mathrm{H_2O}}}\right)$$

Then

$$V = V_{\mathrm{air}} + V_{\mathrm{H_2O}} = \frac{1}{\Delta H}\left(\frac{1}{\rho_{\mathrm{air}}} + \frac{H_2}{\rho'_{\mathrm{H_2O}}}\right)$$

where $\rho'_{\mathrm{H_2O}}$ is the density of water vapor (18/359 lb/ft^3 at STP). So

$$V = \frac{12.38 + 19.94H_2}{(H_2 - H_1)} \qquad (8)$$

Heat loss in vent air q_v (Btu per pound H_2O evaporated) is calculated as

$$\begin{aligned} q_v &= q_a + q_{\mathrm{H_2O}} \\ &= m_a C_{p_{\mathrm{air}}}(t_2 - t_1) + H_1 m_a C_{p_{\mathrm{H_2O}}}(t_2 - t_1) \\ &= (t_2 - t_1)\left(\frac{0.241 + 0.492H_1}{H_2 - H_1}\right) \end{aligned}$$

where C_p is heat capacity (Btu/°F/lb) and q_{H_2O} is sensible heat of the vapor component.

It is interesting to look at venting rates and energy consumption as a function of dryer temperature and relative humidity. Using equations (8) and (9), we can now calculate V and q_v for a dryer operated at two relative humidities, 20 and 80 percent, and different temperature levels (dry bulb), assuming a constant ambient condition of 80 °F, 65 percent relative humidity. The values of H_2 and H_1 can be found in the psychrometric chart (ch. 1, app. 1-A, fig. 1-A-1). The resulting values of V and q_v are given in table 11-4.

The following example uses values V and q_v from table 11-4. Assume the following:

1. Ambient conditions, 80 °F, 65 percent relative humidity, 50,000 fbm red oak kiln
2. Schedule step 1,100 °F, 80 percent relative humidity (6 °F wet-bulb depression)
3. Dry wood weight (WOD) of 145,000 lb
4. Moisture content per day (DR) of 4 percent

Calculate the following:

1. Vent rate (VR) (ft^3/min, STP)
2. Energy to heat vent air (QR) (Btu/min)
3. Drying rate per minute (DW) (lb H_2O per min)

Example:

$$\begin{aligned}\mathrm{DW} &= \mathrm{DR} \times \mathrm{WOD}/(24\ \mathrm{h/day})(60\ \mathrm{min/h}) \\ &= 0.04 \times 145,000/24 \times 60 \\ &= 4.03\ \mathrm{lb/min}\end{aligned}$$

From table 11-4,

$$\begin{aligned}V &= 687\ \mathrm{ft}^3\ (\mathrm{STP})/\mathrm{lb\ H_2O} \\ q_v &= 260\ \mathrm{Btu/lb\ H_2O}\end{aligned}$$

Thus,

$$\begin{aligned}\mathrm{VR} &= V \times \mathrm{DW} \\ &= 687(4.03) = 2,767\ \mathrm{ft}^3\ (\mathrm{STP}) \\ \mathrm{QR} &= q_v \times \mathrm{DW} \\ &= 260(4.03) = 1,048\ \mathrm{Btu/min}\end{aligned}$$

Sensible Heat Demand of Wood and Kiln Structures

By definition, sensible heat is that energy required to raise the temperature of either solids, liquids, or gases without phase-change or chemical reaction. In the case of wood drying, the sensible heat is consumed by raising the wood from ambient temperature to the final discharge temperature as it leaves the kiln. The kiln structure and furnishings must be heated from some low level (ambient and completely cooled) or from an intermediate temperature if little time has elapsed between dryer ‘batch operations. Therefore, the sensible heat demand can be stated as

$$q_s = q_{\mathrm{wood}} + q_{\mathrm{kiln}} \qquad (10)$$

where q_s is total sensible heat.

For wood being dried, the sensible heat is

$$q_{\mathrm{wood}} = \mathrm{WOD} \times C_{p_M}\, \Delta t_s$$

where

C_{p_M} is heat capacity of the combined wood and water at moisture content step MC_i and

At, is temperature change between steps in drying schedule,

with

$$C_{p_M} = C_{p_w} + C_{p_{H_2O}} MC_i$$

where

C_{p_w} is average heat capacity of ovendry wood (C_{p_w} = 0.327 Btu/°F/lb dry wood),

$C_{p_{H_2O}}$ heat capacity of liquid water ($C_{p_{H_2O}} = 1.0$), and

MC_i percent moisture content at any step change.

From this equation, one observes that the heat capacity of wet wood is far greater than that of dry wood; for example, at 100 percent moisture content, C_p = 1.327, while at 10 percent, C_p = 0.427 Btu/lb/°F.

For the kiln structure, the sensible heat is

$$\begin{aligned}q_{\mathrm{kiln}} &= C_{p_M}\ \Delta t \\ \Delta t &= t_2 - t_1\end{aligned}$$

where

t_2 is kiln temperature,

t_1 is beginning kiln temperature, and

$$C_{p_M} = \sum (C_{p_1 m_1} + C_{p_2 m_2} + \cdots + C_{p_i m_i})$$

$C_{p_i m_i}$ represents the product of the heat capacity and weight of individual kiln components other than drying wood.

