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HUMIDITY / MOISTURE HANDBOOK

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INTRODUCTION

Through the years we at Machine Applications Corporations have had the opportunity to discuss many different humidity/moisture measurement and control applications with a large number of users and potential users of moisture measurement equipment. We find that very few have a firm understanding of this somewhat specialized field of engineering.

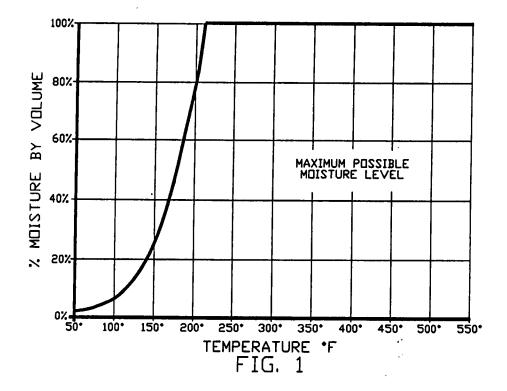
The confusion that exists is probably due to the following.

One, words like humidity, moisture, vapor, dew point, steam, fog, condensation, etc. are used in everyday speech even though their meanings are understood in the most general way. These same words when used by a scientist or engineer have very specific meanings which are easily misinterpreted by someone who does not use them in their scientific sense regularly. An example would be the following sentences. "The water is boiling. I can see steam coming out of the pot." Those who work with steam know that it is invisible and that the cloud that is seen above a pot of boiling water is actually water droplets that form as the steam cools and condenses as it mixes with the air above the pot.

<u>Two</u>, there are many different ways to represent the amount of moisture that is dissolved in the air or other atmosphere. Relative humidity, specific humidity, humidity ratio, dew point, percent by volume, and parts per million are all used to express a measure of the amount of water vapor that is mixed with other gasses.

Relative Humidity

Relative humidity is familiar to most of us because of its everyday usage with regard to the weather. Relative humidity is usually abbreviated "RH" and is expressed as a percentage between zero and 100%. RH indicates the amount of moisture in the air as a percentage of the maximum amount that the air can hold below 212°F. Unfortunately the amount of moisture that the air can hold depends on the temperature of the air. The following graph shows the maximum percentage of water vapor that the air can hold at a given temperature.



The graph shows that the higher the temperature (up to 212°F) the higher the amount of water vapor the air can hold. At 212°F and above it is possible for the air to be totally displaced by water vapor (steam) and the % moisture by volume can reach 100%.

Before we give the technical definition of RH we must explain the terms that will be used in the definition.

Partial Pressure:

Let's take an empty jar and screw the lid on tight. The air in the jar is the same air that is in the room on the outside of the jar. To make things simple assume that the air in the jar is 20% oxygen and 80% nitrogen.

The pressure inside the jar is the same as the atmospheric pressure outside the jar which is about 14.7 PSI. The pressure inside the jar is caused by the oxygen O2 molecules and the nitrogen N2 molecules bouncing around and hitting the sides of the jar. If we could remove the oxygen from the jar there would be fewer molecules to collide with the jar. The pressure would be less and would be due totally to the nitrogen molecules. The pressure exerted by the nitrogen molecules alone would be 80% of 14.7 PSI which is 11.76 PSI. If we left the oxygen in the jar and removed the nitrogen, the pressure would be 20% of 14.7 PSI which is 2.94 PSI.

The partial pressure of a gas is the part of the total pressure that is exerted by that gas alone.

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P_0 = Partial pressure of oxygen = 2.94 PSI

P_N = Partial pressure of nitrogen = 11.76 PSI

P_T = Total pressure = P_0 + P_N = 14.7 PSI
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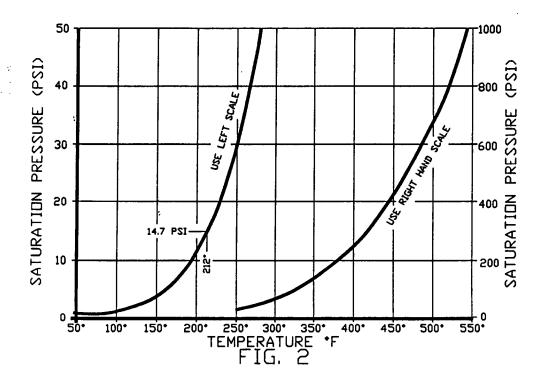
If we took our jar up a mountain to 10,000 ft. above sea level and then sealed it, the total pressure would be only 10.1 PSI.

