ACKNOWLEDGEMENTS

The authors would like to acknowledge the assistance and suggestions of the following persons: Professor Richard A. Hale, School of Forest Resources, University of Maine; Mr. James W. Catterick, Technical Representative of the Irvington-Moore Division, U. S. Natural Resources Company; Mr. Lewis P. Bissell, Extension Forester, School of Forest Resources, University of Maine, Orono, and Mr. Issac A. Okoh, College of Environmental Science and Forestry, SUNY, Syracuse.

Portions of the information contained in this report have been presented at sessions of the Dry Kiln Short Course program, conducted bi-annually by the School of Forest Resources, under the direction of Mr. Hale and Mr. Bissell.

This study was conducted with the support of the McIntire Stennis Program, Public Law 87-788, Project MS 5004.
## CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>BACKGROUND</td>
<td>2</td>
</tr>
<tr>
<td>ELEMENTS OF HEAT CONSUMPTION IN A DRY KILN</td>
<td>3</td>
</tr>
<tr>
<td>PROCEDURE FOR ESTIMATING HEAT CONSUMPTION IN A DRY KILN</td>
<td>6</td>
</tr>
<tr>
<td>EXAMPLE OF ESTIMATING HEAT CONSUMPTION IN A DRY KILN</td>
<td>13</td>
</tr>
<tr>
<td>SUMMARY</td>
<td>22</td>
</tr>
<tr>
<td>SOME SUGGESTED REFERENCES</td>
<td>23</td>
</tr>
<tr>
<td>FPRS KILN DRYING NOTE</td>
<td>24</td>
</tr>
</tbody>
</table>
ESTIMATING HEAT CONSUMPTION IN KILN DRYING LUMBER

James E. Shottafer and Craig E. Shuler*

INTRODUCTION

With increasing emphasis on the cost and availability of energy, the heat consumed in the kiln drying of lumber has become a point of immediate interest to the wood conversion industries. The use of green, or undried lumber is undesirable in most cases, and impossible in many others. Modern production schedules often do not permit the elapsed time necessary to air dry lumber to an acceptable moisture content level, and in many areas of the Northeastern United States, the terminal equilibrium moisture content that may be attained is still unacceptably high. Since the use of heat, often in significant quantities, is necessary to kiln dry wood satisfactorily, some method should be available to quantitatively estimate the consumption of this heat during the drying processes. Such an estimate should provide the kiln operator with some comparative measure of the efficiency of the kiln and the procedures employed in its use, and permit more precise estimates of potential materials processing costs.

This report presents one method for systematically estimating heat consumption in a dry kiln. The basis for evaluating heat use is presented along with a description of the specific elements of heat consumption. A necessary physical relationships are described in detail for those who wish to employ them. One point of interest here is the fact that the system described will readily lend itself to the construction of a mathematical model. The operator with the requisite skills and a small computer, or even a modern electronic calculator, may develop a system model for his kiln operation with which any or all of the elements of heat consumption may be rapidly estimated.

For the operator who prefers a more practical approach to the problem, an example is presented which describes a step-by-step evaluation of heat consumption in a typical kiln drying operation. By substituting the appropriate physical values where necessary, the method may be adapted to most conventional kiln drying processes.

*Professor and Assistant Professor, respectively, School of Forest Resources, University of Maine, Orono.
BACKGROUND

Since the objective in kiln drying wood is basically to reduce the amount of moisture in the material to a specific level, what the heat in a kiln is fundamentally used for is to increase the temperature of the air in the kiln, so that the ability of the air to hold moisture is increased. This will cause the moisture in wood to move, for various reasons, into the air until a balance, called the equilibrium moisture content (EMC), is obtained. When the EMC is at the level we wish, the work of the kiln drying process is done.

All we really wish to do, then, is heat air; but this is complicated by the fact that some of the heat introduced into the kiln does not go where we want it to. Some is absorbed by the wood, water, kiln walls and other equipment inside the kiln. Another problem is that once we have moved the water into the air, we must then move this moist air away from the wood, to prevent the water from simply returning to the wood if the air cools. We must therefore heat new, dry air to replace the moist air we remove from the vicinity of the wood. Finally, a dry kiln or any type of drying chamber will have some loss of heat that simply escapes without performing any useful drying work.

The heat used, therefore, must accomplish four basic things in the process of drying the wood in the kiln:

a). Heat the air in the kiln or entering the kiln
b). Heat any material in the kiln
c). Provide energy for any thermodynamic requirements involved in removing the moisture from the wood
d). Compensate for any loss of heat in the system

Dry kiln engineers make quite precise calculations of the heat requirements when new kilns are being designed or during critical wood drying of kiln research. The average kiln operator seldom needs such levels of precision; however, it is often useful for the operator to have some general estimate of where the heat is going during a kiln run.

