DILUTION AIR REQUIREMENTS

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Much is written about the effects of kiln conditions including temperature, humidity and rate of circulating air flow on drying rate and product quality of different lumber items in conventional kilns. However, this writer is not aware of significant attention being directed to the processing step in which the specific humidity of the spent air after passing through the charge is reduced to the entering air level for repassage through the charge. In most kilns the specific humidity adjustment is accomplished by diluting the moisture-laden spent air with lower humidity air from the outside. This involves a complex system of venting whereby the desired amount of dilution air is admitted to the kiln and the amount of kiln air necessary to maintain a constant volume and pressure in the entering air plenum is exhausted to the atmosphere. The dilution air is admitted either through controlled vents or by means of a system of positive pressure blowers and controlled louvers.

This paper relates to the estimation of approximate dilution air requirements under different entering air temperatures and humidity conditions, drying rates and dilution air temperature and humidity conditions without reference to the venting mechanism.

The data are taken from "Psychrometric Tables and Charts" by Zimmerman and Lavine, second edition (Industrial Research Service, Inc., Dover, New Hampshire) in which specific humidities of air at different dry bulb and wet bulb temperatures are tabulated and charted.

Several assumptions are in the calculations translating the psychrometric table data into dry kiln conditions. Some of the assumptions are sufficiently invalid to render the calculations qualitative only instead of precisely quantitative. However, the relative trends should be valid and worthy of consideration.

Among the assumptions are the following:

1. Pressures throughout both kiln and ambient are one atmosphere. Static pressures across the charge of lumber amount to only a few inches of water which appear to represent differences which can be ignored.
2. The heat of vaporization of water in wood is the same as that of liquid water at the same temperature. This is approximately true for the free water but deviations increase as moisture contents decrease below fiber saturation.
3. The sensible portion of the transferred energy is ignored. It is assumed that the specific humidity increase accompanying a given temperature drop across the charge is that given by the tables. In reality a small portion of the energy is used to

increase the temperature of the wood with the result that the specific humidity increase is slightly less than calculated.

4. The method of mixtures and the ideal gas laws are applicable.

Unfortunately no actual kiln data are available for comparison with the calculated dilution air requirements.

Calculations and results are illustrated in the figures.

Figure 1 is a partial psychrometric chart on which specific humidity of air-water mixtures is plotted against temperature. Specific humidity is defined as mass of water vapor associated with unit mass of dry air and is expressed as pounds of water vapor per pound of dry air or grams of water vapor per gram of dry air or any other system of like mass units.

The curved line represents saturation at a given ambient pressure, in this case, one atmosphere. Only points beneath and to the right of the saturation line may exist as mixtures of water vapor and dry air. Points above and to the left comprise dry air saturated with water vapor and liquid water. At the boiling point of liquid water the specific humidity along the saturation line becomes infinity and the atmosphere contains water vapor only.

The sloping straight lines are called adiabatic saturation lines which, in the case of water vapor-dry air mixtures are substantially identical with constant wet bulb temperature lines. When a mixture of air and water vapor cools under such conditions that all of the energy lost in cooling is used to vaporize liquid water, the specific humidity increases along the adiabatic saturation line or constant wet bulb temperature. If, however, a mixture cools with no vaporization taking place the cooling curve is a horizontal line which intercepts the saturation line at the dew point. During this process the wet bulb temperature decreases.

Figure 2 is a plot of specific humidity of air-vapor mixtures versus temperature for different relative humidities in the temperature range normally encountered in dilution air. The effects of both temperature at constant relative humidity and of relative humidity at constant temperature are seen to be marked. Air at 40°F and 80% relative humidity has the same specific humidity as air at 85°F and 20% relative humidity.

Figure 3 illustrates the specific humidity relations resulting from the mixing of two different specific humidity systems. The familiar equation for additive mixing is easily derived. In this diagram entering air with specific humidity of a mass units of moisture per unit mass of dry air is passed over a charge of lumber. The air cools adiabatically ΔT degrees and leaves the charge with a specific humidity of b mass units of moisture per unit mass of dry air. The unit mass of dry air has picked up b-a units of moisture while the wet bulb temperature remained constant. This unit mass of dry leaving air is mixed with x units of dry dilution air containing cx units of moisture to produce 1+x units of dry air containing (1+x)a units of moisture or a unit of moisture per unit of dry air which is the composition of the entering air.

The familiar relation X=(b-a)/(a-c) is easily derived, and predicts the dilution air requirements. X, the number of mass units of dry dilution air required to adjust the specific humidity of unit mass of dry leaving air, is directly related to the increase in specific humidity as the unit mass of dry kiln air passes through the charge and inversely proportional to the difference in specific humidity between the entering kiln air and that of the dilution air.

When the specific humidity of the dilution air is the same as that of the entering air (a-c=0) the dilution air requirement is infinite--in other words, all of the kiln air must be dilution air.

The term (b-a) depends on a number of factors. For a charge of a given width the increase in moisture content experienced depends on the specific drying rate which is roughly proportional to the temperature change ΔT. For a given drying rate (approximately a given ΔT per unit length of slot) the amount of moisture pick-up is inversely proportional to the load width. Other relations are discussed later.

Obviously the addition of dilution air increases the mass of dry air from x to 1+x units. Therefore, if the entire amount of spent air is diluted the excess of dry air (x) together with ax units of water must be exhausted from the system in order to maintain the unit mass of dry air after humidity adjustment. If the requisite amount of spent air is exhausted before the addition of dilution air, the fraction 1/(1+x)x units of dry dilution air is required.

