INTERACTION OF TEMPERATURE AND CONDITIONS IN KILN DRYING

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When Charlie was putting the program together for this meeting we had a long discussion concerning what my topic should be. Both of us knew that I would prefer to talk about CRT drying and the dramatic performance records which have been established where it is used. I would like to share some of the experiences of short schedules and improved quality that some of you in the audience have had. I would have liked to have talked about drying 6/4 Ponderosa Pine Shop in 24-28 hours or lodgepole studs in 16 hours. I would have been glad to mention that Weyerhaeuser estimates conservatively that CRT use is contributing at least six million dollars per year in net value. It would have been much to my liking to again explain why I so sincerely believe that although all of the answers to this complex problem of lumber drying are not known, CRT technology truly represents a valuable forward step.

Charlie had in mind something of the nature of new research results or the pointing out of economic losses resulting from certain common practices.

We compromised. I will not even mention CRT. Neither will I point with pride nor cry with alarm concerning operational procedures. Rather, I shall revert to my old role of college professor and attempt to review with you some of basic characteristics of kiln drying and discuss some of the interactions of kiln variables. I do this with the sincere hope that it may be of value to many of you in the understanding and operation of your kilns.

In kiln drying water is removed from wood as free vapor. The "free" water is removed first. Liquid water must be vaporized. Later the "bound" water is removed which requires that the chains of hydrogen-bonded water molecules must be broken in order to produce single molecules. Both of these processes require that energy be added. While the number is not precise under all conditions it is valuable to remember that approximately 1200 BTU of added energy is required to remove one pound of water from wood substance. Those of you who having been helping your high school student children with their physics or chemistry problems will immediately challenge the number because it is too high. The heat of vaporization of water at its boiling point under normal atmospheric pressure is only 970 BTU per pound and does not increase a great deal as temperatures in the normal kiln drying range are reached.

However, it must be remembered that, unfortunately, all of the energy which is added to wet wood is not used for the production of free water vapor molecules. Some of the added energy is used to raise the temperature of the wood and its contained moisture. I believe that you will agree that it would solve most of our drying problems if someone would invent a BTU that would interact only with the water. If this were possible it would be necessary only to add energy at a predetermined rate and the wood would remain at the same temperature as it was when it was put into the kiln. However, to the best of my knowledge, no one has yet invented such a single-minded BTU and I know of no one who is working on the problem.

The principal reason why approximately 1200 BTU of added energy is required for the removal of one pound of water instead of 970-1000 BTU is that some of the added energy is used to heat the wood.

It should be stressed at this point that drying can take place almost as efficiently at low temperatures as at high temperatures. For example, if the addition of 1200 BTU to wood at 200 F. results in the removal of one pound of water, the addition of 1200 BTU to wood at 90 F. will result in the removal of almost the same amount of water. Many kiln operators are not aware of this fact. Low temperature drying at fast rate is possible if conditions exist whereby the energy can be transferred to the wood at the required rate.

In most lumber drying operations, the energy which enters the wood comes from the air which circulates over the surfaces of the wood. Although the energy relations are the same I shall ignore such practices as platen drying, dielectric heating, resistance heating, solvent seasoning and drying by use of heated immiscible liquids.

If heat energy is to be transferred from air to wood the temperature of the air must be higher than the temperature of the wood surfaces because heat will flow only from a higher temperature source to a lower temperature sink. Furthermore, the rate at which energy is transferred depends on the difference in temperature between the air and the wood surface.

It must be remembered that if heat energy is transferred from the air to the wood, the air must lose energy - in other words its temperature is reduced. Immediately as air moves into the spaces between the courses of lumber it begins to cool. When the kiln operator says that he is operating his kiln at 160 F. dry bulb temperature he is saying that the wood at the entering air side of the charge is subjected to an air temperature of 160 F. At no other place in the lumber charge does this air temperature exist!

A very useful approximation is that if one cubic foot of air cools 1F., 0.0165 BTU is lost. This number obviously cannot be constant at all temperatures and moisture contents. However, it is sufficiently exact to permit it to be used for rough calculations (and kiln drying has hardly progressed to the exact science stage where highly precise calculations are required or justified). When this number is used in conjunction with the approximation of 1200 BTU per pound of water removed which was mentioned earlier it is seen that 72700 ft^3 of air must be cooled 1 F. to provide the heat required to remove one pound of water (or 7270 ft^3 of air cooling 10 F. or 727 ft^3 of air cooling 100 F.).

However, the kiln air serves a function other than supplying the heat energy which is transferred to the wood. The circulating air must also transport the moisture vapor away from the stack of lumber and in order to accomplish this, the air must be able to accept the moisture vapor. Although, water vapor is a gas and obeys the usual gas laws it differs from many other gases in a very important way. If the gaseous product being released from the wood were carbon dioxide, for example, the quantity of gas released would present no problem because carbon dioxide can mix with the nitrogen and oxygen which comprise "air" in all proportions. With water vapor, however, there is a limit to the quantity which the nitrogen-oxygen mixture can contain. This quantity is called saturation and it represents that quantity of water vapor which will produce a partial pressure of water vapor equal to the vapor pressure of liquid water at the same temperature. Saturation is the condition which exists when the quantity of water vapor is such that it is in equilibrium with a free liquid water surface.

The air-moisture relations are of such critical importance in the operation of a kiln that it appears worthwhile spending some time in review of the principles. This can best be done by the development and use of a simple psychro-metric chart. If you are already familiar with the tables and charts you will agree with me that they represent the most important tool for kiln operation which you have. If for any reason you are not familiar with the chart I urge you to become so. If you do not have a chart available for reference on your control room wall you are invited to pick up one which covers the normal day kiln range of conditions after this session, compliments of Irvington-Moore.

The word "psychrometric" is derived from two greek roots meaning measurement of cold or cooling. It is related to the word "thermometric" which refers to the measurement of heat or heating.

The basic psychrometric chart illustrates temperature - moisture content relations of air-water mixtures on a graph on which the moisture content of the air is shown on the Y axis and the dry bulb temperature is shown on the X axis (horizontal). The blank chart looks like Figure 1.