All kilns, regardless of design or type, tend to be unique, with no two exactly the same in respect to operating characteristics. Comparative estimates of the heat requirement imposed by different species, schedules, or final EMC specifications may prove of great interest to the operator. Of particular use might be an occasional evaluation of the
kiln itself, in terms of the percentage of the total heat used which is lost

ELEMENTS OF HEAT CONSUMPTION IN A DRY KILN

The four basic uses of heat, can be considered as six specific elements. These are discussed separately, since they are treated somewhat differently in calculations.

1. The heat required to raise the temperature of wood substance \( (H_1) \)

All materials have the ability to absorb heat. How much heat is absorbed as the temperature is raised is dependent upon the change from initial to final temperature, the amount of material present, and a unique material property known as the thermal capacity (or specific heat). The thermal capacity of a material is found experimentally and is a constant for any temperature.

For wood substance the thermal capacity \( (c) \) in Btu/lb°F is:

\[
c = 0.266 + 0.000644 (T - 32)
\]

(Where \( T \) is the average temperature in °F.)

For any temperature range this expression becomes:

\[
c = 0.266 + 0.000322 (T_1 + T_0 - 64)
\]

(Where \( T_1 \) is the final temperature of the wood and \( T_0 \) is the initial temperature, both in °F.)

The heat requirements of the wood in the kiln are found by the relationship of:

\[
H_1 = \text{Weight of wood substance} \times \text{thermal capacity} \times \text{change in temperature}
\]

2. The heat required to overcome hygroscopic forces \( (H_2) \)

The chemical structure of wood is such that water vapor is readily attracted to it and held by relatively weak chemical bonds. When the wood is nearly oven dry, the bonds are relatively quite strong while for the free water above the fiber saturation point, there are zero hygroscopic forces. Experiments have indicated that 34 Btu are required to overcome hygroscopic forces whenever one pound of wood substance is dried from green condition to oven dry. This heat require-
ment, known as the heat of desorption, drops off rapidly as higher final moisture contents are desired.

\[ H_2 = \text{ovendry weight of wood} \times \text{heat of desorption} \]

3. The heat required to raise the temperature of any water remaining in the wood \((H_3)\)

Kiln operations do not dry wood to zero moisture content. Thus at the end of the kiln run there is still some water remaining in the wood. Since during the run the temperature of the kiln has been increased, some of the heat has gone to raising the temperature of this water. The heat requirement designated as \(H_3\) is concerned only with the heat absorbed by the wood substance itself. The heat absorbed by the residual water is found in the same manner.

\[ H_3 = \frac{\text{weight of residual water} \times \text{thermal capacity}}{\text{temperature change}} \]

The thermal capacity of water is not truly constant but is dependent upon the temperature when the measurement is made. For practical considerations, however, the thermal capacity of water can be considered to be 1 Btu/\(\text{lb}^{\circ} \text{F}^{\circ}\).

4. The heat required to raise the temperature and evaporate the water removed from the wood \((H_4)\)

The heat absorbed by the water which is actually removed from the wood is also the product of the weight of the water, thermal capacity, and the temperature involved. Before the water can be removed by the air circulating in the kiln, however, it must also be evaporated. To cause this change from liquid to vapor at a given temperature requires a considerable amount of energy. This energy is effective only in bringing about the change in the physical state of the material and does not function in raising the temperature of the material. This energy is known as the latent heat of vaporization. The latent heat of vaporization for water is not a constant but is dependent upon the particular temperature at which evaporation occurs. Consequently, the heat requirement for this element must be calculated for each temperature step of the kiln schedule. The total heat consumption is simply the sum of that used in all the steps. The heat consumption \(H_4\) at any step "a" in the kiln schedule may be calculated as:

\[ H_4 (a) = \left( \text{weight of water removed at step "a"} \times \text{thermal capacity} \times \text{temperature change} \right) + \left( \text{weight of water removed at step "a"} \times \text{latent heat of vaporization "a"} \right) \]
\[ H_4 = H_4(a) + H_4(b) + H_4(c) \text{ etc. for all the schedule steps.} \]

5. The heat required to raise the temperature and humidify the incoming vent air \((H_5)\)

As water is removed from the wood, it becomes water vapor in the air circulating within the kiln. When the air becomes saturated with water vapor, new dry air must be introduced into the kiln or the drying process will cease. This new air must then be elevated to the temperature in the kiln. Since kiln controls are not sufficiently precise to allow only the exact amount of necessary air into the kiln, a certain amount of excess air will also be admitted. The incoming air already contains some moisture, depending on the outside temperature and relative humidity conditions. This moisture also absorbs some heat. The excess air behaves like the required air, but since it is just excess it must be humidified to be brought up to the humidity conditions of the required kiln air, which is being humidified by water vapor from the wood. This humidification is brought about by the direct spraying of steam into the kiln. The total heat consumption of this element is dependent upon: the weight of the air brought into the kiln, the weight of water held in the vent air, the thermal capacities of the air and the water vapor, the temperature change, and the latent heat of vaporization needed for the production of the humidifying vapor.