The term x, while explicit, is an awkward term to visualize. Therefore, dilution air requirements have been calculated as fractions of dilution air in the circulating air. This is accomplished by transforming the compositions of the air-vapor mixtures into moles using molecular weights of 28.96 for dry air and 16.00 for water. The ratio of the moles of dilution air to the total moles of mixture is the fraction of dilution air in the mixture.

Transformation of specific mass relations into rates is accomplished by dividing by time.

The molar quantities are transformed into volumes by use of the ideal gas law assuming normal atmospheric pressure. In English units the relation is

$$V = 0.7297\ n\ T_R$$

where V is volume in cubic feet, n is the number of moles of air-vapor mixture, T_R is absolute temperature (T°F + 460) and 0.7297 is the ideal gas constant having units of cubic foot-atmospheres per degree.

In Figure 4 the effect of relative humidity of dilution air on the dilution air requirements at one set of conditions--namely dilution air at 60°F and various entering air dry bulb temperatures with constant wet bulb temperature depression of 40°F and a temperature drop across the load of 30°F.

As predicted by the relation x=(b-a)/(a-c) the dilution air requirement for a given set of entering and leaving air conditions (temperatures and wet bulb temperature depression) increases as the relative humidity of the dilution air increases due to the increase in specific humidity (c) of the dilution air.

Of greater practical significance is the fact that the curves have negative slopes and that as entering air temperature increases the dilution air requirements decrease and the effects of dilution air humidity become smaller. This is due to the fact that the specific humidity (a) of the entering air increases at an exponential rate as entering air temperature increases. Dilution air requirement becomes zero when the wet bulb temperature of the entering air becomes equal to the normal boiling point at the existing ambient pressure--212°F at one atmosphere pressure. At conditions above this level the circulating air consists entirely of water vapor and the intake vents are completely closed and the exhaust vents operate only to pass the excess water vapor picked up from the wood as the air passed over the charge.

It is important to note the magnitude of the dilution air requirements. For example, if the kiln is capable of only 10% dilution air in the circulating air, entering air conditions of at least 115-115°F dry bulb and wet bulb temperatures must be maintained if a drying rate equivalent to that produced by a 30°F temperature drop across the charge is produced. However, if 20% dilution air is possible the entering air dry bulb temperature may be in the 140°F range depending on the relative humidity of the dilution air.

It should be pointed out again that dilution air requirements approach zero as the entering air dry bulb increases.

Figure 5 shows the effect of dilution air temperature at constant relative humidity on dilution air requirements for the same kiln operating conditions as used in Figure 4. The effects of dilution air temperature are dramatic at lower entering air temperatures, again reflecting the effects of temperature on the specific humidities of both dilution air and kiln air.

Figure 6 shows the dependence of dilution air requirement on the temperature drop across the charge. For a given charge width the temperature drop across the load is an approximate measure of drying rate. For a given specific drying rate the temperature drop across the load is directly related to the charge width. Therefore, the temperature drop across a four foot wide load is one-half that for an eight foot wide load for the same kiln residence time and entering air conditions. Reference to Figures 4 and 5 shows that the curves in Figure 6 will be significantly affected by changes in the temperatures and/or relative humidity of the dilution air.

Figure 7 illustrates the effects of wet bulb temperature depression on the dilution air requirements. As pointed out earlier, the smaller the difference between the specific humidity of the spent air and the dilution air, the greater the relative amount of dilution air required for humidity adjustment. An increase in wet bulb temperature depression is associated with a decrease in specific humidity. Figure 8 shows the dilution air requirements for 60°F 60% relative humidity dilution air at different kiln air (entering) wet bulb temperature depressions at three entering air dry bulb temperatures and two temperature drops across the load. As explained above, the dilution air requirement depends upon both the temperature drop across the charge and the difference between the specific humidities of the dilution air and the spent air.

Thus far attention has been focused only upon relative quantities of dilution air in the circulating air. A more practical consideration relates to the actual quantities of dilution air required. For example, a conventional kiln having a total slot area of 312.5 ft^2 (100 feet long, 50 courses, 3/8" sticks) and an air velocity of 400 fpm passes air through the charge at the rate of 125,000 cfm. If the circulating air comprises 10% dilution air approximately 12,500 cfm (to be corrected for difference in temperatures of dilution air and kiln air) must be taken into the kiln from the outside through intake vents or by other means. If the total intake vent area is 25 ft^2 the intake rate of flow would be 500 fpm. If the circulation rate through the kiln were increased to 1000 fpm the dilution air intake rate would be increased 2.5 times to 1250 fpm to maintain the 10% dilution air content. This writer claims no knowledge concerning the mechanics of the operation of vents but it appears reasonable to assume that kilns operating at higher air flow rates and at fast drying schedules must depend on forced dilution air admission rather than on intake vents alone.

Data indicate that dilution air requirements are approximately constant for kiln wet bulb temperatures over a wide range of entering air wet bulb temperature depressions. Figure 8 shows 60°F 60% relative humidity dilution air rates of addition for different kiln wet bulb temperatures and drying rates based on a total airflow through the charge of 125,000 cfm. Dilution air volumes are calculated for one atmosphere pressure.

Thus far no discussion has been addressed to the comparison of double track and single track kilns. If the double track kiln has booster heating coils between the tracks which serve to raise the dry bulb temperature of the spent air from the first track back to the dry bulb temperature of the air entering the first track the wet bulb temperature will be raised significantly. If the temperature drop across the second track is the same as that through the first track the total moisture pickup (b-a) will be substantially double that for the same temperature drop across a single track (same kiln residence time). Therefore the dilution air requirement for a given rate of drying in a double track kiln will be substantially double that for a single track kiln.