For our purposes we will express moisture content of the air in units of pounds of water in one pound of dry air and the temperature in Fahrenheit degrees. In normal kiln work we are interested in the range of moisture contents between 0 ("bone day") and about 0.6 pound of water per pound of dry air and in temperatures below 300 F. A point on the graph represents a unique combination of temperature and moisture content. For example, point "A" represents an air sample at 150 F. dry bulb temperature which contains 0.1 pound of moisture vapor mixed with one pound of dry air. If you wish to locate the point on the chart representing a moisture content of 0.3 pound of moisture per pound of dry air at 240 F., locate the value of 0.3 on the vertical axis and follow it across horizontally until it intersects the line drawn vertically upward from 240^{o} F. on the X axis. This gives point "B".

It was stated earlier that dry air was capable of holding only a limited quantity of moisture - saturation. Therefore, in building a psychrometric chart a first step is to locate the saturation line as in Figure 2.

The saturation line divides the chart into two areas. All points below and to the right of the saturation line can exist. Any point which lies above and to the left of the saturation line cannot exist because any point in this region represents more moisture than one pound of dry air can hold. Therefore, the excess moisture must condense out as liquid.

Figure 2 permits certain conclusions concerning the characteristics of air-water relations to be drawn. For example, assume point "A" which describes an air-water mixture at 160 F. with a composition of 0.10 pound of water for each pound of dry air. If the sample is cooled without changing the moisture content point "B" will be reached at 127 F. which lies on the saturation line. Moisture begins to condense at this point. The temperature at which condensation begins upon cooling is called the "dew point."

Again consider point "A". If moisture vapor is added without a change in temperature, saturation will be reached when the moisture content reaches 0.30 pound of water in each pound of dry air (point C). If

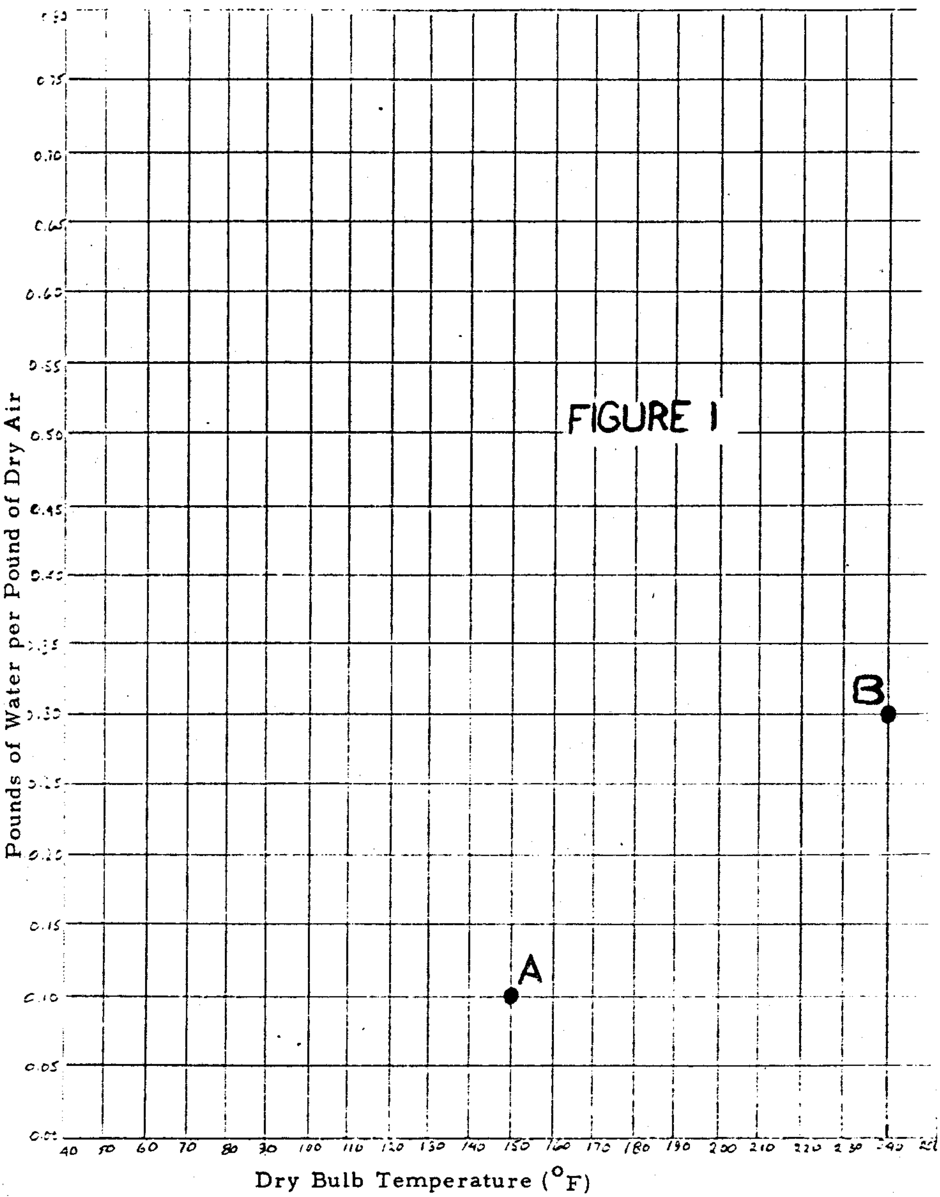
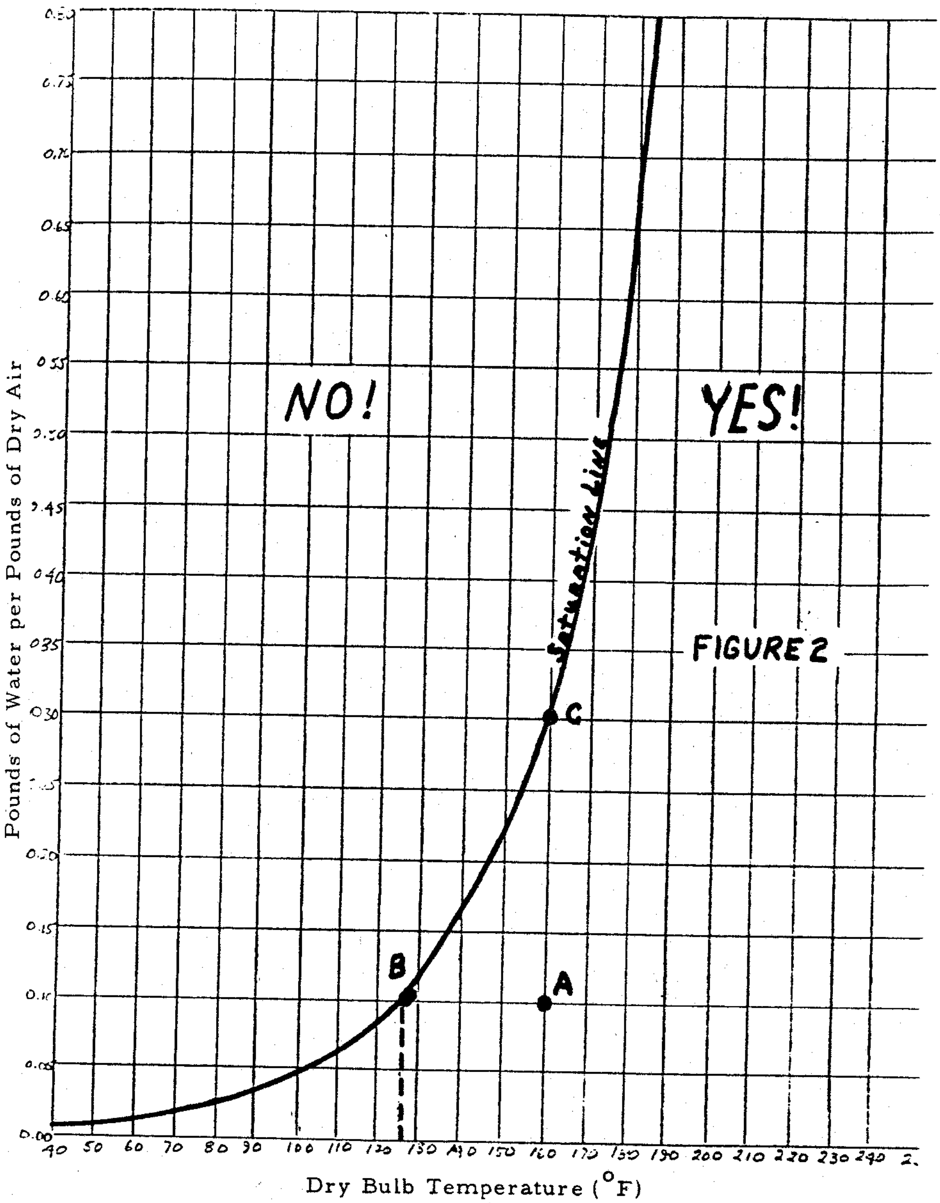