6. The heat required to replace losses from the system \((H_6)\)

Some heat will be absorbed by the kiln structure itself. This heat will be conducted through the structure to the outside. In order to maintain the desired temperature in the kiln, these losses must be replaced. The amount of loss in this manner is dependent upon the thermal conductivities of the various materials making up the kiln walls, roof, floor, and other items such as doors. The combination of several materials in a single unit (such as a wall) makes it difficult to evaluate each thermal conductivity. As a result, a coefficient of heat transmission is used for the component as a whole unit. These coefficients are determined for most types of kiln construction and may be obtained from the kiln construction company. The heat consumption for this element is dependent upon the heat transmission coefficients of the kiln materials, the surface area in question, the temperature change, and the total time involved.
The estimate of the heat consumption during a kiln run is the sum of the heat requirements imposed by these six elements.

PROCEDURE FOR ESTIMATING HEAT CONSUMPTION IN A DRY KILN

Since each of the elements of heat consumption is responsible for some of the heat used by the kiln during a drying run, some estimate of each element must be made in order to determine the total amount of heat used. The particular method for calculating the amount of heat consumed by each element is somewhat different, but certain information is needed throughout the procedure.

The dry bulb temperature (DBT), wet bulb temperature (WBT), moisture content (MC), and the various time relationships during the kiln run must be known. All of these are available, of course, from the particular drying schedule used. An actual schedule, such as those recommended in the Dry Kiln Operators Manual, a schedule developed and followed by the kiln operator, or a graph of the schedule, such as Figure 1, may be used.

The schedule used as an example is only one of numerous possibilities. It is recognized that in many mills, eastern white pine is being dried at temperatures of at least 180°F. Also, this example does not show any equalizing or conditioning treatments. The only effect this has on heat consumption is to increase the element replacing heat losses. Since the temperatures and moisture content are no longer changing, the other elements are effectively zero.

The following thermal capacity values are used as constants throughout the entire procedure:

- Air: \( c_a = 0.24 \text{ Btu/lb}^\circ\text{F} \)
- Water vapor: \( c_{wv} = 0.45 \text{ Btu/lb}^\circ\text{F} \)
- Water: \( c_{H_2O} = 1.0 \text{ Btu/lb}^\circ\text{F} \)

All temperatures are expressed as degrees Fahrenheit (°F), and thermal capacity or heat capacity values as British thermal units per pound per degree Fahrenheit (Btu/lb°F).

1. Determine \( H_1 \) The heat required to raise the temperature of the wood substance (Btu)
A. Determine the temperature of wood in the yard (°F) \( T_0 \)

B. Determine the maximum temperature reached during the kiln run (°F) \( T_1 \)

C. Calculate the average heat capacity of the wood substance (Btu/lb°F)
\[
c_w = 0.266 + 0.000322 (T_1 + T_0) = 64
\]

D. Determine the specific gravity of wood, based on green volume. (See Wood Handbook or Dry Kiln Operator's Manual).

E. Determine the volume of wood in the kiln (ft³) assuming the kiln is filled to capacity:
\[
V_w = \text{bd. ft. capacity of the kiln}
\]

F. Calculate the ovendry weight of the wood substance in the kiln (lb)
\[
\text{ODW} = V_w \times \text{SGgr} \times 62.4 \text{ (lbs/ft}^3\text{)}
\]

G. Determine the maximum change in temperature (°F)
\[
\Delta T = T_1 - T_0
\]
and:
\[
H_1 = \text{ODW} \times c_w \times \Delta T
\]

2. Determine \( H_2 \) The heat required to overcome hygroscopic forces (Btu)

A. Using Figure 2, determine the heat of desorption at final moisture content in the kiln schedule (Btu/lb of ovendry wood)

and:
\[
H_2 = \text{ODW} \times D
\]

3. Determine \( H_3 \) The heat required to raise the temperature of any water remaining in the wood (Btu)
A. Calculate the amount of water remaining in the wood at the final moisture content in the kiln

\[ W = ODW \times \text{final MC expressed as a decimal} \]

and

\[ H_3 = W \times c_{H_2O} \times \Delta T \]

4. Determine \( H_4 \) - The heat required to raise the temperature of the water removed from the wood, and to evaporate it (Btu)

Note: The first four steps in this section of the procedure must be repeated for each dry bulb temperature stage in the kiln schedule.