More and more kilns are now being direct fired by passing the combustion gases directly into the kiln. These combustion gases from organic fuels comprise both water vapor and dry dilution substances. Because dilution gases are continually entering the kiln it is impossible to maintain high wet bulb temperatures. No attempt has been made in this study to address the dilution air requirements of direct fired kilns quantitatively.

In summary dilution air requirements are highly sensitive to both dilution air and kiln air conditions. This paper has attempted to point out a number of the inter-relationships on a qualitative basis.

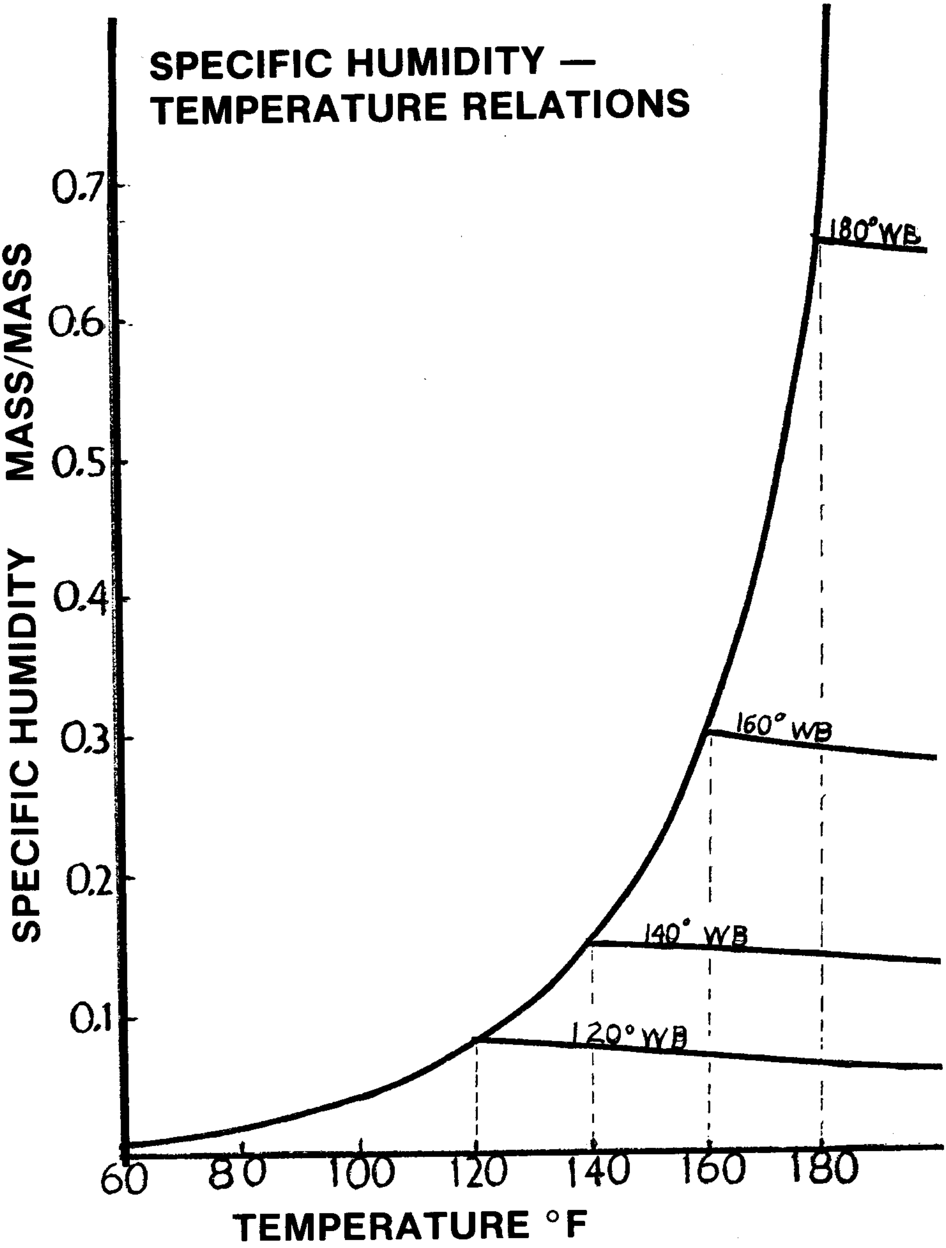

SPECIFIC HUMIDITY — TEMPERATURE RELATIONS
SPECIFIC HUMIDITY MASS/MASS
0.7
0.6
0.5
0.4
0.3
0.2
0.1
60
80
100
120
140
160
180
TEMPERATURE °F
180°WB
160° WB
140° WB
120° WB