FIGURE 1
Pounds of Water per Pound of Dry Air
Dry Bulb Temperature (°F)
A
B
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.15
0.10
0.05
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
230
240



NO!
YES!
Saturation Line
FIGURE 2
C
B
A
Pounds of Water per Pounds of Dry Air
Dry Bulb Temperature (°F)

additional moisture vapor is added condensation will take place to maintain the moisture content at the saturation level.

Since the composition at point "A" is 0.1 pound of water per pound of dry air and one pound of dry air at the same temperature can contain 0.3 pound of moisture, point "A" is 1/3 or 33% saturated.

Obviously neither of the paths "A-B" or "A-C" is followed during kiln drying. Path "A-B" represents cooling of the air but no drying takes place. This would be the situation in a kiln if the lumber were bone dry. Heat energy would be lost by the air as it passed over the charge. But all of the transferred energy would be used in heating up the wood. Path "A-C" is impossible in a kiln. If it took place the moisture content of the air would be increasing without the expenditure of any energy. This would be the equivalent of getting something for nothing which does not occur in real life situations.

Kiln operators are well aware that the humidity or moisture content of kiln air is expressed, measured and controlled in terms of a unit called the wet bulb temperature. Although I shall not take the time to derive the term mathematically it is defined as the lowest temperature which is achieved by liquid water when the energy and mass flow rates are so balanced that the vapor pressure of the liquid water is exactly equal to the partial pressure of the moisture in the air. If the air is saturated the wet bulb temperature is the same as the dry bulb temperature. The dryer the air the greater the difference between the dry bulb and wet bulb temperatures.

Wet bulb temperatures may be incorporated on the psychrometric chart as is shown in Figure 3.