A. Using Figure 3, determine the latent heat of vaporization of water at dry bulb temperature level concerned (Btu/lb of water)

B. Using the kiln schedule, determine the moisture content change during the dry bulb temperature period concerned (%). Express as a decimal.

\[ \Delta MC = \frac{(MC \text{ at start of period})}{(MC \text{ at end of period})} \]

C. Determine the change in temperature represented by the dry bulb temperature level concerned (°F)

\[ \Delta t = DBT - T_0 \]

D. Calculate \( H_{4i} \) at \( i \) °F DBT level (Btu)

(i indicates only the particular DBT level at which the value is being calculated)

\[ H_{4i} = ODW \times \Delta MC \times [c_{H_2O} \times \Delta t + h] \]

REPEAT FOR EACH DBT LEVEL IN THE KILN SCHEDULE

and:

\[ H_4 = \Sigma H_{4i} \text{ values, i.e. the sum of all the } H_{4i} \text{ values, or the } H_4 \text{ values calculated at each DBT level in the kiln schedule.} \]
5. Determine the heat required to raise the temperature and humidify the incoming vent air (Btu)

A. Using Figure 4, determine the pounds of water vapor contained in each pound of incoming vent air, based on outside temperature \( T_0 \) and relative humidity. \((lb/lb)\)

B. The following calculations must be made for EACH COMBINATION OF WET AND DRY BULB TEMPERATURES, OR STAGE, IN KILN SCHEDULE.

a) Using the kiln schedule, determine the relative humidity in the kiln at the WBT-DBT combination concerned.

b) Using Figure 4, determine the pounds of water vapor that can be held by a pound of heated air in the kiln \((lb/lb)\)

c) Calculate the amount of water vapor that can be absorbed by the incoming vent air \((lb/lb\ of\ air)\)
\[ d = j - b \]

d) Using the kiln schedule, determine the moisture content change in the wood during the WBT-DBT period concerned \((\%)\). Express as a decimal.
\[ \Delta mc = (MC\ at\ start\ of\ period) - (MC\ at\ WBT\ or\ DBT\ change) \]

e) A certain percentage of excess air will be required ranging from 5 to 25\%, depending on the kiln. If specifications are not available for the individual kiln, a value must be assumed \((\%)\). Express as a decimal.

f) Determine the temperature of the cold water going to the boiler. \((\degree F)\)

\[ S_0 \]

g) Calculate the change in temperature of the humidifying air \((\degree F)\)
\[ \Delta S \]
\[ DBT \]
\[ S_0 \]
Table 1. Procedure for Calculating Total $H_5$ Element
(Heat Consumed in Heating and Humidifying Vent Air)

a) Calculate \( K \), a factor used only as a convenience in completing the calculation
\[
K = (ODW) (1 + E) \left[ c_a + (b) (c_{vw}) \right]
\]

b) Calculate \( A \), a factor used only as a convenience in completing the calculation
\[
A = (ODW) (E)
\]

and:
\[
H_5 = K \left[ \Delta mc_1 (\Delta t_1) + \Delta mc_2 (\Delta t_2) + \ldots \text{ etc} \right] + A \left[ \Delta mc_1 (\Delta S_{cH_2O} + h_1) + \Delta mc_2 (\Delta S_{2cH_2O} + h_2) + \ldots \text{ etc} \right]
\]

Note that the subscripts 1 and 2, etc. refer to stages 1 and 2 etc. in the kiln schedule.
C. If only the total heat consumption by this element, $H_5$, is needed it may be calculated by following the procedure in Table 1.

If the heat consumption by this element, $H_5$, is needed for each stage, or set of conditions, in the kiln schedule, the calculations outlined in the following steps of the procedure must be completed.

D. For each stage in the kiln schedule, or combination of wet and dry bulb temperature conditions, the heat required for the following must be calculated:

a) Heat the required vent air (Btu)
$$H_a = \frac{ODW \times \Delta mc \times c_a \times \Delta t}{d}$$

b) Heat any water vapor entering with the vent air (Btu)
$$H_b = \frac{ODW \times \Delta mc \times b \times c_{wv} \times \Delta t}{d}$$

c) Heat any excess vent air, and any water vapor in the excess vent air (Btu)
$$H_e = (H_a + H_b) E$$

d) Vaporize the water needed to humidify the excess vent air (Btu)
$$H_h = ODW \times \Delta mc \times E \left[ \left( c_{H_2O} \times \Delta S \right) + h \right]$$

E. For each stage in the kiln schedule, the heat required to raise the temperature and humidify the incoming vent air must be determined (Btu)
$$H_{5i} = H_{ai} + H_{bi} + H_{ei} + H_{hi}$$

Where $i$ indicates only the particular kiln schedule stage at which the $H_5$ value is being calculated.