Figure 1

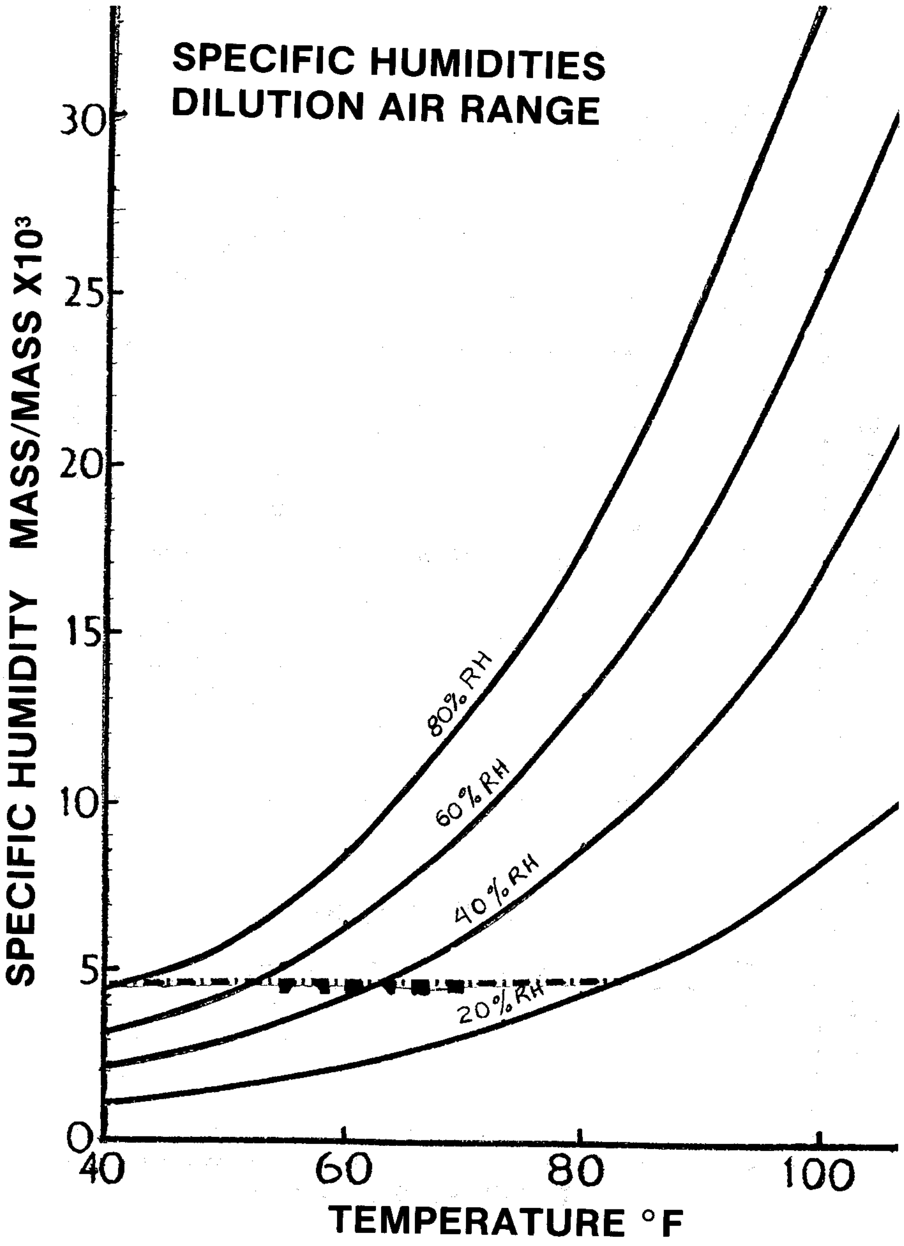

SPECIFIC HUMIDITIES
DILUTION AIR RANGE
SPECIFIC HUMIDITY MASS/MASS X10^3
30
25
20
15
10
5
0
40
60
80
100
TEMPERATURE °F
80% RH
60% RH
40% RH
20% RH