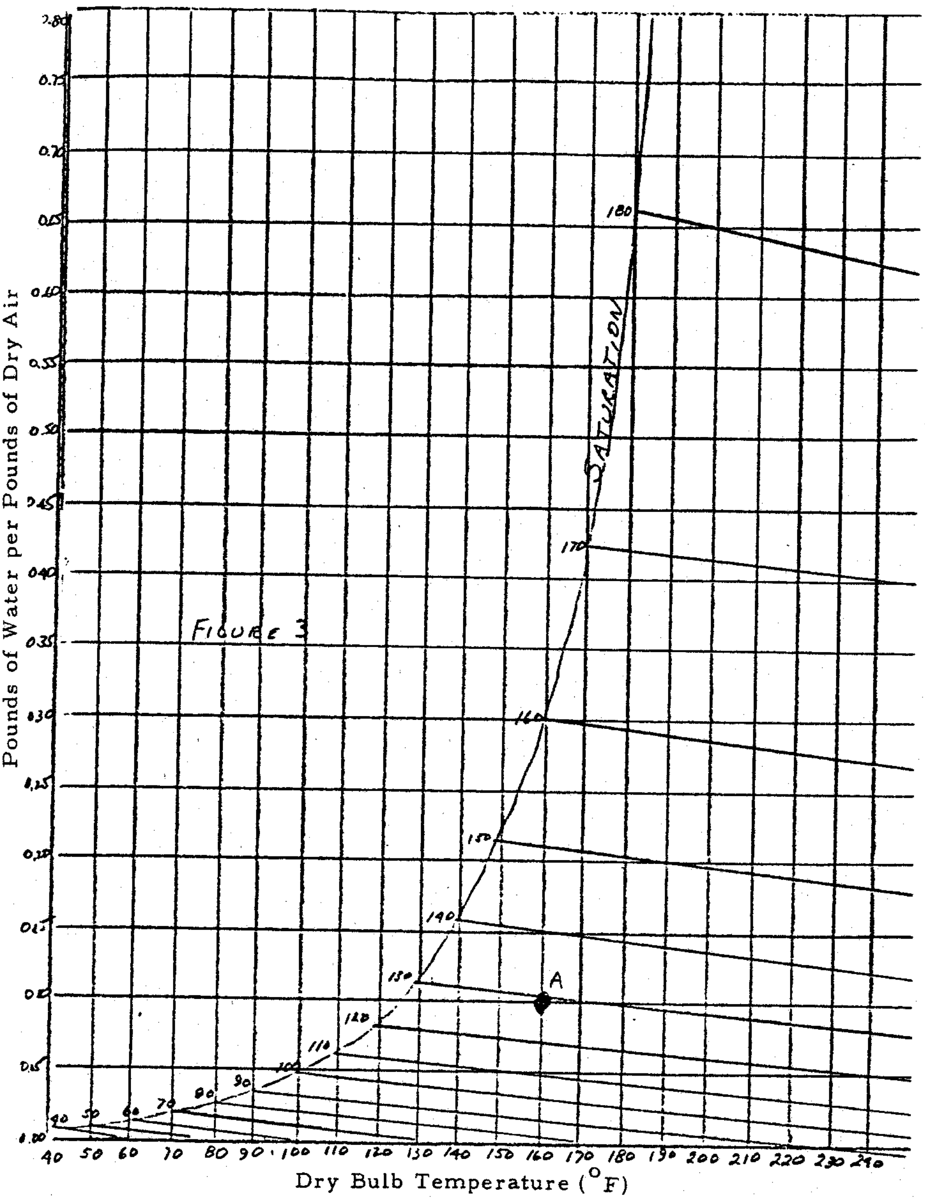
The wet bulb temperature curves are of great significance to the kiln operator. Several points should be noted. First, many combinations of moisture content and dry bulb temperature have the same wet bulb temperature. Second, for a given wet bulb temperature, the higher the dry bulb temperature the lower the moisture content or, in other words, the lower the moisture content of the air the greater the wet bulb temperature depression for a given wet bulb temperature. Third, the constant wet bulb temperature lines are substantially straight. Fourth, the constant wet bulb temperature lines are substantially parallel. Fifth, the wet bulb temperature lines intersect the saturation line at a dry bulb temperature identical to the wet bulb temperature (at saturation there is no wet bulb temperature depression).

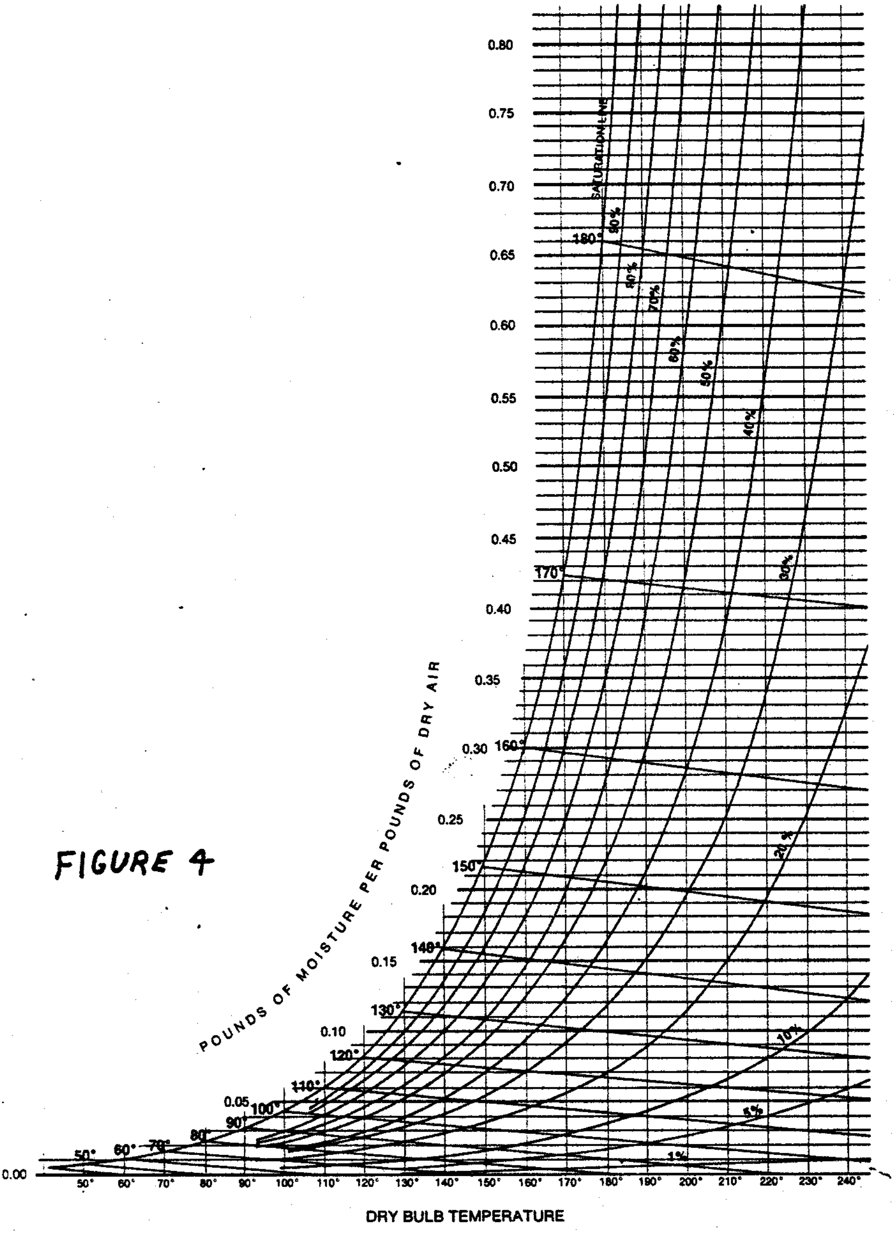
Addition of the wet bulb temperature lines to the chart provides much more information than was available before. Point "A" now represents:

Dry Bulb Temperature 160 F.
Humidity 0.10 lb. H_2O/lb. dry air
Dew Point 127 F.
Wet Bulb Temperature 130 F.
Wet Bulb Temperature Depression 30 F.