Electrical Energy for Air Movement

Electric power is needed for air circulation in most dryer types. For any given kiln, the actual power demand for circulating the air will vary with air velocity, package width, board roughness, and sticker thickness. An increase in velocity and package width and a decrease in sticker thickness all will increase the power demand. For one sticker thickness and package width, a maximum attainable velocity exists that corresponds to the maximum power load. A 1-hp motor at maximum load would dissipate 2,547 Btu/h, or 0.746 kW/h. Electrical energy is converted to thermal energy within the dryer in two ways. If the motors are external to the dryer, then only the work done in air movement is converted to heat by friction (air and bearing friction) minus the work of venting. The heat generated within the motor is lost to the external environment (approximately 10 percent of power input). If the motors are within the dryer compartment, then all the electrical consumption appears as heat.

Steam Generations and Delivery Loss

For indirect fire, steam is the most frequent heat transfer medium from fuel to dryer for heating. (Oil, water, and rarely air are other possible heat transfer media.) The closed system of fuel burner, boiler tubing, and steam delivery to finned tube heating coils (condensate return to the boiler) is the drying system most frequently encountered. The net heat as delivered to the kiln represents a fraction of the total energy available in the fuel (heating value) charged to the boiler. Delivery losses may be incomplete combustion, high fuel moisture content, high stack gas temperatures, steam supply line losses, and boiler heat losses. The delivered energy may be of the order of only 75 percent of the heating value of the fuel used.

Energy Demand in Various Wood Drying Systems

Six distinct energy-consuming factors in drying systems were identified in the previous section. Each of these may be present in different dryers to varying relative and absolute degrees. The various drying systems to be considered, in decreasing frequency of use, are as follows:

1. Forced-air convective drying-most common drying method
2. Air drying followed by kiln drying
3. Predrying followed by kiln drying
4. Dehumidification drying
5. Solar drying (alternately with supplemental energy)
6. Vacuum drying (platen, radiofrequency, and forced air)
7. Platen pressdrying

Forced-Air Drying

Latent Heat of Evaporation

Latent heat demand is unalterably dependent only upon the amount of water evaporated. Thus, the magnitude of the quantity of latent heat is only a function of the initial and final moisture content, species, density, temperature of evaporation, and total volume of wood in the dryer. To reduce fuel use for this purpose, one would have to lower initial moisture content by air drying. The quantity of latent heat may represent 20 to 60 percent of the energy consumed within the drying chamber.

Heat Loss

One can reduce heat loss through the kiln walls by selecting equipment with good insulating proper-ties (high *R* values), which remain so under the harsh conditions found in most kilns. Special care must be considered in roof construction and maintenance. Heat loss through the floor can be substantial, and insulation applied during construction will be worth the extra cost. From equation (7) one can see that for given walls, roof, and floor construction, the important factors that increase heat loss are area, temperature difference (inside compared to outside), and time. To a lesser extent, increased air velocity within and outside the dryer will also increase heat loss. Small dryers have a larger heat loss per board foot because of the greater surface area per unit volume (related to wood capacity). The greater the temperature difference, the greater the heat loss; the longer the drying time at a given temperature, the greater the heat loss. While high dryer temperatures will increase the heat loss per unit time, the shorter drying time may actually reduce the total loss.

Vent Air *Loss*

Vent air loss may represent more than 25 percent of the total fuel consumed in the drying system. In equation (9) for heat loss in vent air, note that the important factors in necessary venting are temperature difference between the dryer and makeup air, and the difference in absolute humidity between inside and makeup air. Thus, the most efficient operation of a given system is high absolute humidity in the dryer (vent gases), along with low ambient humidity. Examples are shown in table 11-4. It should not be overlooked that equation (9) assumes that the desired humidity is established by controlled venting-no steam spray humidification. If the dryer is not tight (air leakage) or is overvented because of bad control, steam will be introduced to maintain the humidity, resulting in greater energy demand.

Sensible Heat

When the dryer is cold and charged with cold or even frozen lumber, energy is consumed in heating the wood and kiln structure, in addition to drying and venting. This places the maximum demand on the heat delivery system; this energy demand is shown as a calculated example in figure 11-2 for the case of a red oak hardwood dryer. If the capacity of the heat supply system, such as boiler, is insufficient, the heat-up period will take longer. The current boiler capacity in forced convection kilns is about 30 Btu/fbm/h for hardwoods and 225 Btu/fbm/h for high-temperature drying of softwoods. It is in the nature of the thermodynamics of the dryer operation that the energy required to heat

