

HUMIDITY OF COMBUSTION PRODUCTS FROM WOOD AND GASEOUS FUELS

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The capital and operating costs of steam kilns and the boilers necessary for their operation are so high in Canada that they are not economically feasible for small operations drying softwoods. About thirty years ago, direct fired or hot-air kilns were introduced. In such kilns natural gas, propane, butane or oil is burned and the combustion products conducted directly into the drying chamber. This design eliminates the high capital and operating costs of the steam boiler, and permits the small operator to dry lumber economically. However, such kilns are not as versatile as steam kilns. While they permit good temperature control, their humidity control is limited: they can only reduce excess humidity by venting, they cannot increase it and therefore cannot relieve drying stresses at the end of drying. For this reason, they are usually limited to the drying of structural lumber.

Due to the decreasing supplies and increasing costs of fossil fuels, there is growing interest in burning wood residues to provide the heat for drying. Although wood residue was often the fuel for steam boilers, the capital and operating costs of boilers are no more acceptable now to the smaller operator than they were a few years ago. The present trend is rather to burn wood cleanly and conduct the combustion products into the kiln in the same manner as is done with gaseous fossil fuels. This is now being done successfully with at least one type of burner, and others are in the pilot stage. However, some questions have arisen as to whether kilns heated by wood combustors have a similar range of humidity as gaseous fossil fuels, whether fuel moisture content affects the humidity of the kiln, and what changes in kiln schedule may be required to maintain drying degrade at acceptable levels.

Humidity in Gas-Fired Kilns

Humidity in gas-fired (natural gas, propane or butane) kilns is affected by three factors: the proportion of excess combustion air, the rate of evaporation of moisture from the lumber, and the tightness of the kiln.

Proportion of Excess Combustion Air

To burn one pound of fuel completely requires a specific amount of air, and this quantity varies with the composition of the fuel. Less than this quantity results in incomplete combustion, a smokey flame, and less than maximum heat generation. In practice, an excess of air over theoretical is needed to ensure that all fuel has access to sufficient oxygen for combustion. With gaseous fuels, the mixing process is so efficient that only a few percent excess air is required. With wood, somewhat higher ratios are to be expected.

More excess air than required should be avoided, since it reduces the temperature of the burner, and also dilutes the humidity of the products of combustion.

Rate of Evaporation of Moisture

When green lumber is dried in a kiln, the rate of evaporation of moisture is rapid at first, and gradually diminishes until the lumber is dry. Heat must be supplied in proportion to the rate of evaporation, and in addition, heat is required at a more or less constant rate to replenish heat lost through the kiln walls.

While the humidity exceeds the set point (the wet-bulb temperature for which the kiln controller is set), the excess humidity is automatically vented to atmosphere by the wet-bulb controller. When the humidity falls to or below the set point, automatic venting ceases. This does not mean, however, that no more venting takes place. As heat is required to maintain kiln temperature, hot and relatively dry gases from the burner displace the kiln atmosphere, with the resulting loss in humidity. The kiln dew point temperature thus approaches the dew point temperature of the products of combustion -- a value of about 130°F.

Leaky Kilns

In addition to automatic venting, and humidity displacement which accompanies the influx of heat from the burners, there is uncontrolled entry of atmospheric air below walls, around doors, and under roofs of leaky kilns and this displaces humid kiln gases. Suction created by the circulating fans as well as convection currents due to kiln temperature encourage this uncontrolled exchange of air.

There is some doubt if air enters to any extent during periods of rapid drying. The large quantities of steam generated appear to come out of all the openings of leaky kilns. Leakage is compensated for by less automatic venting. But when drying is slow, leakage results in a rapid loss of kiln gases, with the resulting undesirable loss of control of the wet-bulb temperature.

Humidity in Wood-Fired Kilns

Wood-fired kilns have much in common with gas-fired systems, and similar factors, excess air, rate of drying, and leakages, affect their humidity. However, there are other features of wood combustors that also affect kiln humidity.