Still another commonly used characteristic of air-water combinations is relative humidity which is defined as the ratio of the partial pressure of water vapor at the stated conditions to the partial pressure at saturation at the same dry bulb temperature.

Lines of constant relative humidity can be added to the psychrometric chart, Figure 4.


0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Pounds of Water per Pounds of Dry Air
40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240
Dry Bulb Temperature (°F)
SATURATION
FIGURE 3
A



SATURATION LINE
90%
80%
70%
60%
50%
40%
30%
20%
10%
5%
1%
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
50°
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180° 190° 200° 210° 220° 230° 240°
POUNDS OF MOISTURE PER POUNDS OF DRY AIR
DRY BULB TEMPERATURE

FIGURE 4

The chart now permits another definite number to point "A" - the relative humidity is 42%.

Reaction on the part of some of you at this point may probably be a resounding "So what?" or even an evaluation couched in terse but generally unprintable terms. What is the value of the psychrometric chart to the kiln operator?

As was stressed earlier as air passes over the lumber surfaces it loses heat to the wood and becomes cooler if the air temperature is higher than the wood surface temperature. Now, if all of the energy which is transferred is used by the wet wood for the evaporation of moisture the air will cool at constant wet bulb temperature - the point on the psychrometric chart which represents the temperature and moisture content properties of the leaving air will be at a lower temperature but on the same wet bulb temperature line as the entering air point, Figure 5.

Let us concentrate on Figure 5 for a moment. Notice first that when one pound of dry air having the temperature and moisture content shown at point "A" cools ΔT degrees a certain amount of moisture ΔM is picked up by the wood. This is the maximum amount of drying that can take place under these conditions.

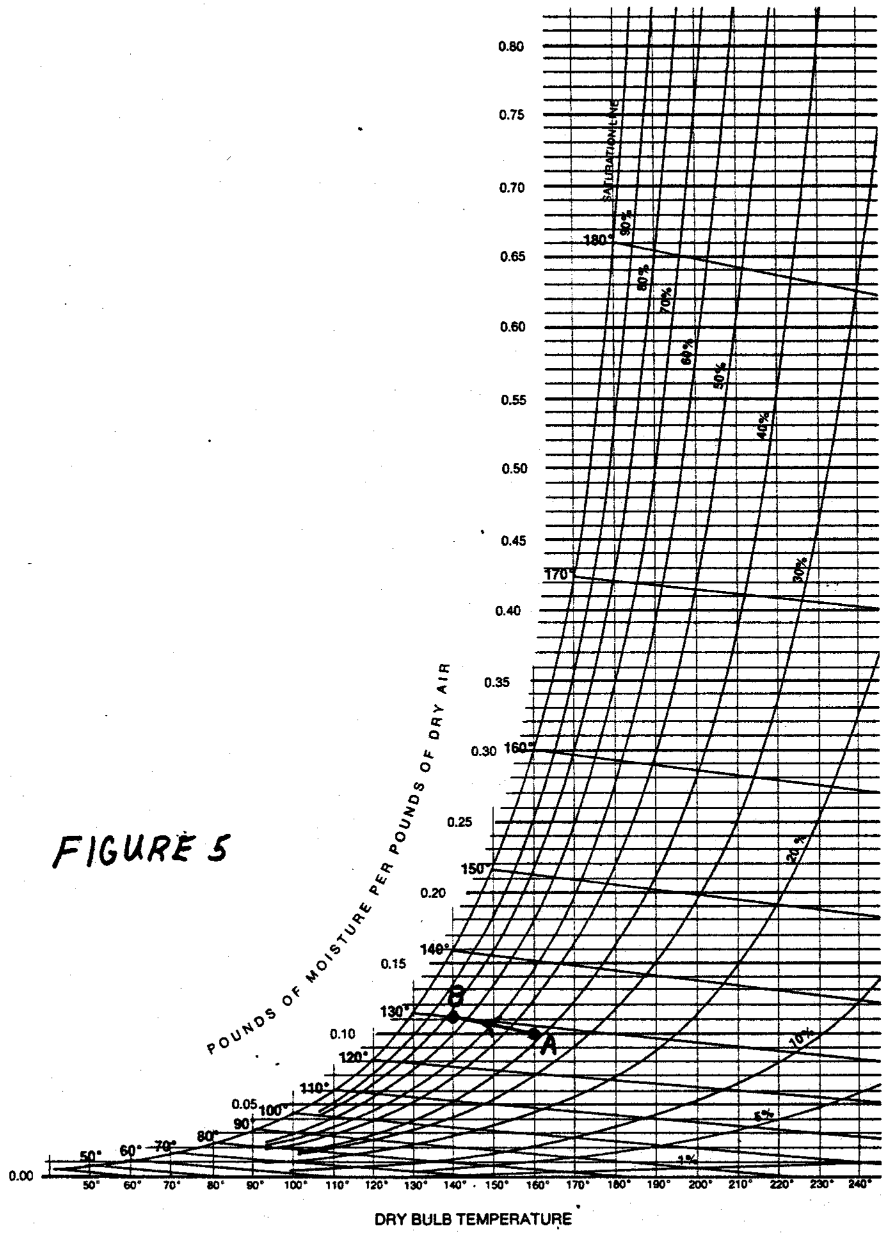
Second, note that although the air is more moist after passing through the load of lumber as is shown by the higher relative humidity, the wet bulb temperature has not changed. (Among other significant facts this suggests that it makes no difference whether the wet bulb temperature sensing bulb is placed on the entering or the leaving air side of the load. The important concern is that the wet bulb temperature sensor is placed so that a true indication of the wet bulb temperature is obtained.)

Third, note that the amount of moisture picked up by the air is directly related to the amount of cooling which the air experiences. If, for any reason, the air cooled only half as much as is shown in the example the amount of moisture pick-up would have been one-half as much as shown. One reason for a decreased amount of cooling is a decreased temperature difference between the air and the wood which is caused by the heating up of the wood while the air temperature remains constant. This is the principal cause for the typical falling rate drying that is experienced in conventional drying processes and which CRT technology tends to correct.