**REPEAT FOR EACH STAGE IN THE KILN SCHEDULE**
H₅ = Σ H₅ⱼ values  

\[
H₅ = \sum \text{i.e. the sum of all the } H₅ⱼ \text{ values calculated at each stage of the kiln schedule.}
\]

6. Determine H₆ - The heat required to replace any losses from the system (Btu)

A. Calculate the weighted average DBT for the entire kiln run (°F)

\[
T_{\text{avg}} = \frac{(\text{DBT}_1)(n_1) + (\text{DBT}_2)(n_2) + \ldots \text{ etc.}}{n_1 + n_2 + \ldots \ldots \text{ etc.}}
\]

Where \( n \) \( x \) is the elapsed time at DBT \( x \)

B. For each kiln component (walls, floor, roof, etc.) determine the difference in temperature inside and outside the kiln (°F)

\[
\Delta T_L = T_{\text{avg}} - T_y
\]

Where \( T_y \) is the ground or air temperature outside the kiln, depending on the location of the component.

C. Determine the coefficients of heat transfer for each of the kiln components (Btu/ft² hr). These values, for different materials are available from a variety of handbooks, the kiln specifications, or FPL report R1646.

D. Determine \( H₆ᵢ \) the heat loss through kiln component \( i \) (Btu/hr)

\[
H₆ᵢ = U_i \times \text{Area (ft}²) \times \Delta T_L
\]

Where \( U \), \( \text{Area} \), and \( \Delta T_L \) are for component \( i \)

**REPEAT FOR EACH KILN COMPONENT**

and:

\[
H₆ = \sum H₆ᵢ \times \text{Total drying time (hrs)}
\]

eg: The sum of the \( H₆ᵢ \) values for each kiln component, multiplied by the length of the kiln run in hours.
Total heat consumption may now be de-
termined, as indicated in the description
of the various elements.

\[ H_{\text{total}} = H_1 + H_2 + H_3 + H_4 + H_5 + H_6 \]

While the calculations appear complex,
they are actually quite simple, provided
one proceeds through them carefully, step-
by-step. An example illustrating the use
of the formulas may also prove helpful.

**EXAMPLE OF ESTIMATING HEAT CONSUMPTION IN A DRY KILN**

Assume a dry kiln is located in the northeast region of
the country. The kiln is 18 feet wide, 33 feet deep, and
27 feet high. The walls, roof and door are prefabricated
sheet aluminum with insulation, and the concrete slab floor
is 6 inches thick.

The proposed kiln charge is 25,000 board feet of 4/4
eastern white pine (*Pinus strobus*), with initial moisture
content in the yard of 120 percent. The drying schedule
used will be Forest Products Laboratory Schedule T7-E6
(modified). The temperature of the water going to the
boilers that will heat the kiln is 45°F, and it is estimated
that 5 percent excess ventilation air will be required.

The temperature of the air outside the kiln is 35°F,
and the relative humidity is 69 percent. The ground tem-
perature is estimated to be about 45°F.

1. Determine \( H_1 \) The heat required to raise the tem-
perature of the wood substance.

The initial temperature of the wood is 35°F, and the
maximum temperature reached during the kiln run is 160°F.
The heat capacity of the wood is calculated:

\[ c_w = 0.266 + 0.000322(160 + 35 - 64) = 0.31 \text{ Btu/lb}^\circ\text{F} \]

Specific gravity of the wood on green volume basis is 0.34
(Dry Kiln Operator's Manual)

\[ V_w = \frac{25000}{12} = 2083.33 \text{ cu. ft. of wood in the kiln} \]

\[ \text{ODW} = 2083.33(0.34)(62.4) = 44,200 \text{ lbs of oven dry wood in the kiln} \]

Maximum change in temperature, \( \Delta T \) is found by:

\[ \Delta T = 160 - 35 = 125^\circ\text{F} \]

\[ H_1 = \text{ODW} \times c_w \times \Delta T = (44,200)(0.31)(125) = 1,712,750 \text{ Btu} \]
Figure 1. Temperature and moisture content for drying 4/4 eastern white pine (Schedule T7-E6, modified)
Figure 2. Heat required to overcome hygroscopic forces as related to final moisture content.