Dilution of Combustion Products

Natural gas burners are relatively small devices and are housed immediately adjacent to the kiln. Part of the kiln atmosphere is drawn in and mixed with combustion gases from the burner to reduce their temperature to about 400°F before they are discharged into the kiln. Because wood combustors are much larger than gas burners, they are sometimes situated at a greater distance from the kiln. This results in the need to transport the flue gases from some distance to the kilns. Since few conduit materials can withstand the temperatures involved, it is necessary to dilute the gases to a manageable temperature, usually 1200 to 1600°F for transfer to the kiln. They are then diluted with recycled kiln gases to 400°F before entry.

Some current installations use atmospheric air for this dilution, and maintain kiln humidity by means of a supplementary steam boiler. Others use recirculated kiln air. Maximum theoretical wet bulb temperatures for these various installations are shown in this report.

Dry or Wet Fuel

Wood combustors can be designed for dry or wet fuel. The decision as to which is best for any operation depends on a number of factors.

A more efficient burner can be designed if fuel is dry and consistent as to particle size. In most operations, planer shavings will provide sufficient dry waste to fuel the drying of all lumber produced. Preparation usually involves the grinding of dry fuels to a uniform size.

Where planer shavings are required for other products, e.g. flakeboard, it is necessary to dry other wastes, e.g. bark and sawdust, for fuel. Wet fuel systems reduce fuel preparation to a minimum. Preparation normally involves only screening to eliminate larger pieces of wood from sawdust.

The effect of fuel moisture content on kiln humidity cannot readily be predicted without knowledge of the amount of excess air required for combustion. Wet fuel provides more humidity per heat unit produced. However, because more excess air is usually required for complete combustion, this advantage over dry fuel may be partly or totally lost. The matter ultimately rests on how little excess air is used, and this is largely determined by burner design.

Calculation by Kiln Humidity

In order to provide kiln designers with some guidelines as to the effect of design parameters on kiln humidity, a series of calculations were made of maximum theoretical humidities attainable under various conditions. An outline of the reasoning and calculations appears in the appendix.

Calculations for natural gas apply with little error for propane and butane also. It has been necessary to make certain assumptions in the calculations for the burning of wood, and these will be described.

Heat value for wood is approximately 8500 Btu/lb. dry measure. From this must be deducted the heat of vaporization of any moisture in the effluent gas, assumed here to be about 0.54 pound per pound of dry fuel. After rounding off, a net heating value of 7900 Btu/lb was assumed.

Combustion was assumed complete in all cases, so that the products of combustion consist entirely of carbon dioxide and water, together with excess oxygen and the nitrogen carried in with the oxygen.

Composition of the wood fuel was assumed to be carbon 0.52, oxygen 0.41 and hydrogen 0.06, values in the range of analytical results (Greaves and Schwartz, 1951).

No loss of heat due to radiation or conduction through the burner shell was allowed for. However, within the kiln itself 660 Btu were lost through the walls for each pound of water evaporated. This is similar to values used by kiln designers.

No uncontrolled loss of kiln atmosphere under doors, walls and roofs was considered, but allowance was made for displacement of kiln gas by hot gases admitted from the burner.

Results

Figures 1 to 3 list the dew points of the kiln atmosphere for gas-fired and for wood-fired systems. The wet-bulb temperature is approximately 1°F higher than the dew point, but is not constant

for any degree of kiln humidity, since it varies somewhat with the dry bulb temperature also. For these purposes the dew point can be assumed as equal to the wet-bulb temperature.

While the maximum dew point obtainable in a kiln falls from about 185 to 136°F during drying when natural gas is burned with 10% excess air (Fig. 1), the comparable range for wood fuel is probably 155 to 120°F (Figs. 2 and 3), provided that the burner is close enough to the kiln to permit the use of recycled kiln air to cool the hot gases before they are transported to the kiln. Where a decision is made to cool the stack gases by dilution with atmospheric air, the kiln's maximum wet bulb temperature will be expected to range from about 145 to 110°F.