Fourth, note that the amount of cooling which the air can undergo is limited by the saturation line on the chart. When point "B" is moved to the left to the saturation line no further drying is possible. This means that if drying is to take place across the entire stack of lumber the leaving air must still have drying potential - that is, it must still have a wet bulb temperature depression.

Fifth, (and closely related to the fourth point above) note that the wet bulb depression of the entering air dictates the amount of cooling which can take place, which in turn determines the amount of drying which can take place. A very important corollary is that substantial drying can take place at very low entering air dry bulb temperatures if sufficient wet bulb temperature depression can be provided. For example, one pound of dry air at 72 F. dry bulb and 50 F. wet bulb with the dry bulb cooling 20 F. to 52-50 F. will pick 0.0045 pound of water whereas one pound of dry air at 160-130 cooling to 140-130 will pick up 0.0056 pound of water, drying at the lower temperature level is 80% as effective for the same cooling as at the higher temperature. Why not take advantage of this?

FIGURE 5



SATURATION LINE
90%
80%
70%
60%
50%
40%
30%
20%
10%
5%
1%
180°
170°
160°
150°
140°
130°
120°
110°
100°
90°
80°
70°
60°
50°
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
B
A
POUNDS OF MOISTURE PER POUNDS OF DRY AIR
50° 60° 70° 80° 90° 100° 110° 120° 130° 140° 150° 160° 170° 180° 190° 200° 210° 220° 230° 240°
DRY BULB TEMPERATURE

Thus far we have concentrated attention on the ideal situation in which all of the transferred heat is used to evaporate water and the cooling of the air follows a constant wet bulb temperature line on the psychrometric chart. As was mentioned above this does not take place in real life. Since a part of the energy which is transferred from the air to the wood is used to heat up the wood instead of evaporating water, less water is removed than we considered above.

Referring again to Figure 5, point "A", the entering air had a dry bulb temperature of 160 F., a wet bulb temperature of 130 F., a specific humidity of 0.1030 pound of water per pound of dry air and a dew point of 127 F. Point "B", the ideal leaving air condition would have a dry bulb temperature of 140 F., (corresponding to a temperature drop across the load of 20 F.), a wet bulb temperature of 130 F., a specific humidity of 0.1086 pound of water per pound of dry air, a dew point of 129 F. and a relative humidity of 75%. The amount of moisture removed would be 0.1086-0.1030 = 0.0056 pound of water per pound of dry air circulated.

But since all of the transferred energy is not used for evaporation of water the moisture loss in this example will be somewhat less than 0.0056 pound of water per pound of dry air. The value of 0.0049 pound of water per pound of dry air is a realistic approximation. The moisture content of the spent or leaving air is therefore about 0.1079 pound of water per pound of dry air.

A comparison of the entering and leaving air conditions is given in the following table:

	Entering Air	Leaving Air
Dry Bulb Temp.	160° F	140° F
Wet Bulb Temp.	130° F	129.8° F
Specific Humidity	0.1030	0.1079
Relative Humidity	42%	74%

The point is belabored because I consider it to be important to be aware of what is taking place within the kiln during drying. So let us refer again to the table and redraw some basic conclusions:

1. For a given entering air condition and a given change in dry bulb temperature as the air passes across the load (in the example 160-130 F. with a 20 F. temperature) there is a maximum amount of moisture which can be removed by one pound of dry air (about 18.5 cubic feet under the conditions of the example).
2. This maximum amount of moisture removal is not attained in practice because only a portion of the transferred energy is used to evaporate water. The remaining portion is used to heat up the system.
3. Note that the above two statements are independent of time. The amount of water removed during a given period of time depends upon the number of pounds of dry air which circulates over the lumber during a given time and the amount of cooling which the air experiences. For example, if 1,000,000 pounds of dry air having the conditions in the example passes over the lumber charge in one hour and the air cools 20 F. as it passes through the stack, 4,900 pound of water may be removed during that hour. If the same rate of air flow experiences only a 10 F. cooling, 2,450 pounds of water will be removed during the hour. And if the air flow is only 500,000

pounds of dry air per hour and the cooling is 10 F., the rate of moisture loss will be approximately 1,225 pounds per hour.

4. Although the spent (leaving) air contains more moisture than the entering air as is shown by the increase in relative humidity and dew point values the wet bulb temperature actually decreases slightly during the passage through the load.

Thus far we have discussed only one passage of air through the charge of lumber. If the spent air is to be discarded and not used again our analysis is basically complete. But if the spent air is to be recirculated the psychrometric chart shows that there is a problem. The spent air is cooler than the entering air should be. This represents no problem. The spent air can simply be heated up to the desired entering air level, Figure 6.

But in heating the spent air (line "B-C") there is no change in moisture content and the conditions at point "C" are wetter than described. Actually, the conditions at point "C" compared to point "A" are:

Property	Point "A"	Point "C"
Dry bulb	160 F.	160 F.
Wet bulb	130 F.	131.3 F.
Specific humidity	0.1030	0.1079

The humidity of the spent air must obviously be reduced. This is generally accomplished by mixing the spent air with dryer outside air.