Figure 2

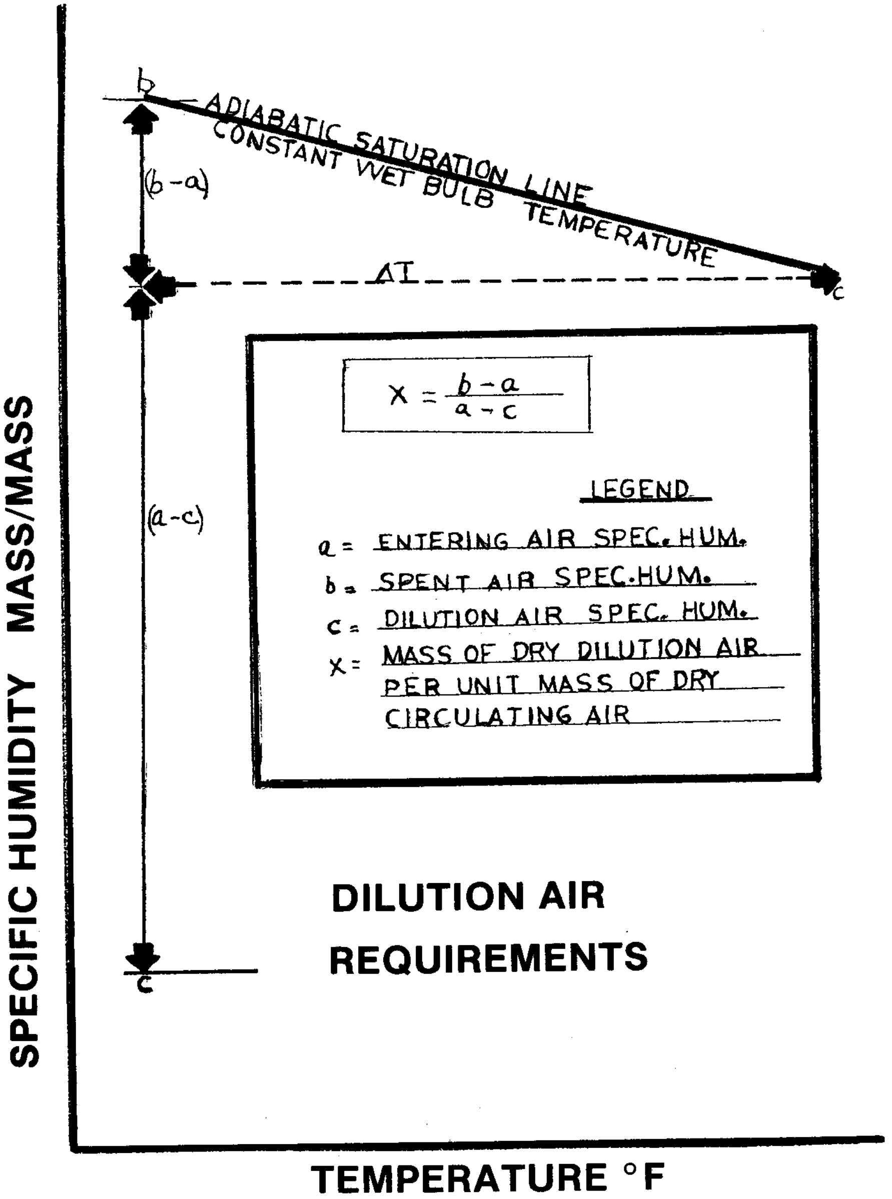

b
ADIABATIC SATURATION LINE
CONSTANT WET BULB TEMPERATURE
(b-a)
ΔT
c
X = (b - a)/(a - c)
LEGEND
a = ENTERING AIR SPEC. HUM.
b = SPENT AIR SPEC. HUM.
c = DILUTION AIR SPEC. HUM.
X = MASS OF DRY DILUTION AIR PER UNIT MASS OF DRY CIRCULATING AIR
(a-c)
c
DILUTION AIR REQUIREMENTS
SPECIFIC HUMIDITY MASS/MASS
TEMPERATURE °F

Figure 3

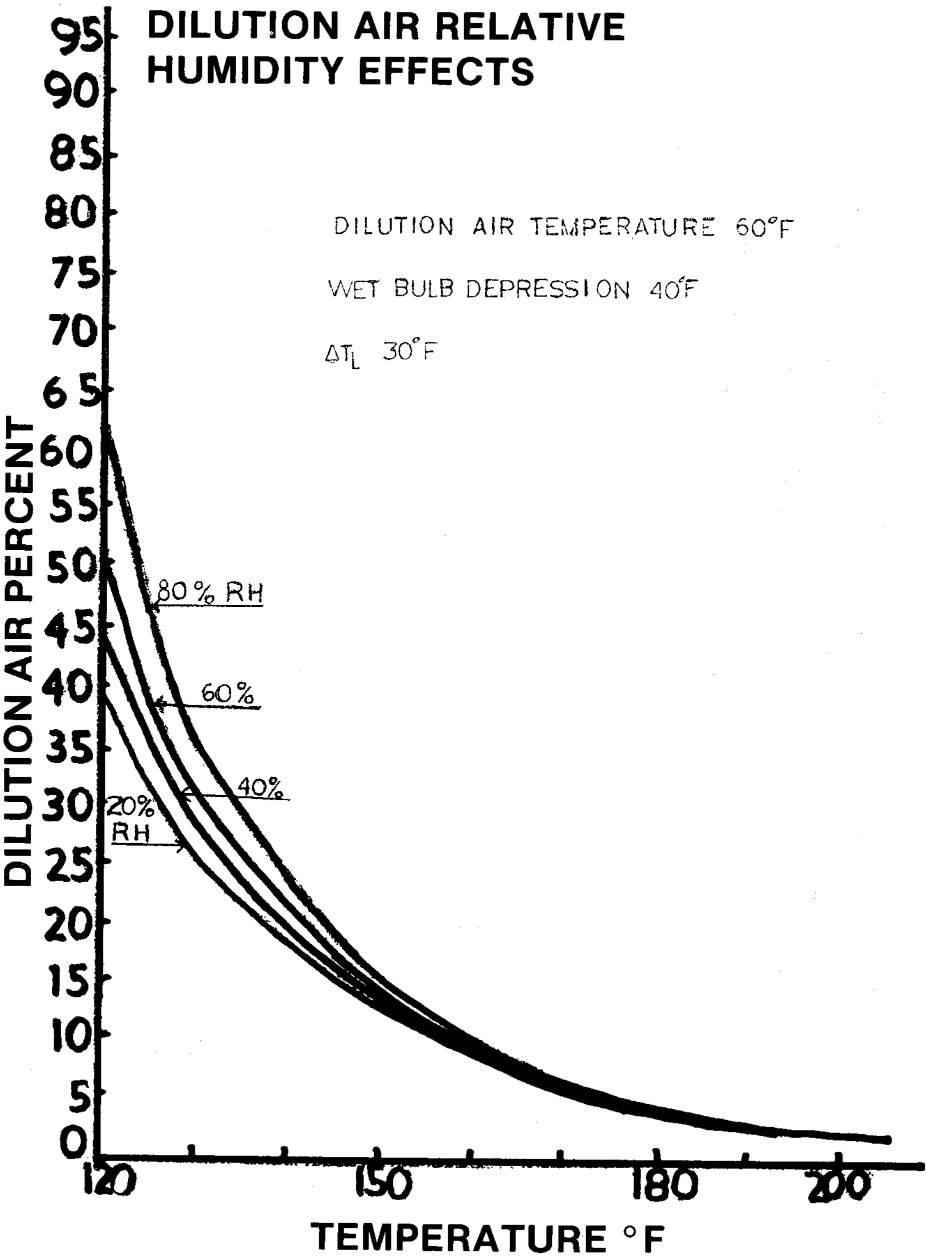

DILUTION AIR RELATIVE HUMIDITY EFFECTS
DILUTION AIR TEMPERATURE 60°F
WET BULB DEPRESSION 40°F
ΔT_L 30°F
80% RH
60%
40%
20% RH
DILUTION AIR PERCENT
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
120
150
180
200
TEMPERATURE °F