Calculations have shown that if the stack gases were cooled to 1200°F entirely by means of a water spray, the dew point in the kiln atmosphere would be in the range of 150 to 185°F, depending on excess air used and lumber drying rate.

It is necessary to emphasize that, particularly in the case of burning wet fuel, the reader must determine by oxygen analysis of stack gases what proportion of excess air is actually being used before the maximum dew point can be read from these figures. Without real data on fuel moisture content and excess air required for combustion, it is not possible to compare with certainty the humidities attainable with dry and wet fuel.

Industry Experience

It is expected that mills installing wood-residue burning equipment to replace fossil-fuel burners for lumber drying will wish to make as little change as possible in their operational procedure. Yet differences in burner layout and the humidity of stack gases between the two systems are such that accommodation may be necessary in some cases. At the present time in British Columbia only four wood-burning direct-fired kilns are in service. One of these dilutes gas to about 1200°F with atmospheric air, and adds steam from an independent boiler to control humidity. Another, using wet fuel dilutes combustion gas with recycled kiln gases. No problems have been found with lumber quality. The remaining two burn dry wood waste and dilute the combustion gas with recycled kiln gas. Only one of the latter two has found it necessary to modify drying practice. This burner is used to heat an old kiln which permits more than average leakage. Because normal wet-bulb temperatures are not attainable, the kiln is operated at relatively low temperatures, and requires about 50% longer than normal times for drying. No decrease in lumber quality in any of these kilns has been observed.

Appendix

CALCULATION OF KILN HUMIDITY FROM WOOD FUEL

Stage 1. Combustion of Fuel

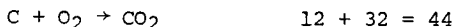
Composition of Flue Gases

Data for the burning of natural gas, propane and butane are:

Fuel	Composition		BTU value/lb.
	C	H	
Natural gas	0.749	0.238	21000
Propane	0.818	0.182	19944
Butane	0.828	0.172	19680

While wood of different species has minor differences in composition, a typical ultimate analysis is used in these calculations: carbon (C) = 0.52; oxygen (O) = 0.41 and hydrogen (H) = 0.06. Fuel value of dry wood is 8500 Btu/lb. (Stamm, 1964). Unless otherwise stated, the following calculations are based on the combustion of 1 lb dry wood. Moisture content is calculated on the oven-dry weight. Ambient air is assumed to be 60°F and 50% rh, and contains 0.0055 lb moisture per lb. dry air.

Combustion reactions and corresponding molecular weights are:



Carbon dioxide produced from 1 lb dry wood is

$$*W_{1,1} = 0.52 \times 44/12 = 1.907 \text{ lb}$$

Oxygen required for combustion is that to combine with the carbon, plus that to combine with the hydrogen, less that available in the wood:

$$(0.52 \times 32/12) + (0.06 \times 16/2) - 0.41 = 1.457 \text{ lb.}$$

Oxygen in flue gas is

$$W_{1,2} = 1.457 \times \text{lb.}$$

where X is the proportion of excess air used in combustion. The weight ratio of nitrogen to oxygen in air is 3.327.

Therefore the nitrogen in flue gas is

$$W_{1,3} = 3.327 (1.457) (1+X) \text{ lb.}$$

Water vapor comes from three sources:

Water of reaction is $0.06 (18/2) = 0.54 \text{ lb.}$

Water in combustion air is $0.0055 (4.327) (1.457) (1+X) = 0.03467 (1+X)$

where 4.327 is the weight ratio of air to oxygen.

Water from wood moisture, where M is fractional moisture content, is M lb.

Total moisture in combustion gas =

$$W_{1,4} = 0.54 + 0.03467 (1+X) + M$$

Flue Gas Temperature

Enthalpies above absolute zero in Btu per lb-mol over the range -160 to 4920°F are given by Keenan and Kaye (1948) for common gases. For convenience of use by computer, equations for calculating these values were derived, and divided by molecular weight, to give enthalpies in Btu per lb. These equations are given in Table A1.