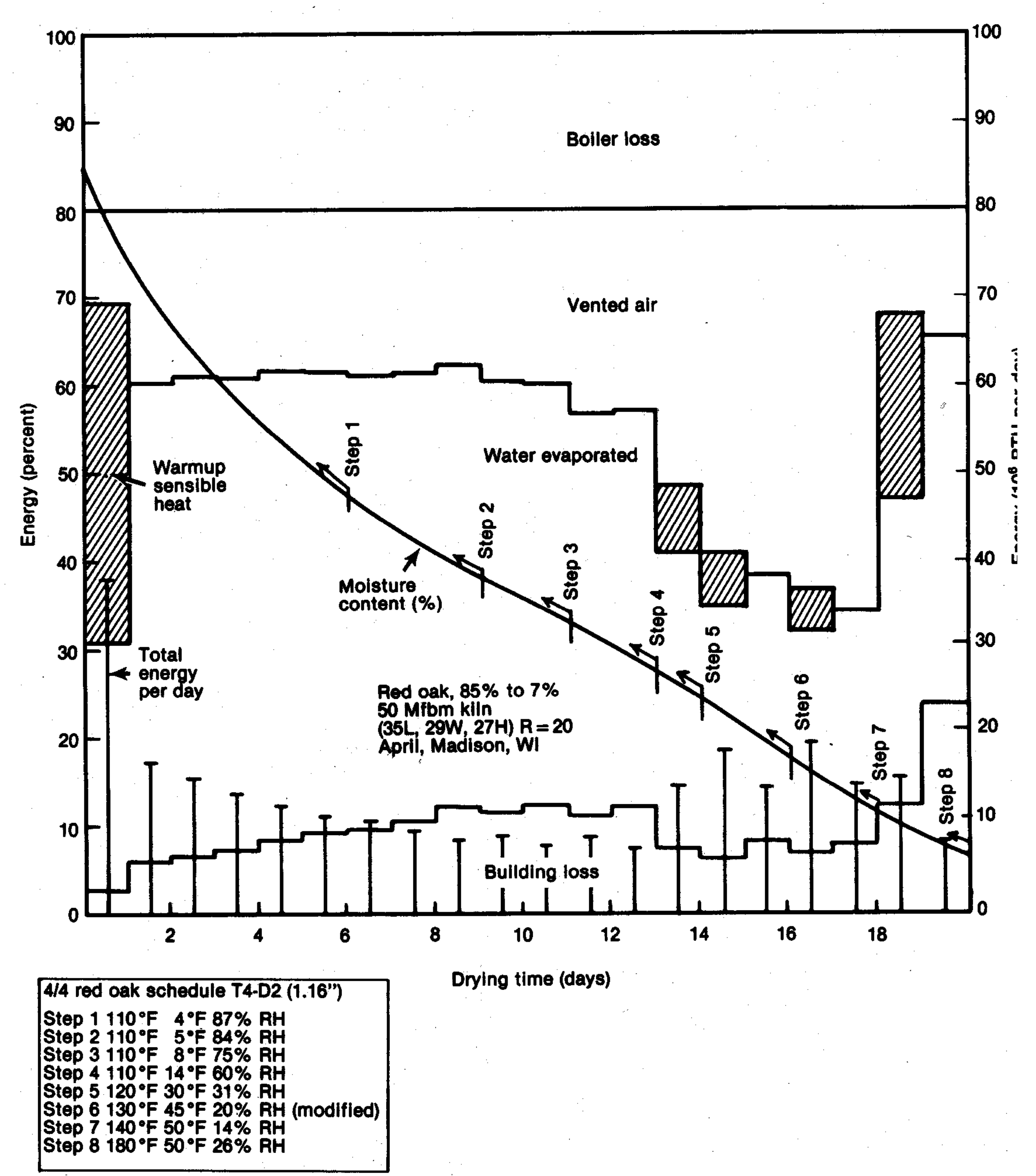

Figure 11-2—Energy partition in kiln drying 4/4 red oak. (ML88 5613)

the wood is actually utilized in evaporating the water (the latent heat of evaporation decreases with increased temperature). The actual sensible heat loss is associated with the final temperature of the dry wood and the kiln structure.

Electrical Energy for Air Movement

Sufficient air movement through a stickered package of lumber is important for optimum drying of wood. The level of airflow (or velocity) needed will depend upon the rate of drying (high or low temperature), width of package, sticker thickness, and hardwood in contrast to softwood operation.

Particularly in hardwoods and thicker stock, the need for high air velocity (for effective heat transfer and removal of evaporated water) is diminished as the average moisture content of the wood drops below 30 percent. Electric power consumption (cost) can be reduced if one can control the air velocity over wide limits. Three fan laws allow us to better understand this phenomenon. These laws are based on constant air density and fan configuration.

1. The total airflow (volume per unit time) is directly proportional to the speed of the fan in revolutions per minute (rpm).
2. The total pressure (head) is proportional to the square of the speed.
3. The power (bhp) is proportional to the cube of the speed.

Thus, if fan speed is reduced by 50 percent, the air velocity will be reduced 50 percent; the pressure head will drop by 75 percent, and the shaft power by 87.5 percent. In actual performance tests under controlled conditions of axial and centrifugal fans of many designs, these three fan laws have been proven correct. The combined motor-shaft-drive system may reduce the power savings as predicted by the third (cubic) fan law. Actually a properly designed electronic speed control fan-motor unit will come close to obeying the cubic law-all other factors being constant. There will always be bearing losses, but for the most part, these are small. With adequate speed control of the motor-drive system, power savings approaching 87.5 percent can be realized with a 50-percent reduction in fan speed. The efficiency of a fan-motor installation, expressed as cubic feet per minute of delivered air per horse power, will vary with actual fan design even though the cubic law still applies.