Figure 4

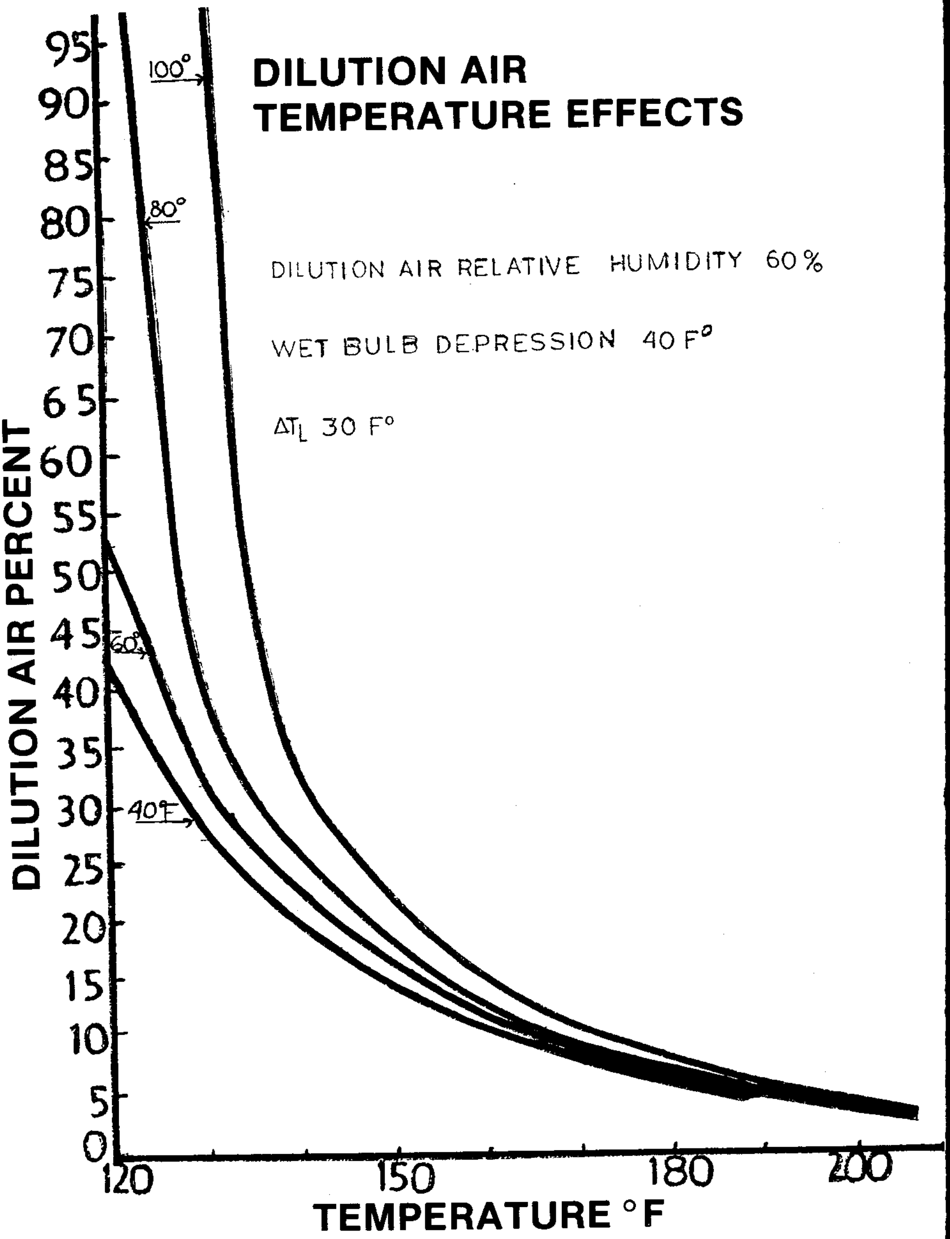
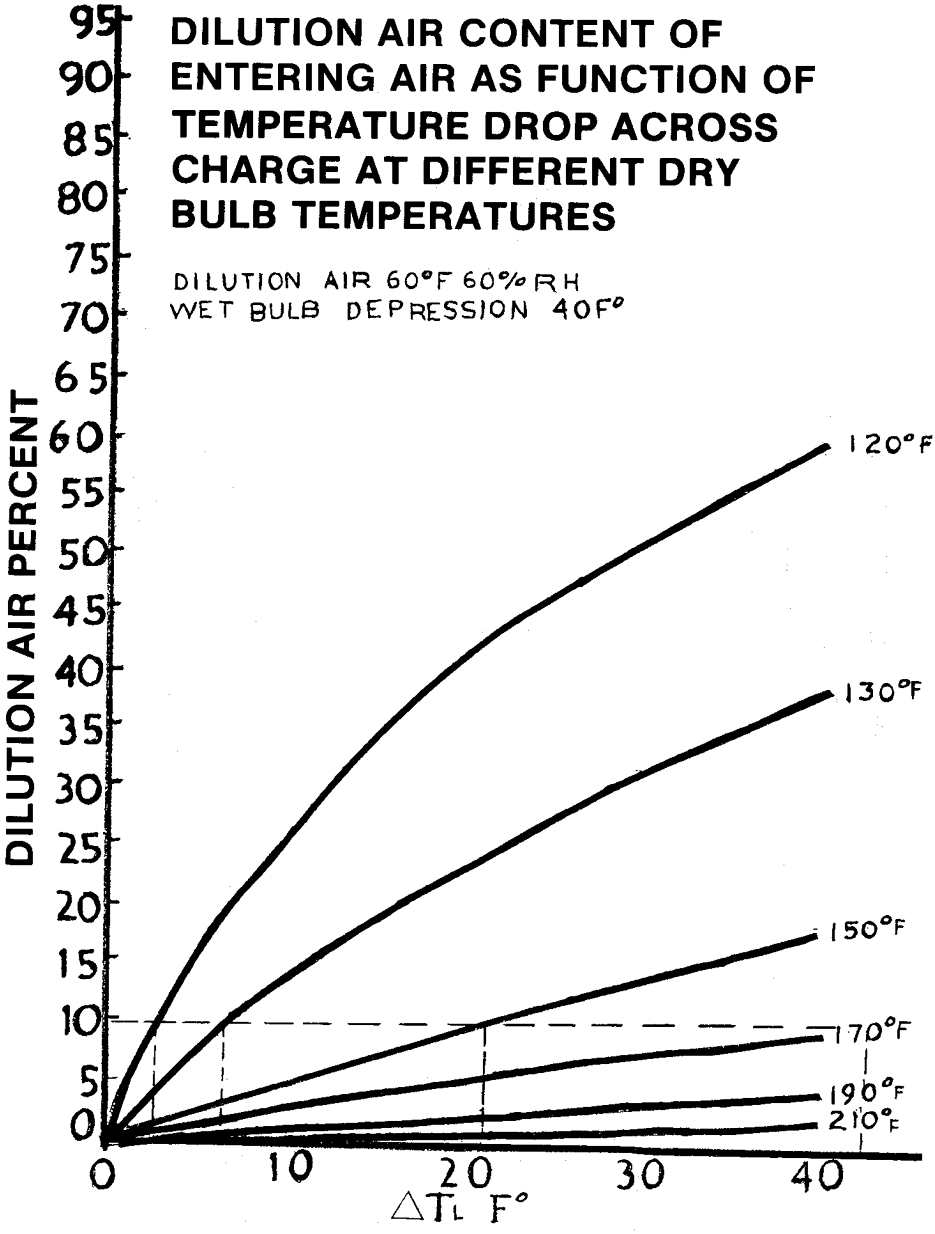