The temperature of the flue gases, assuming complete combustion of the fuel, and ignoring radiation losses, is calculated by

*For convenience of nomenclature, symbol W for weight is double subscripted, as $W_{i,j}$ where i represents the stage of processing, and j represents the component being considered: 1 for CO_2 , 2 for O_2 , 3 for N_2 and 4 for H_2O . ΣW_i is total weight in first stage. For E (enthalpy) the first subscript is temperature.

an iterative procedure, starting from an assumed temperature of 3000°F. The basic equation is a heat balance:

$$\begin{aligned} &\text{Enthalpy of stack gases at } 60^\circ\text{F} = \text{Heat of reaction} \\ &\quad - \text{Latent heat of evaporation of moisture produced} \\ &\quad (1060 \text{ Btu per lb at } 60^\circ\text{F}) = \text{Enthalpy of combustion} \\ &\quad \text{production at flue gas temperature.} \end{aligned}$$

The equations used are:

$$T = 3000$$

$$(1) \quad \text{TEMP} = [\sum E_{60} + 8500 - 1060M] / (\sum E_T / (T + 459.7)) - 459.7$$

$$(2) \quad T = \text{TEMP}$$

Iterate (1) and (2) until the difference between two successive values is less than 1°F.

Stage 2. Dilution to 1200°F

To protect conduits from high-temperature combustion products, flue gases are diluted to 1200°F before transport to the kiln, and then diluted with recycled kiln gas to 400°F before entry. (In some cases the dilution to 400°F is by use of atmospheric air. This latter instance is handled separately.) To determine the amount of dilution gas, it is necessary to determine the enthalpies of (1) air at 60°F, (2) air at 1200°F, (3) combustion gas at flame temperature, (4) combustion gas at 1200°F. Quantity of dilution air (lb) required is then

$$D = \frac{(3) - (4)}{(2) - (1)}$$

and the composition of the diluted flue gas (lb) at 1200°F is

$$W_{2,1} = W_{1,1}$$

$$W_{2,2} = W_{1,2} + 0.23 D$$

$$W_{2,3} = W_{1,3} + 0.7645 D$$

$$W_{2,4} = W_{1,4} + 0.0055 D$$

$$\sum W_2 = W_{2,1} + W_{2,2} + W_{2,3} + W_{2,4}$$

Stage 3. Entry and Mixing in Kiln

Heat Required to Dry 1 Mfbm Lumber

Assume wood is dried from 65% to 15% MC. Then 2 lb net wood drying yields 1 lb water. The following quantities of heat are required to evaporate this water.

(1) Heat to raise wood temp 60 to 180°F = 120 (.25)2 = 60 Btu
where 0.25 is the specific heat of wood

(2) Heat to raise wood moisture from 60 to 180°F =
2(.65)120 = 156

where 0.65 is the MC of wood

(3) Latent heat of evaporation at 180°F = 990

(4) Heat to raise temp of venting air 60 to 180°F

approx 169

Total 1375 Btu

In addition, there is a total loss of about 660 Btu through kiln walls for each pound of water evaporated. Assuming that drying requires 48 hours, this is a steady loss of 13.75 Btu per hour for each pound of water evaporated.

One thousand fbm (Mfbm) of rough lumber occupies approximately 80 cu.ft. One cu.ft. weighs approximately 25 lb when dry. Thus, one thousand board feet dry lumber weighs 2000 lb, and drying from 65% to 15% MC removes 1000 lb water. Therefore, the steady loss of 13.75 Btu per hour per pound of water evaporated is a steady loss of 13750 Btu per hour per Mfbm dried. Furthermore, a loss of 1% MC is 80 (25) (0.01) = 20 lb. After the lumber is hot, the heat required for evaporation of 1 lb water is the sum of the latent heat and the heat for venting air = 990 + 169 = 1160 Btu. Thus, the heat demand per Mfbm at any time is

$$13750 + 20 R (1160) = 13750 + 23200 R$$

When R is the drying rate in percent MC per hour.