In the past, velocity could be reduced economically only by using two-speed motors or variable mechanical drives (dc motor controls were possible, but costly). With the advent of solid-state electronic controls, it is now possible to vary the speed of ac induction motors as well as dc motors. For ac induction motors operating at constant voltage, the speed can be changed by varying the frequency and current. This is generally called-a variable frequency drive (VFD) system.

Likewise, for fans with dc drives, the electronic controls can vary the voltage to change the speed. This system is called a silicon-controlled rectifier (SCR) system. The advantage of a VFD over a SCR system is that it can be retrofit into existing drying systems without replacing the motor. However, the operator should be aware that some fan motors are not immediately compatible with this modification, and care must there fore be taken to ensure that the fan works properly. Moreover, the state of the art is such that the solid-state circuits are not as stable at first as they are represented to be. The cost of frequent breakdown and subsequent repair can negate any power savings. Be cause of these disadvantages, the SCR has become the "old workhorse" for continuous speed control.

Energy Source and Delivery System

Forced-air convection dry kilns can be heated indirectly with steam as supplied to heating coils (indirect fire), directly by heated gases (direct fire), or with low-pressure exhaust steam (to coils) from a turbogenerator assembly (co-generation).

Indirect fire.—The most common source of steam for drying is a boiler. The capacity of boilers is frequently rated as boiler horsepower. In terms of Btu, one boiler horsepower is 33,446 Btu/h. For a 50,000-fbm hardwood package dryer, the supply design is about 30 Btu/fbm/h, or 45 boiler hp. For high-temperature southern pine drying, 100,000-fbm capacity, the boilers are sized to at least 225 Btu/fbm/h or more than 675 boiler hp. The choice and availability of fuels for a boiler system affect energy costs. The current and past trends in fuel costs are shown in table 11-5.

The most desirable furnace boiler system would be capable of using multiple fuel types to take advantage of changing fuel markets, but capital costs would be prohibitive. Depending upon completeness of combustion, excess combustion air, stack gas temperature, and fuel moisture content, the net energy delivered to the dryer as steam should be between 70 and 80 percent. The operator should always be vigilant that the boiler system is operating at highest efficiency. For wood-waste fuel, a special concern is the moisture content of the fuel because this affects combustion efficiency and net available energy. Figure 11-3 shows the realized heating values of wood-waste fuels as a function of moisture content (wet basis).

Although indirect fire (steam) is inherently less efficient than direct fire, the advantage of a steam source for equalizing and conditioning cannot be ignored.

Direct **fire.-**As the name implies, direct fire sends the products of combustion from a burner assembly into the dryer chamber. Direct-fired systems inherently use leas fuel than indirect-fired systems. Natural gas burners are particularly efficient for dry kilns when gas supplies are cheap and available. Wood-waste direct-fired burners are also available. Ash flyover into the kiln can occur with this type of burner; burner design and performance need to be scrutinized. In certain improper installations, kiln fires have occurred.

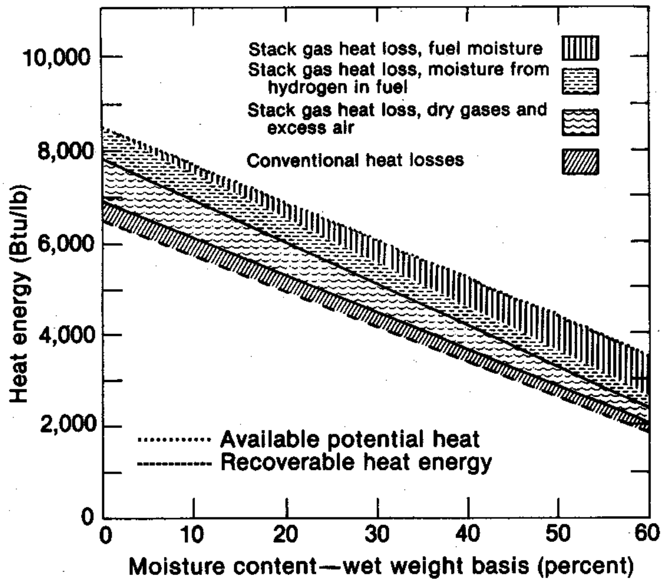

Figure 11-3—Recoverable heat energy, available potential heat, and heat losses for a typical wood fuel per pound of wet fuel at various moisture contents. The fuel has a higher beating value of 8,500 Btu per pound. The higher heat value considers all the water of combustion to be liquid. The combustion heat recovery system is assumed to be operating with 40 percent excess air and a stack gas temperature of 500 °F, fairly typical for an industrial system. A constant conventional heat loss factor of 4 percent and complete combustion are also assumed (Ince 1979). (ML88 5611)

Co-generation.—A growing trend in U.S. industry is co-generation: high-pressure steam is generated in the boiler system, passed through a turbine generator combine for production of electricity, and then exhausted as low-pressure steam for process heating. This system is particularly attractive to firms using large quantities of thermal energy since it can result in 8 to 20 percent savings in energy costs. However, the usefulness of co-generation must be evaluated on a case-by-case basis, taking into account local fuel supply and costs, along with electric power rates.