DILUTION AIR
TEMPERATURE EFFECTS
DILUTION AIR RELATIVE HUMIDITY 60%
WET BULB DEPRESSION 40 F°
ΔT_L 30 F°
100°
80°
60°
40°F
DILUTION AIR PERCENT
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
120
150
180
200
TEMPERATURE °F

Figure 5



DILUTION AIR CONTENT OF ENTERING AIR AS FUNCTION OF TEMPERATURE DROP ACROSS CHARGE AT DIFFERENT DRY BULB TEMPERATURES

DILUTION AIR 60°F 60% RH
WET BULB DEPRESSION 40F°

Figure 6

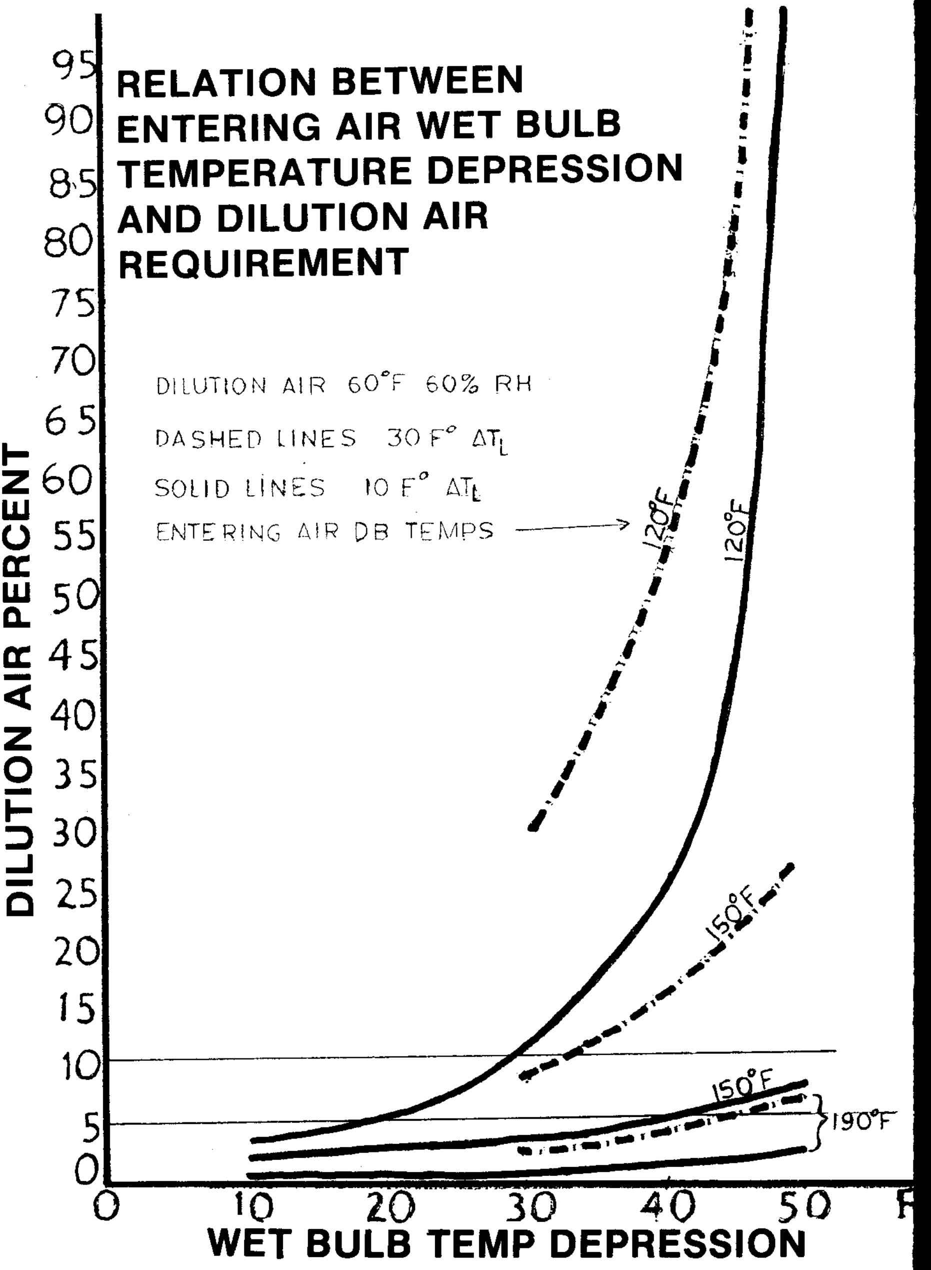

RELATION BETWEEN ENTERING AIR WET BULB TEMPERATURE DEPRESSION AND DILUTION AIR REQUIREMENT
DILUTION AIR 60°F 60% RH