Hot Gas Required to Dry Lumber

When the flue gases generated from 1 lb dry fuel are cooled from 1200°F to the dry bulb temperature of the kiln (assumed to be 180°F), the heat given up is

$$\Sigma E_{1200} - \Sigma E_{180}$$

Consequently, the rate of fuel consumption per hour is

$$WF = (13750 + 23200 R) / (\Sigma E_{1200} - \Sigma E_{180})$$

where ΣE_{1200} and ΣE_{180} are the enthalpies at 1200° and 180°F respectively of the quantity of gas described by ΣW_2 . Thus, the total gas entering the kiln is

$$(WF) (\Sigma W_2)$$

Humidity of Exhaust Gas from Kiln

The gas entering the kiln is mixed with the water vapor evaporated from the lumber and then exhausted. Thus, the quantities of the four components of exhaust gas passing through the kiln per hour are:

$$W_{3,1} = W_{2,1} \times WF$$

$$W_{3,2} = W_{2,2} \times WF$$

$$W_{3,3} = W_{2,3} \times WF$$

$$W_{3,4} = W_{2,4} \times WF + 20 R$$

The vapor pressure of the water vapor component, based on an atmospheric pressure of 760 mm Hg is

$$VP = \frac{W_{3,4}}{W_{3,1} + W_{3,2} + W_{3,3} + W_{3,4}} \times 760$$

The dew point of °F can be calculated from the following equation

$$DP = \frac{-9196.5}{\ln VP - 20.336} - 459.7$$

A similar calculation can be made for gaseous fuels. However, since these are diluted to about 400°F by means of recirculated kiln atmosphere, and subsequently enter and are cooled in the kiln to dry-bulb temperature, stage 2 (dilution to 1200°F) must be deleted, and the compositions W₂ made identical with W₁.

Table A1. Equations to Calculate Enthalpies of Common Gases. Enthalpies in Btu per lb.

Gas	Equation
CO ₂	$E_1 = (39884) + 16.24T - 6658 \ln T - 0.146 \times 10^7 / T) / 44$
O ₂	$E_2 = (14620 + 9.27T - 2356 \ln T - 5.785 \times 10^5 / T + 0.477 \times 10^{-4} T^2) / 32$
N ₂	$E_3 = (446.4 + 6.14T - 0.47 \times 10^{-3} T^2 - 0.13 \times 10^{-14} T^5 - 0.80 \times 10^5 / T) / 28$
H ₂ O	$E_4 = (309.1 + 6.927T + 0.828 \times 10^{-3} T^2 - 0.675 \times 10^{-15} T^5) / 18$

where T = (°F + 459.7)

To calculate the enthalpy ΣE of a mixture of gases, where the components are measured in pounds, the component enthalpies are summed.

$$\Sigma E = W_1 E_1 + W_2 E_2 + W_3 E_3 + W_4 E_4$$

Bibliography

- Greaves, C. and H. Schwartz. 1951. The chemical utilization of wood. Chapter 8. Canadian Woods. Canada Resources and Development. Forest Products Laboratories Division. Ottawa.
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- Stamm, A.J. 1964. Wood and cellulose science. Ronald Press. New York.