Air Drying Followed by Kiln Drying

Standard practice, at least in hardwood drying, has been air drying followed by kiln drying. The merits and limitations of air drying are discussed by Rietz (1971). Our concern here is energy savings. If one considers our previous example of a 50,000-fbm kiln as operated in Madison, WI, which dries red oak from different moisture levels, various total energy demands can be calculated for various lumber thicknesses. These calculated estimates are shown in table 11-6. The energy savings are self-evident.

Predrying Followed by Kiln Drying

In recent years, utilization of predryers for controlled "air drying" of hardwoods has increased markedly. The quality of predried wood is high; kiln capacity needs are reduced; and, depending upon the season, kiln location, and construction, energy needs are somewhat reduced compared to those for drying green lumber. Wall insulation, tightness of the building structure, and controlled ventilation are important. The biggest design problem other than structural integrity, however, is air distribution in heated structures holding 1 million fbm of lumber. These dryers operate in the range of 85 to 95 °F. All the elements of increased energy demand are present here.

Dehumidiication Drying

Discussions of dehumidification drying appear in chapters 2 and 7. Since the only energy source for drying is electric power, the cost of this method of drying will depend upon local electric rates, which vary greatly in different parts of the United States. With the use of a closed refrigeration cycle, the net energy to evaporate 1 lb of water is much less than 1,000 Btu, but one must carefully understand the manner in which fuel savings are expressed. A system that uses 50 percent less energy is not a bargain, because the energy costs three times as much as other types of fuel; electric power costs are as high as \$20 per 10^6 Btu. Because of the closed heat cycle, a tight kiln is very important. Modern kilns of this design operate at temperatures as high as 160 °F.

Solar Drying

Analysis has shown that caution should be exercised in considering solar energy as a means of lowering fuel costs; it is not a universal solution to energy economy in wood drying. Therefore, no one should leap into investing in such technology without carefully considering engineering criteria as well as the overall operating economics (Tschernitz 1986).

For a passive solar kiln with supplemental energy, the following observations are made:

1. Supplemental energy is necessary to maintain rapid, consistent drying times for all seasons and all locations.
2. The solar surfaces (if the kiln is essentially a greenhouse in design) should be isolated from the dryer during night hours and during periods of low solar influx.
3. The proper choice of solar cover material and kiln wall insulation is critical for enhanced fuel savings.

4. The winter months in the north are not practical for solar drying on any scale.
5. The supplemental energy could be direct-fired gas when available. Wood waste, while cheaper, might require greater capitalization. Electrical energy is too expensive under most circumstances, although capitalization would be low. Use of electrical energy in conjunction with dehumidification is possible (Chen 1982), but capital costs would be high in this case.
6. The choice of collector surfaces in practice is restricted to roof and south wall (or sloping roof only).
7. The solar kiln, operating as a scheduled dryer, requires that conditioning for stress relief must be provided in some manner at the end of the drying cycle.
8. For noncommercial operators who require only limited quantities of dried wood, a small do-it-yourself unit (1-fbm capacity) built with low-cost materials (such as discarded glass and plastic) would be useful even in the northern tier of states for at least 9 months of the year, even without supplemental energy (Bois 1977, Rice 1987).

Vacuum Drying

For many years, vacuum drying has been promoted periodically. The energy used to evaporate the water can be conductive heating (platen), radiation (radiofrequency or infrared), cyclic heating (forced air), or a combination thereof. No vent air is required; some conducted heat losses occur. The cost of energy, primarily electrical, is high and capital costs are also high. Vacuum drying has a special place in the family of drying systems as a fast method for drying thick lumber.

Platen Pressdrying

In platen pressdrying, heat loss from high-temperature presses is high although no vent air is lost. High-pressure steam or oil is required. Energy is not the principal concern in the choice and operation of platen drying equipment. The virtue of this method is speed and the possible improved properties of wood products.

Practical Applications

Energy Partition in a Typical Forced-Air Kiln

If the drying rate of a given wood species can be established as a function of temperature, relative humidity, moisture content, board thickness, and air velocity (which is related to sticker thickness), then it is possible to model the energy consumption at any time in the drying schedule. The results of such computations for a red oak drying system are shown in figure 11-2, where the percentage of each day's energy demands (which varies day to day) attributed to evaporation of water, vent losses, building losses, and boiler losses are plotted as a function of time. The average moisture content of the lumber after each day is also shown, along with total energy demand per day.

This analysis assumes a 50,000-fbm dryer (35 ft long, 29 ft wide, 27 ft high) as operating in Madison, Wisconsin, in the month of April, which approximates the average condition for a total year. The example is for 4/4 red oak, using a slightly modified T4-D2 schedule (ch. 7).