DASHED LINES 30 F° ΔT_L
SOLID LINES 10 F° ΔT_L
ENTERING AIR DB TEMPS
120°F
120°F
150°F
150°F
190°F
DILUTION AIR PERCENT
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0
0
10
20
30
40
50
WET BULB TEMP DEPRESSION

Figure 7

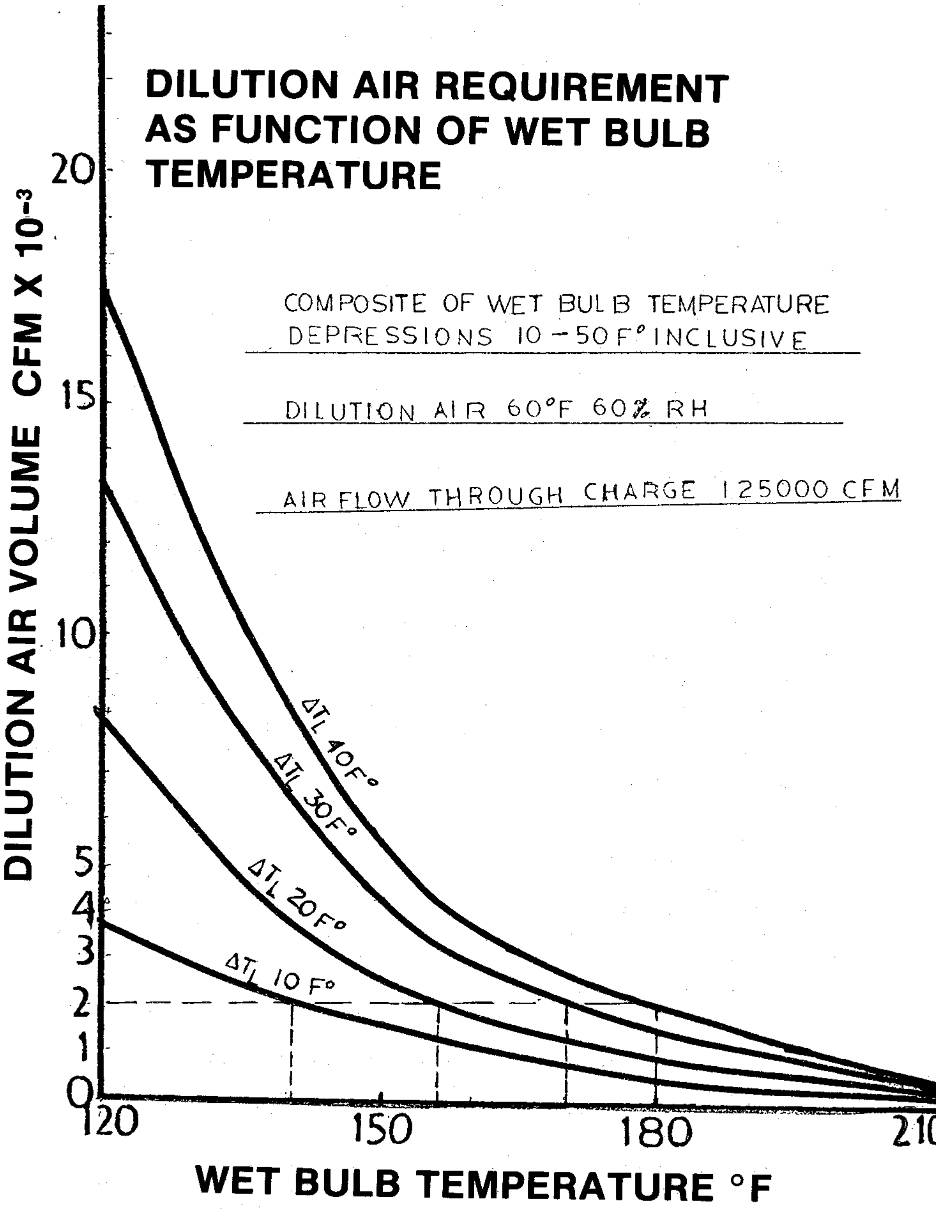

DILUTION AIR REQUIREMENT AS FUNCTION OF WET BULB TEMPERATURE
COMPOSITE OF WET BULB TEMPERATURE DEPRESSIONS 10-50 F° INCLUSIVE
DILUTION AIR 60°F 60% RH
AIR FLOW THROUGH CHARGE 125000 CFM
ΔTL 40F°
ΔTL 30F°
ΔTL 20F°
ΔTL 10 F°
DILUTION AIR VOLUME CFM X 10-3
0
1
2
3
4
5
10
15
20
120
150
180
210
WET BULB TEMPERATURE °F

Figure 8