Figure 3. Latent heat of vaporization of water for various temperatures.
Figure 4. Weight of vapor per pound of dry air at various combinations of temperature and relative humidity. (From U.S. FPL Report No. R1265, March, 1954)
2. Determine $H_2$ - Heat required to overcome hygroscopic forces. From Figure 2, the heat desorption at the final moisture content in the Schedule (D) is 18.5 Btu/lb (Final moisture content is 7%).

$$H_2 = ODW \times D = (44,200)(18.5) = 817,700 \text{ Btu}$$

3. Determine $H_3$ The heat required to raise the temperature of any water remaining in the wood.

The water remaining in the wood at the final moisture content in the schedule (W) is calculated: (MC expressed as a decimal)

$$W = ODW \times \text{Final MC} = (44,200)(.07) = 3094 \text{ lbs}$$

$$H_3 = W \times c_{H_2O} \times \Delta T = (3094)(1)(125) = 386,750 \text{ Btu}$$

4. Determine $H_4$ The heat required to raise the temperature of the water removed from the wood, and to evaporate it.

First determine the latent heat of vaporization of water ($h$) at each dry bulb stage in the schedule, using Figure 3. Next, from the kiln schedule, determine the moisture content change ($\Delta MC$) during each dry bulb stage in the schedule. Next, determine the temperature change ($\Delta t$) from the initial temperature at each dry bulb stage in the schedule.

<table>
<thead>
<tr>
<th>DB Stage</th>
<th>DBT</th>
<th>$h$</th>
<th>$\Delta MC$</th>
<th>$\Delta t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>130</td>
<td>1.20</td>
<td>.30 = .90</td>
<td>130 - 35  = 95</td>
</tr>
<tr>
<td>2</td>
<td>140</td>
<td>1.20</td>
<td>.20 = .10</td>
<td>140 - 35  = 105</td>
</tr>
<tr>
<td>3</td>
<td>160</td>
<td>1.30</td>
<td>.07 = .13</td>
<td>160 - 35  = 125</td>
</tr>
</tbody>
</table>

$$H_{41} = ODW \times \Delta MC \times [(c_{H_2O} \times \Delta T) + h] \text{ at each DB stage}$$

$$H_{41} = (44,200)(.9)[(1)(95) + 1020] = 44,354,700 \text{ at DB stage 1}$$

$$H_{42} = (44,200)(.1)[(1)(105) + 1014] = 4,945,980 \text{ at DB stage 2}$$

$$H_{43} = (44,200)(.13)[(1)(125) + 1002] = 6,475,742 \text{ at DB stage 3}$$

Total $H_4 = H_{41} + H_{42} + H_{43}$

Total $H_4 = 55,776,422 \text{ Btu}$
Table 2. Example Calculation of Total H5 Element
(Energy Required to Heat and Humidify Vent Air)

\[
H_5 = K \left[ \Delta m c_1 \left( \Delta t_1 \right) + \Delta m c_2 \left( \Delta t_2 \right) \ldots \text{etc.} \right] + A \left[ \Delta m c_1 \left( S_1 \times c_{H_2O} + h_1 \right) + \Delta m c_2 \left( S_2 \times c_{H_2O} + h_2 \right) \ldots \text{etc.} \right]
\]

\[
K = \text{ODW} \left( 1 + E \right) \left[ c_a + \left( b \right) \left( c_{wv} \right) \right] = 44,200 \left( 1 + .05 \right) \left[ .24 + (.003) (.45) \right] = 11,201.05
\]

\[
A = \text{ODW} \times E = 44,200 \times .05 = 2210.00
\]

\[
c_{H_2O} = 1.0
\]

\[
H_5 = 11,201.05 \left[ (.6)(95) + (.2)(95) + (.1)(95) + (.1)(105) + (.13)(125) \right]
\]

\[
+ 2210 \left[ (.6)(85 + 1020) + (.2)(85 + 1020) + (.1)(85 + 1020) + (.1)(95 + 1014) + (.13)(115 + 1002) \right]
\]

\[
H_5 = 26,038,761 \text{ Btu}
\]
Determine the weight of water vapor per pound of incoming vent air (b) using Figure 4. At an outside temperature of 35°F, and 69% RH, \( b = 0.003 \text{ lbs/lb} \). At each stage in the kiln schedule, or combination of wet and dry bulb temperatures, determine:

(a) the relative humidity in the kiln
(b) the weight of water vapor per pound of air in the heated kiln (\( j \)) using Figure 4.
(c) the amount of water vapor that can be absorbed by the incoming vent air (d) \( d = j - b \)
(d) from the kiln schedule, determine the moisture content change (\( \Delta mc \)) during the drying stage. Express as a decimal (MC%/100).

The kiln manufacturer has estimated the excess air required (\( E \)) as 5 percent (0.05). The temperature of the cold water going to the boiler is measured as 45°F (\( S_Q \)).

Determine the change in temperature of the humidifying air (\( \Delta S = DBT - S_Q \)).

In the manner shown for the calculation of \( H_4 \), determine \( \Delta t \) for each stage of the kiln schedule.