The highest daily energy demand is the first day warmup; as the drying rate decreases, the building energy loss fraction tends to increase; as the dryer temperature is raised and relative humidity drops, the vent energy losses are greater. This pattern will shift winter to summer and location to location. Building energy losses will be higher in the winter; vent losses will increase with very humid ambient conditions. The seasonal change in total energy demand can be illustrated by a series of calculated total energy demands for a small (1,000 fbm) and a large (30,000 lbm) 4/4 red oak dryer as operated in different regions of the United States. In addition, the reduced energy consumption of a large kiln compared to a small one is indicated. These calculated values are shown in table 11-7.

Fuel Costs and Delivery Systems

The economic criterion for choosing fuel for drying wood is not simply the fuel with the lowest cost. If that were the case, solar energy would be the first choice, electricity the last. The values shown in table 11-5 are average past and current fuel costs. There is much local variation in fuel costs, particularly electricity, as well as seasonal variation.

To select the best fuel, the most obvious consideration is the uninterrupted availability of fuel supply. The next and perhaps most important consideration is the capital cost of the equipment needed to convert the fuel into useful thermal energy. This is best illustrated in converting solar energy, where collecting the energy and its intermittent delivery are currently too costly for most large-scale commercial wood drying operations.

Thirdly, the efficiency of converting fuel to useful energy must be examined. A low-cost conversion apparatus may consume much larger quantities of fuel and may therefore incur a higher net operating expense. Direct fire (wherein the combustion gases enter the drying chamber) should be considered since a steam boiler and heat transfer coils are not needed. Direct fire is therefore 100 percent efficient, requiring less capital investment.

Decreasing drying time may be a way to compensate for a high-cost fuel such as electricity. For example, rapid drying of the stock in an electrically heated dryer may be economically sound considering both the quantity and value of the product and sharply reduced drying time.

Maintaining High Energy Efficiency in Existing Forced-Air Kilns

The following list (McMillen and Wengert 1978) should be helpful in increasing the efficient use of energy during kiln drying.

1. Use as much air drying or forced-air drying as possible--preferably drying to 25 percent moisture content or less. While this will reduce the cost of energy, lumber degrade costs may offset the energy savings.

2. Do not use steam spray or water spray in the kiln except during conditioning. Let the moisture coming out of the wood build up the humidity to the desired level. Steam may have to be used, however, when very small wet-bulb depressions are required.

3. Repair and caulk all leaks, cracks, and holes in the kiln structure and doors to prevent unnecessary venting and loss of heat. Make sure the doors close tightly, especially at the top. Temporarily plug any leaks around the doors with rags, and order new gaskets, shimming strips, or hangers if necessary. In a track kiln, use sawdust-filled burlap bags to plug leaks around tracks. Adjust and repair the vents so that they close tightly.

4. For brick or cinder block kilns, maintain the moisture vapor-resistant kiln coating in the best possible condition. This will prevent the walls and the roofs from absorbing water. Dry walls conduct less heat to the outside.

5. For outdoor aluminum kilns only, paint the exterior walls and roof a dark color to increase the wall temperature by solar heat and reduce heat loss from the kiln. Check to ensure that weep holes are open, not plugged. Painting would be disastrous on permeable walls like brick or cinder block.

6. In many kilns, more heat is lost through the roof than through the walls, and much of this loss is due to wet insulation. To reduce heat loss, consider installing a new roof or repairing an old one. Add more insulation if necessary. Make sure the interior vapor barrier or coating is intact (see suggestion 4).

7. Install or repair baffling to obtain high, uniform air velocity through the lumber and to prevent short circuiting of the airflow. This pays off in saving energy. Reverse air circulation every 6 h only.

8. Research has shown that in the early stages of drying, high air velocities (more than 600 ft/min) can accelerate drying. In the late stages, low velocities (250 ft/min) are as effective as high velocities and use less energy. Therefore, adjust fan speeds during a run if possible.

9. Calibrate and check the recorder-controller for efficient operation. Kiln conditions should not oscillate between periods of venting and steam spraying, and venting and steaming should not occur at the same time.

10. Check the remainder of the equipment. Are traps working? Do traps eject mostly hot water with little, if any, steam? Do valves close tightly? Are heating coils free of debris? Is valve packing tight? Is there adequate water for the wet bulb?

11. Accurately determine the moisture content of the drying wood. Do not waste energy by overdrying be cause the sample boards do not represent the load. Try to plan the loads so that when they are sufficiently dry, someone will be available to shut off the kiln (and, if possible, to unload, reload, and begin a new run). Do not allow a kiln load of dry lumber to continue to run overnight or through a weekend.

12. Unload and reload the kiln as fast as possible, but avoid doing this until the air temperature has warmed up from the morning low temperature. Do not cool the kiln unnecessarily.

13. In a battery of adjacent kilns, avoid unloading or loading a kiln while the adjacent kiln is at 180 °F or another high temperature.

14. During nonuse periods, close all valves tightly and keep kiln doors closed. Use a small amount of heat, if necessary, to prevent freezing of steamlines and waterlines.

15. Use accelerated schedules where possible. Check chapter 7 for schedules for accelerating schedules with minimum risk. The higher the drying temperature, the more efficient the energy use.