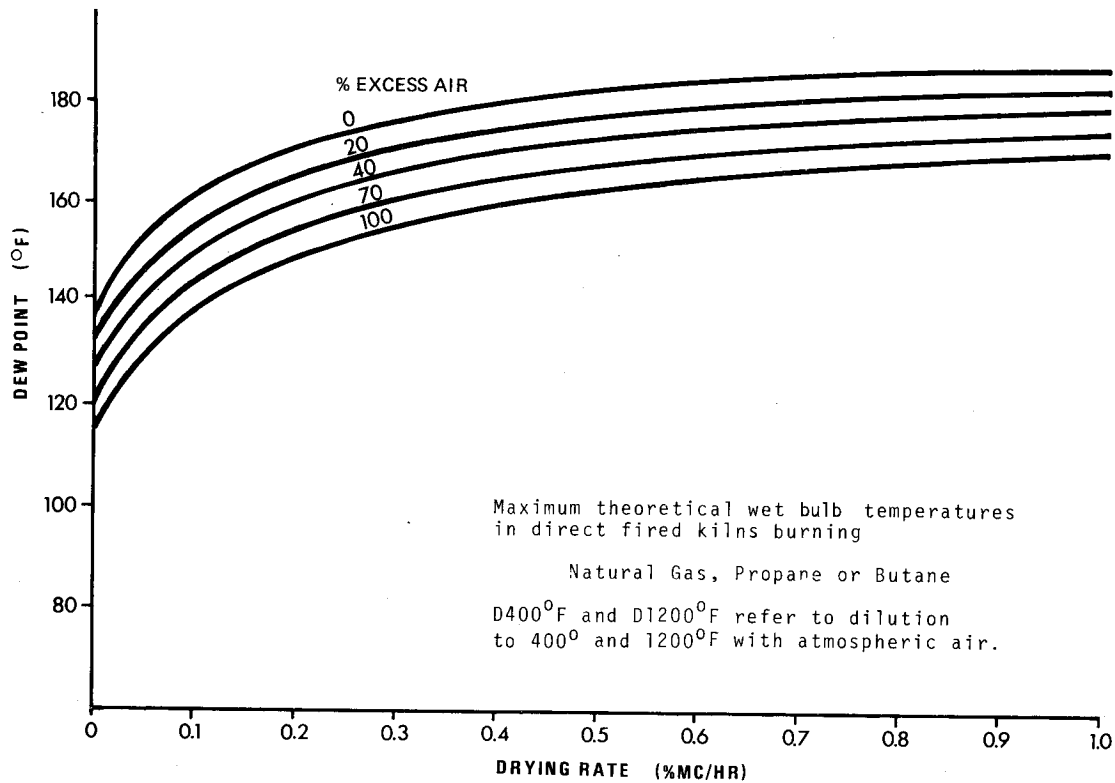


FIGURE 1

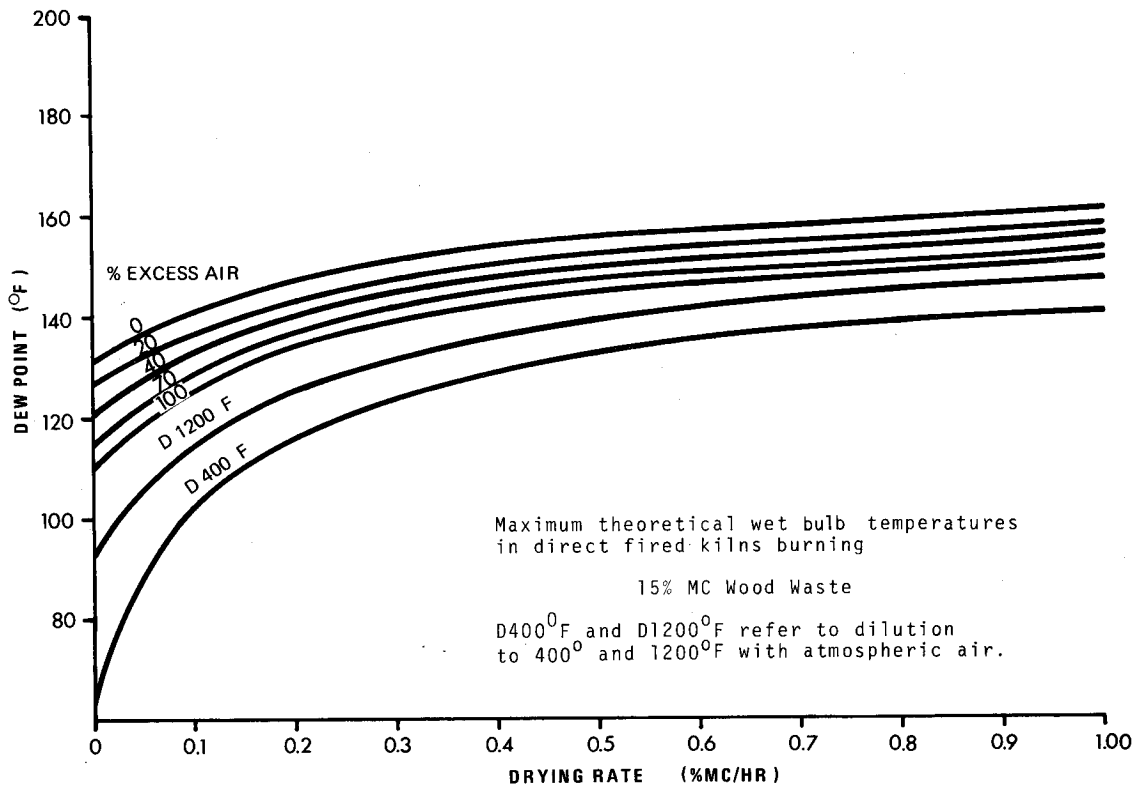