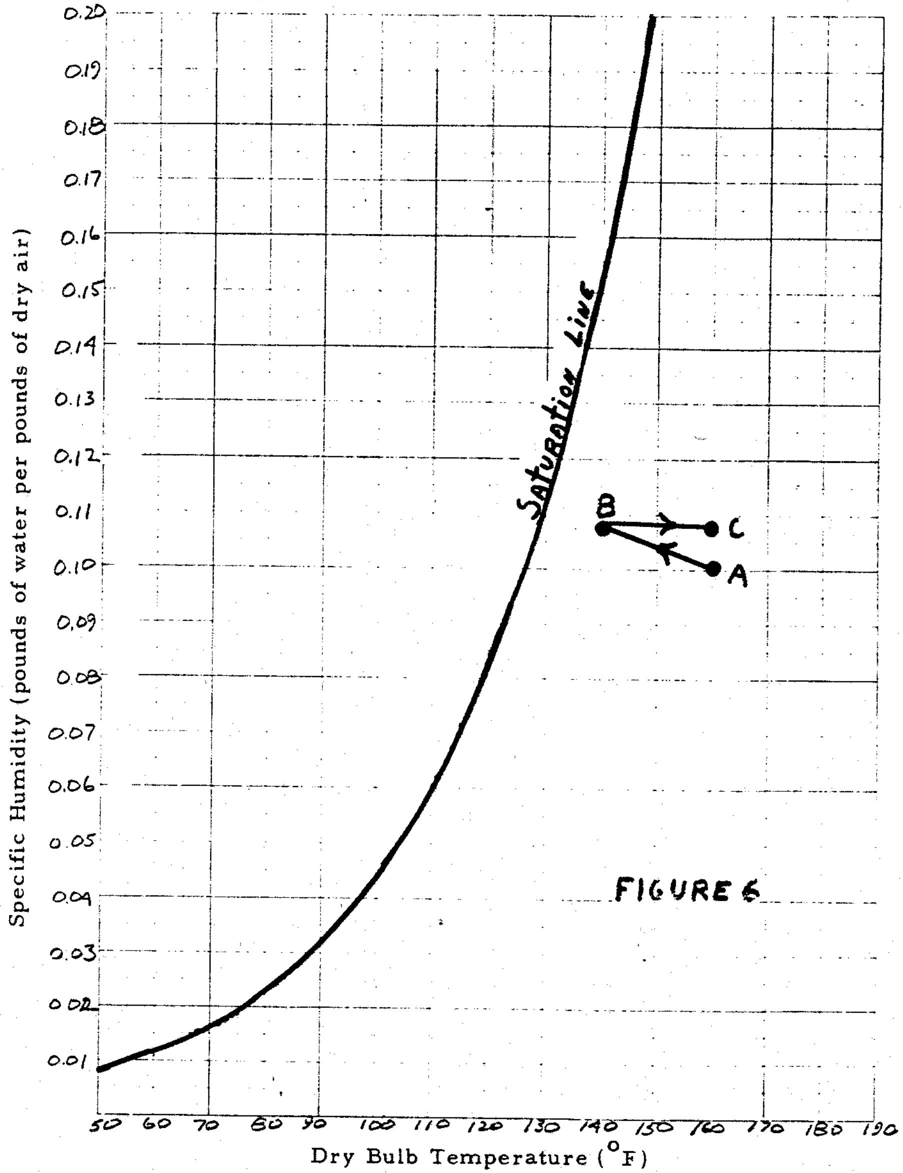
For purposes of illustration, assume that the outside air conditions are dry bulb temperature 70 F., relative humidity 70%, specific humidity 0.011 pound of water per pound of dry air. This condition on the psychrometric chart is indicated by point "D".

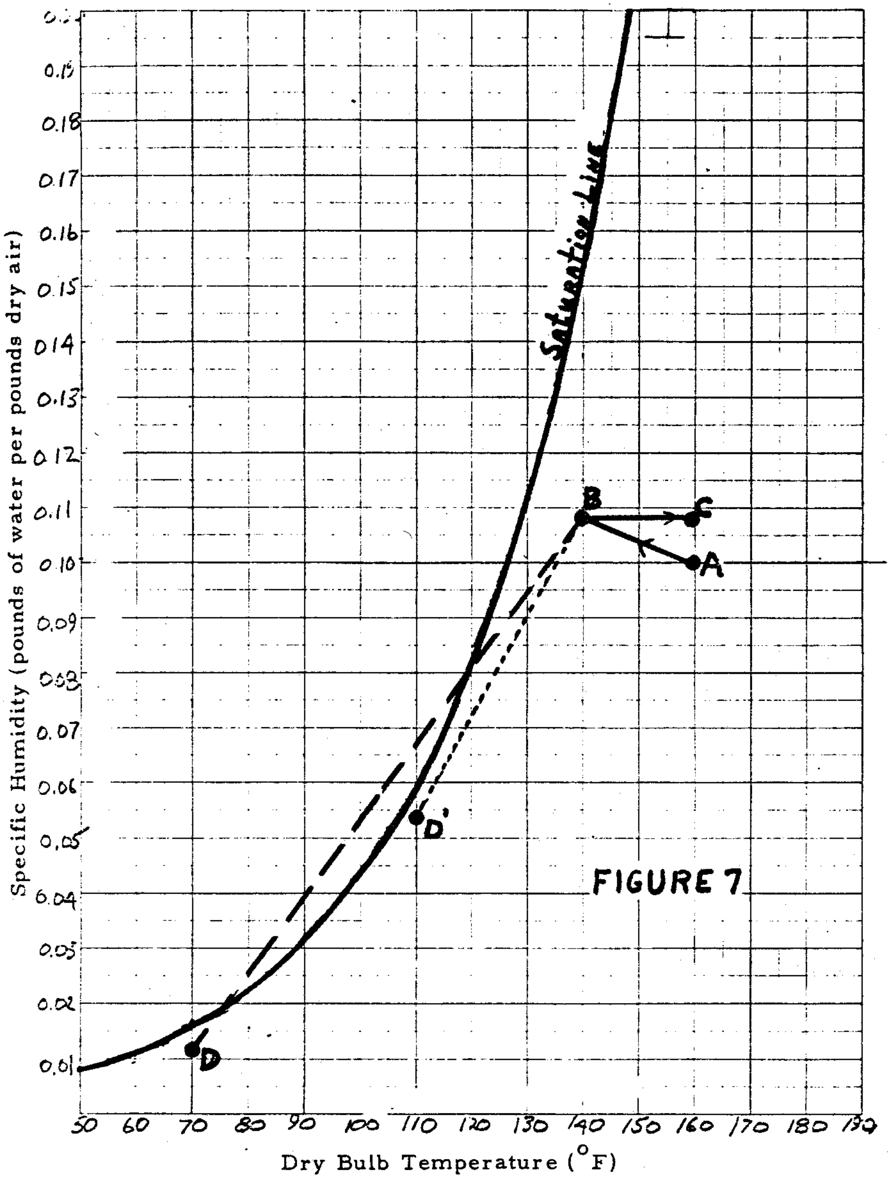
It is a simple calculation to determine the relative quantities of air-water compositions which must be mixed in order to obtain a given composition. For example, the psychrometric chart may be used. A straight line is drawn between the points representing the composition to be mixed (Point "B"). This line crosses the line representing the desired moisture content (that of point "A"). The ratio of the length of the upper leg ("B" to intersection) to the length of the lower leg ("D" to intersection) is the ratio of the quantity of dilution air to the quantity of spent air required to yield the desired intermediate moisture content, Figure 7.