16. If possible, reduce the length of time used for conditioning; some low-density hardwoods can be conditioned in 6 h.

17. Finally, check with the manufacturer of your equip ment to determine if steam pressures can be lowered or gas or oil flow rates reduced during periods of constant dry-bulb temperature. For top efficiency, check the burner as well.

Heat Recovery From Vent Air

The use of air-to-air heat exchangers-sometimes called economizers-for partial recovery of energy exhausted from dry kilns has been considered ‘for decades. Cost, efficiency, and design problems made practical application of these units marginal. Rising fuel and boiler costs, along with new designs, again make such recovery systems worth considering. In addition to conventional air-to-air heat exchangers, “heat pipes” (Perry and Chilton 1973) have recently been incorporated into a new design for dry kilns with interesting possibilities.

List of Symbols

A surface area (ft^2)

C_p heat capacity (Btu/°F/lb)

C_{p_w} heat capacity of ovendry wood (Btu/°F/lb dry wood)

DR moisture content per day (percent)

DW rying rate per minute (lb H_2O/min);

H_1 pounds water per pound dry air in ambient air

H_2 pounds water per pound dry air in vent air

h_c, h_h heat transfer coefficient of surface air layers

k thermal conductivity (Btu/h/ft/°F)

ℓ substance thickness (ft)

M_f final moisture content (percent)

M_i intermediate moisture content (percent)

M_o original moisture content (percent)

m_a pounds air needed to vent 1 lb evaporated water

MC_i moisture content at any step change (percent)

Q energy (Btu/h)

q heat loss through walls (Btu)

q_a energy needed to evaporate water in wood (Btu)

q_b energy needed to evaporate bound water per drying run (Btu)

q_f energy needed to evaporate free water per drying run (Btu)

q_{kiln} sensible heat of kiln structure (Btu)

q_s total sensible heat (Btu)

q_v energy lost in vent air (Btu)

q_{wood} sensible heat of wood (Btu)

QR energy needed to heat vent air (Btu/min)

T absolute temperature (°R)

t_c air temperature outside dryer (°F)

t_h air temperature within dryer (°F)

U overall heat transfer coefficient (Btu/h/ft^2/°F)

V vented moist air volume at standard temperature and pressure (ft^3)

V_{air} vented dry air volume at standard temperature and pressure (ft^3)

V_{H_2O} vented water vapor volume at standard temperature and pressure (ft^3)

VR vent rate (ft^3/min)

WOD dry wood weight (lb)

ΔH pounds water per pound dry air evaporated ($H_2 - H_1$)

Δh_a differential heat of wetting (Btu/lb)

Δt temperature difference (°F)

Δt_s temperature change between steps (°F)

q drying time (h)

λ latent heat of evaporation (Btu/lb)

λ' $\lambda + \Delta h_a$

r density (lb/ft^3)

r'_{H_2O} density of water vapor

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Table 11-1—Heat capacity and other properties of selected materials

Material	Heat capacity (C_p) (Btu/lb/°F)	Thermal conductivity (k) (Btu/h/ft/°F)	Density (p) (lb/ft³)	Specific volume (1/p) (ft³/lb)
Water				
Solid	0.46	1.28	57.2	0.0175
Liquid	1.00	0.375	62.4	0.0160
Gas	0.492	0.0142	[1]0.0373	26.8
Wood	[2]0.327	0.11	35	0.0286
Air	0.241	0.0174	0.081	12.4
Steel	0.11	25	489	0.002
Concrete	0.21	0.47-0.81	130	0.007
Aluminum	0.21	100	170	0.005[illegible]
Urethane foam		0.02		
Stainless steel	0.11	7	510	0.002
Copper	0.092	220	559	0.001[illegible]

[1]14.7 lb/in²: 212 °F.
[2]Dry Wood.
[3]14.7 lb/in²: 32 °F.

Table 11-2—Differential heat of wetting and latent heat of bound water at 150 °F[1]

Moisture content (percent)	Differential heat of wetting (Δh_a) (Btu/lb)	Latent heat of evaporatio (Btu/lb)[2] λ'	$\overline{\lambda'}$
20	27	1,034	1,034
15	55	1,062	1,048
10	113	1,120	1,072
8	151	1,158	1,094
6	203	1,210	1,117
4	270	1,277	1,144
2	360	1,367	1,1[illegible]
1	416	1,423	1,2[illegible]

[1]For moisture contents less than 20 percent.
[2]λ = 1,007 Btu/lb H_2O at 150 °F
$\lambda' = \gamma + \Delta ha$ Btu/lb H_2O removed at M_i
$\overline{\lambda'}$ = Btu/lb H_2O removed in the internal MC of 20 percent to M

Table 11-3—Calculated R value for aluminum panel

Panel[1]	[2]h_i	k_i	P_i	$1/R_i$	R_i
Cold air side (1)	1.5	—	—		0.667
Aluminum layer (2)	—	100	0.0156 (3/16 in)	6,369	0.0002
Urethane foam[3] layer (3)	—	0.02	0.333 (4 in)	0.0606	16.50
Aluminum layer (4)	—	100	0.0156 (3/16 in)	6,369	0.0002
Hot air side (5)	0.6	—	—		0.16666
					[4]R = 17.33

[1]Numbers in parentheses correspond to notation in Figure 11-1.
[2]Gas film heat transfer coefficient, h_i (Btu^2 ft·h °F).
[3]The thermal conductivity k_i of urethane foams will vary with mode of manufacture.
[4]Reciprocal of R is U = 1/R = 0.058 (Btu/ft^2·h °F).