Since only the total heat consumption by \( H_5 \) is needed, it may be calculated directly. This computation is shown in Table 2.

\[ H_5 = 26,038,761 \text{ Btu} \]
6. Determine $H_g$ - The heat required to replace any losses from the system. The weighted average DBT for the the entire kiln run must be calculated.

$$T_{avg} = \frac{DBT_1(n_1) + DBT_2(n_2) + DBT_3(n_3) + \ldots \text{ etc.}}{n_1 + n_2 + n_3 \ldots \text{ etc.}}$$

Where $n$ is the time in hours

$$T_{avg} = \frac{130(95) + 140(25) + 160(90)}{95 + 25 + 90}$$

$T_{avg} = 144 \, ^\circ F$

The difference between the average DBT in the kiln and the temperature of the air and the ground ($\Delta T_L$) must be calculated.

$\Delta T_1 \quad 144 \quad 35 = 109 \, ^\circ F$ for walls, door and roof

$\Delta T_2 \quad 144 \quad 45 = 99 \, ^\circ F$ for floor

The coefficients of heat transfer ($U$) for the various structural components of the kiln are provided by the kiln manufacturer:

- walls - $U = 0.118$
- door - $U = 0.220$
- roof - $U = 0.116$
- floor - $U = 0.900$

The variations in the coefficients of heat transfer are due to structural difference, such as metal reinforcement parts, in the kiln components. The heat loss through each structural component of the kiln is calculated as:

$$H_g = U \times \text{area} \times \Delta T_2, \text{ for each component}$$

$$H_{61} = (0.118)[(2 \times 27 \times 33) + (18 \times 27)] (109) = 29,171 \text{ Btu through the walls}$$

$$H_{62} = (0.116)(18 \times 33)(109) = 7,510 \text{ Btu through the roof}$$

$$H_{63} = (0.220)(18 \times 27)(109) = 11,654 \text{ Btu through the door}$$

$$H_{64} = (0.900)(18 \times 33)(99) = 52,925 \text{ Btu through the floor}$$

$$H_g (\text{total}) = H_{61} + H_{62} + H_{63} + H_{64} = 101,260 \text{ Btu/hr}$$

$$H_g (\text{total}) = 101,260 \text{ (210)}$$

$= 21,264,600 \text{ Btu for the kiln run}$
<table>
<thead>
<tr>
<th>Total Heat Consumption</th>
<th>Btu</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$ - Heat the wood substance</td>
<td>1,712,750</td>
<td>1.6</td>
</tr>
<tr>
<td>$H_2$ - Overcome hygroscopic forces</td>
<td>817,700</td>
<td>0.8</td>
</tr>
<tr>
<td>$H_3$ - Heat residual water in wood</td>
<td>386,750</td>
<td>0.4</td>
</tr>
<tr>
<td>$H_4$ - Heat and evaporate water removed from wood</td>
<td>55,776,422</td>
<td>52.6</td>
</tr>
<tr>
<td>$H_5$ - Heat and humidify vent air</td>
<td>26,038,761</td>
<td>24.5</td>
</tr>
<tr>
<td>$H_6$ - Replace heat losses</td>
<td>21,264,600</td>
<td>20.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>105,996,983</td>
<td>100.0</td>
</tr>
</tbody>
</table>

For purposes of comparison two other examples have been worked out. The summaries of these examples are given below.

1. If the same load of eastern white pine is dried under the same conditions except that the initial moisture content is 80%, the heat requirements are:

<table>
<thead>
<tr>
<th>Total Heat Consumption</th>
<th>Btu</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$ - Heat the wood substance</td>
<td>1,712,750</td>
<td>2.3</td>
</tr>
<tr>
<td>$H_2$ - Overcome hygroscopic forces</td>
<td>817,700</td>
<td>1.1</td>
</tr>
<tr>
<td>$H_3$ - Heat residual water in the wood</td>
<td>386,750</td>
<td>0.5</td>
</tr>
<tr>
<td>$H_4$ - Heat and evaporate water removed from wood</td>
<td>36,063,222</td>
<td>47.6</td>
</tr>
<tr>
<td>$H_5$ - Heat and humidify vent air</td>
<td>18,196,785</td>
<td>24.0</td>
</tr>
<tr>
<td>$H_6$ - Replace heat losses</td>
<td>18,546,551</td>
<td>24.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>75,723,758</td>
<td>100.0</td>
</tr>
</tbody>
</table>

11. A kiln charge (25,000 bd. ft.) of 4/4 sugar maple is dried from 70% MC to 10% MC in 14 days using schedule T 8-C3. The heat requirements are:

<table>
<thead>
<tr>
<th>Total Heat Consumption</th>
<th>Btu</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H_1$ - Heat the wood substance</td>
<td>3,271,821</td>
<td>3.0</td>
</tr>
<tr>
<td>$H_2$ - Overcome hygroscopic forces</td>
<td>982,638</td>
<td>0.9</td>
</tr>
<tr>
<td>H3 - Heat residual water in wood</td>
<td>1,055,455</td>
<td>1.0</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-----------</td>
<td>-----</td>
</tr>
<tr>
<td>H4 - Heat and evaporate water removed from wood</td>
<td>48,855,306</td>
<td>45.3</td>
</tr>
<tr>
<td>H5 - Heat and humidify vent air</td>
<td>17,964,494</td>
<td>16.7</td>
</tr>
<tr>
<td>H6 - Replace heat losses</td>
<td>35,666,736</td>
<td>33.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>107,796,450</strong></td>
<td><strong>100.0</strong></td>
</tr>
</tbody>
</table>

**SUMMARY**

There are several points that should be discussed regarding the manner in which this procedure can best be utilized. First of all, it is essential that good records are kept of each kiln charge in order to have the necessary data to satisfactorily estimate the active heat consumption in a plant kiln. These records provide a means of constructing a good picture of the kiln run (such as shown in Figure 1). They are also necessary in order to have a reference point for making schedule modifications, which is the next point of discussion.

Any schedule modifications will have to be tried in order to check for degrade, but in some instances it will be beneficial to do some theoretical heat consumption calculations before the kiln runs are made in order to see which alternatives may be the most favorable.

The Dry Kiln Operator's Manual suggests that the first step in systematic schedule modification is to change wet-bulb depression. This is followed by shifting temperatures, and the last step is to modify certain steps with the schedule.

Some factors to be considered in analyzing the results are:

1. It is obvious from all the examples that over ninety percent of the heat consumed is used to heat and evaporate the water, heat and humidify the vent air, and replace losses.

2. As the outside air temperature increases, kiln heat requirements decrease.

3. For the same moisture content percentage, higher specific gravity woods contain more water and result in
higher consumption.

4. For a particular kiln charge, all the elements of heat consumption, except one, are essentially fixed values since they are dependent primarily upon the amount of wood and the amount of water present. The exception is heat loss which is time-dependent. This effect of time may be adjusted by either using lower temperature for longer times or using higher temperatures for shorter times.

As a final suggestion, a reprint of a Forest Products Research Society news bulletin is presented on the following page. It contains many practical ideas for reducing kiln fuel costs.

SOME SUGGESTED REFERENCES


Function and Calculation of Ventilation in Drying Compartments. Forest Products Laboratory Report No. P 1265. USDA, Madison. 1941.


This winter, and probably for several winters to come, the fuel supply for heating dry kilns is quite low. Therefore, in order to keep the kilns running as economically as possible, kiln operators and foremen should look at their operations and improve them as necessary. Without delving into the why's and wherefore's, the list below presents several ideas on where to improve typical drying operations with the aim of reducing fuel consumption.

1. Get as much air drying done as possible. Improve the air-drying yard as necessary. (See your June 1973 News-Digest.) With a hardwood, each 2 percent moisture content loss in air drying will save about 3 percent in fuel compared with drying green from the saw. This is probably the most profitable area.

2. Do not use steam spray or water spray in the kiln except during conditioning. Keep the vents tightly closed and let the moisture coming out of the wood build up the humidity to the desired level. Remember that when the vents open, hot air is exhausted.

3. Repair and caulk all leaks and holes in the kiln structure to prevent unnecessary venting and loss of heat.

4. For brick or cinder block kilns, coat the inside of the kiln with a vapor-resistant coating. This will prevent the walls from getting wet since dry walls will conduct less heat outside.

5. For 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. This will be disastrous for permeable walls like brick or cinder block.

6. Install better baffling and obtain uniform air velocity in the kiln. This is a high payoff item. Reverse circulation only every 6 hours or longer, if possible.

7. Have the recorder-controller calibrated and checked for proper operation. Another $ Saver In a steam kiln, check your traps.
(8) Unload and reload the kiln as fast as possible. Try not to do this until the air temperature has warmed up a little from the morning low—don't cool the kiln unnecessarily.

(9) During non-use periods, close all valves tightly.

(10) In a battery of adjacent kilns, try not to have one kiln being unloaded or loaded while the adjacent kiln is at 180°F. or other high temperature.

(11) Use advanced schedules. Check your manuals to see how to accelerate schedules without risk. This can be a big savings area. Also note that the higher the temperature at which drying is done, the more efficient the use of energy.

(12) Accurately determine the moisture content of the wood you're drying. Don't waste energy by overdrying or by taking too long because your samples are not adequate.

(13) Finally, check with the manufacturer of your equipment and see if you can lower steam pressures or reduce gas or oil flow rates during periods of constant dry-bulb temperature.