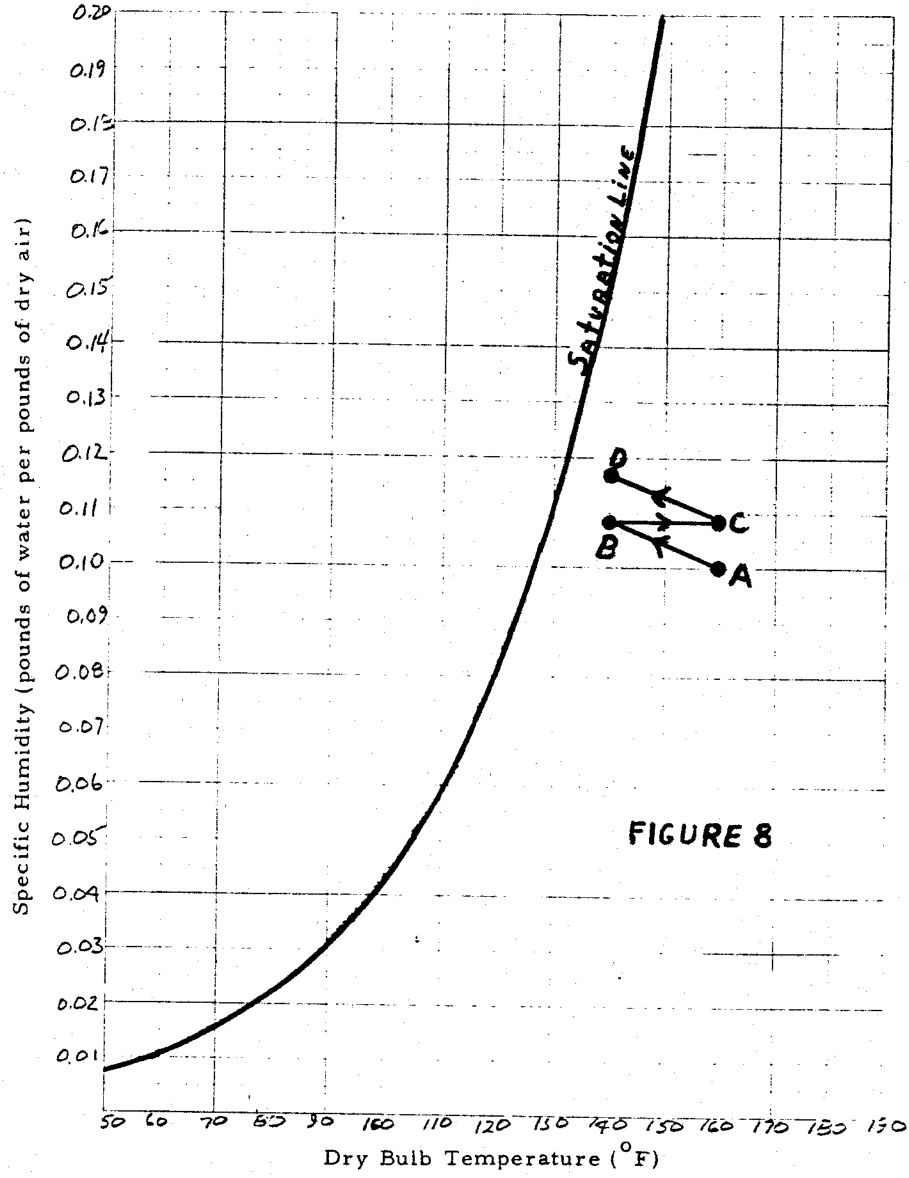
In the example which we have been using the ratio is 0.051 to 1.00. In other words the amount of dilution air required is 5.1% of the quantity of circulating air.

It is immediately apparent that the relative quantity of dilution air is highly dependent upon the humidity of the dilution air. For example, if the dilution air is 110 F. and 90% relative humidity the specific humidity is 0.0529. The quantity of dilution air would then become 9.3%.

The quantity of dilution air required to re-establish a starting point humidity depends not only upon the humidity of the outside air but also upon the initial dry bulb temperature and humidity. For example, if the initial dry bulb temperature were 110 F. and the wet bulb temperature at 80 F., the specific humidity would be 0.01524 pounds of moisture per pound of dry air. If the temperature drop across the load during drying were 20 F. the spent air specific humidity would be 0.01990 pound of water per pound of dry air. Now if the dilution air composition were 0.0110 pound of water per pound of dry air (corresponding to 70 F. and 70% R.H.) the relative quantity of dilution air would be 53.5%.


Specific Humidity (pounds of water per pounds of dry air)
Dry Bulb Temperature (°F)
Saturation Line
B
C
A
FIGURE 6


Specific Humidity (pounds of water per pounds dry air)
Dry Bulb Temperature (°F)
Saturation Line
FIGURE 7
A
B
C
D
D'
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190


Saturation Line
D
C
B
A
FIGURE 8
Specific Humidity (pounds of water per pounds of dry air)
Dry Bulb Temperature (°F)

The venting systems of most kilns which use conventional intake and exhaust vents on the roofs are capable of taking in only 10-15% of dilution air.

Many kilns are of double track construction. In these kilns the spent air from the first track is heated and passed into the charge on the second track. However, there is no humidity adjustment between the two tracks. On the psychrometric chart the operation of the double track kiln looks like Figure 8. Entering air is shown as point "A". Leaving air from the first track is point "B". Entering air to the second track is point "C" and leaving air from the second track is point "D". It is immediately obvious that the intake and exhaust venting requirements for a double track kiln are much greater than for a single track kiln.

I have barely touched on the information which the kiln operator can gain from the use of the psychrometric chart. For your initiation simple charts are being distributed to each of you, compliments of Irvington-Moore. I hope that you will use them to good advantage.