Table 11-4—Vent rates and associated heat losses per pound of water evaporated at various dryer temperatures and relative humidities[1]

Dryer temperature (°F)[2]		Absolute humidity		Vent rate[3] (ft^3/lb H_2O evaporated)	Vent heat loss[4] (Btu/lb H_2O evaporated)
tDB	tWB	H_2	$H_2 - H_1$		
DRYER RELATIVE HUMIDITY OF 80 PERCENT					
100	94	0.034	0.019	687	260
120	113	0.066	0.051	269	194
140	132	0.117	0.102	144	145
160	151	0.216	0.201	83	98
180	170	0.430	0.415	50	60
200	190	1.090	1.075	32	28
DRYER RELATIVE HUMIDITY OF 20 PERCENT					
100	70	0.0085	—	—	—
120	82	0.0161	0.0011	11,645	9,020
140	95	0.0250	0.0100	1,288	1,488
160	110	0.045	0.0300	446	661
180	127	0.072	0.0570	242	435
200	135	0.118	0.103	143	289

[1]Ambient temperature (t_1) is 80 °F, relative humidity is 65 percent, and H_1 = 0.015 pound H_2O per pound dry air.
[2]DB is dry-bulb temperature (t_2): tWB is wet-bulb temperature.
[3]Equation (8).
[4]Equation (9).
Note: For total energy loss in the vent gases, add the latent heat of evaporation of water, λ, to this value, q_v.

Table 11-5—Fuel costs

Fuel type	Industrial fuel costs per 10^6 Btu				Energy per unit supply (Btu)
	1967[1]	1979[2]	1982[3]	1986[4]	
Power (electric)[5]	$1.20-4.40	$11.70	$17.56	$19.35	1 kW (3,414 Btu/h/kW)
Coal	0.16-0.35	1.25	1.66	1.53	10,500 Btu/lb
Oil no. 6	0.25-0.85	3.07-3.40	4.75-5.50	2.99-3.47[6]	138,700 Btu/gal
Natural gas	0.18-0.60	2.80-3.00	3.27-5.21	2.90-4.72	1,030 Btu/ft[3]
Liquid propane (LP)	0.33-0.60	4.50	8.10-11.50[7]	6.17-7.36[7]	92,400 Btu/gal
Wood waste (50 percent moisture content, wet basis)[8]	—	0.50-2.00	0.50-2.00	0.50-2.00	3,400 Btu/lb[9]
Solar	0	0	0	0	1,000-1,900 Btu/day/ft^2 [10]

[1]Data from Chemical Weekly 101.83, October 28, 1967.
[2]Data from Monthly Energy Review, Department of Energy, February 1980.
[3]Data from Monthly Energy Review, Department of Energy, March 1982.
[4]Data from Monthly Energy Review, Department of Energy, November 1986.
[5]1967, 0.4-1.5¢/kWh; 1986, 6.59¢/kWh.
[6]Oil no. 2.
[7]Local supplier (Madison, WI).
[8]*Forest Service, large local variation in cost.*
[9]Ince 1979.
[10]United States. (Horizontal surface. Add 1,000 for June.)

Table 11-6—Total energy demand for kiln drying air-dried red oak

Lumber Size[1]	Energy demand[2] at various levels of initial moisture content		
	30%	50%	80%
4/4 (1.156)	2.54 (8)	3.92(15)	5.58(20)
5/4 (1.438)	2.69(11)	3.97(20)	5.81(27)
6/4 (1.688)	2.78(13)	4.09(25)	6.09(36)
8/4 (2.250)	3.50(23)	5.02(41)	6.88(56)

[1]Green size.
[2]Energy (10^6 Btu/thousand fbm) required to dry lumber to 7 percent moisture content for the average climate in Madison, WI, by schedule T4-D2 for 4/4 and 5/4 lumber and schedule T3-D1 for 6/4 and 8/4 lumber. Numbers in parentheses indicate drying days.

Table 11-7—Energy demands for a low-temperature drying schedule for 4/4 red oak in three regions of the United State!

Kiln size (1,000 fbm)	Package height[2]	Energy demand (10^6 Btu/thousand fbm)			
		Annual average	January	July	Difference
SOUTHWEST (PHOENIX, AZ)					
1	1	5.93	7.92	3.88	4.04
30	2	4.06	4.06	2.45	1.61
SOUTHEAST (ATLANTA, GA)					
1	1	7.34	9.05	5.93	3.12
30	2	4.41	4.64	3.74	0.90
NORTH CENTRAL (INTERNATIONAL FALLS, MN)					
1	1	9.51	13.11	6.42	6.69
30	2	4.67	5.96	3.50	2.46

[1]Without fan energy; 28-day schedule, maximum temperature 120 °F.
[2]Package height in terms of number of packages.