FIGURE 2

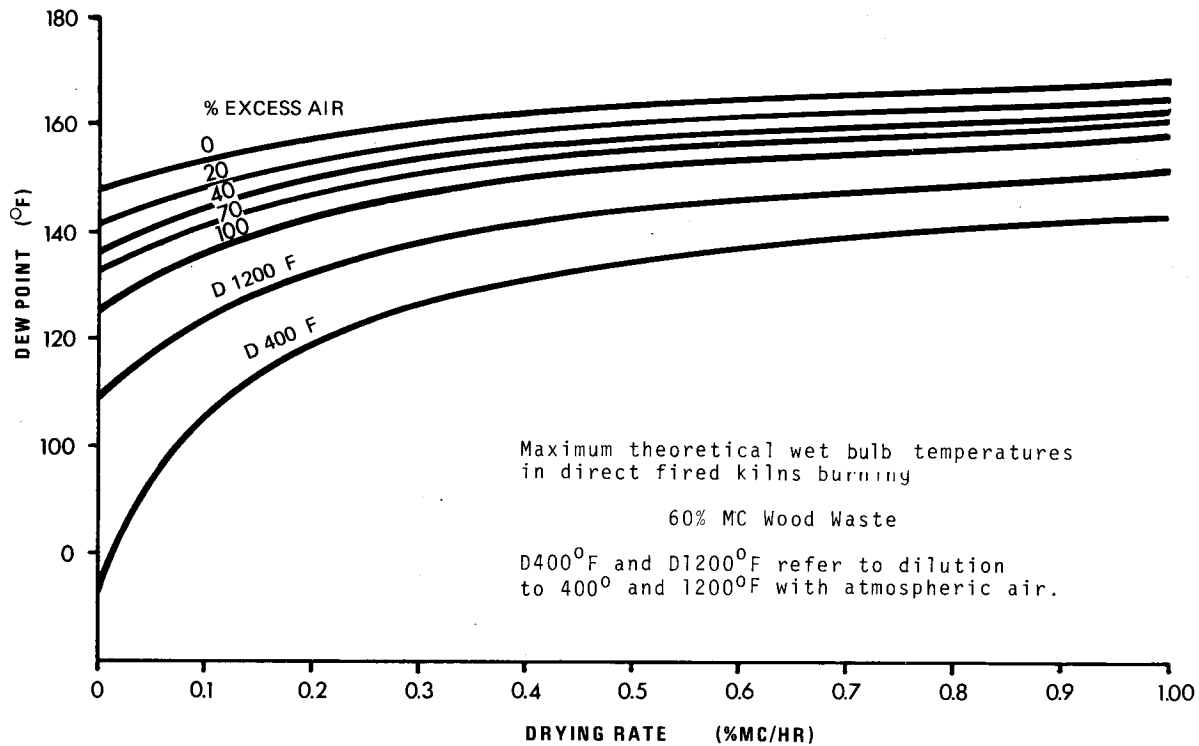


FIGURE 3