$$P_0 = 2.02 \text{ PSI}, P_N = 8.08 \text{ PSI}, P_T = 10.1 \text{ PSI}$$

Saturation Pressure (Ps):

The saturation pressure of water vapor is the partial pressure of water vapor at 100% humidity. 100% humidity is the point where liquid water and water vapor are in equilibrium, that is the water is evaporating into vapor and the vapor is condensing into liquid. Since water boils at 212°F at atmospheric pressure, the pressure Ps must go above atmospheric when the temperature goes above 212°F. To maintain 100% humidity at 250°F would require a pressure near 30 PSI or two times atmospheric pressure.

Figure 2 shows the saturation pressure for water vs temperature from 50°F to 550°F.

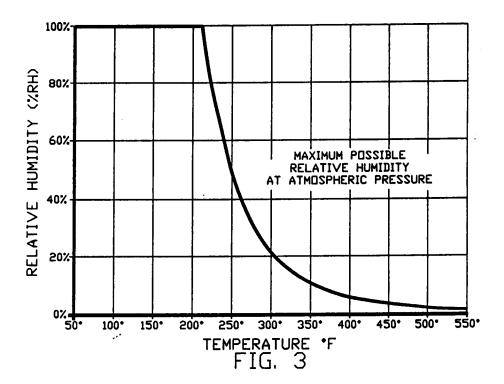


As we shall see this rapid increase in saturation pressure above 212°F is why it is impossible to reach 100% RH at atmospheric pressure above 212°F.

The physics definition of RH is expressed by the following equation:

$$RH = Pw/Ps X100$$

Pw is the partial pressure of water vapor in the air and Ps is the saturation pressure. Above 212°F Pw is equal to the atmospheric pressure when the moisture level is 100%, but Ps, the saturation pressure, increases rapidly with temperature. The graph in Figure 3 shows the maximum RH vs temperature. Note that below 212°F it is possible to achieve 100% RH even though the % moisture in the air by volume is less than 100% (as shown on the graph in Figure 1). Above 212°F the maximum RH is less than 100% even when the atmosphere is 100% water vapor (100% moisture by volume).



At 400°F the maximum possible RH is 5.9%. At 700°F the maximum possible RH is .48%.

Although there are instruments available to measure RH up to 400° F, it can be seen from the graphs of Figure 1 and Figure 3 that relative humidity is a useless and even misleading scale for indicating moisture level above 212° F. An instrument that could measure relative humidity with a $\pm 1\%$ accuracy at 400° F would give us a measure of the % moisture by volume to an accuracy of ± 1 part in 5.9 or $\pm 17\%$.

The relative humidity scale gives us some surprising results at ordinary room temperatures as well. Let us assume that the room we are in is at a temperature of 60°F and that the relative humidity is 50%. The % water vapor in the room under these conditions is .87%. If we turn on our electric heater and increase the room temperature to 72°F the RH will drop to 33% even though the % moisture by volume remains at .87%.

With this example we begin to get an idea of the difference between a relative moisture scale and an absolute moisture scale. The relative humidity changes when the temperature changes, but the % water vapor by volume does not change with temperature. It changes only when water vapor is added or removed from the atmosphere.

The atmosphere around us is composed of a mixture of gasses in the following proportions when the air is totally dry:

Nitrogen						78.084%
Oxygen.						20.948%
Argon						.934%
Carbon Di	ioz	kide	e .			.0314%
Neon						.00182%
Helium .		•				.000524%
Methane.						.00015%
Hydrogen						.00005%
Other trac						.000056%

Since the air is seldom totally without water, the above percentages change depending on the amount of water vapor that is mixed with the other gasses.

As we have already stated, 50% RH at 60°F corresponds to .87% water vapor. 50% RH @ 95°F corresponds to 2.8% moisture, and 100% RH @ 95°F is a moisture level of 5.6%.

The atmosphere inside a gas fired boiler will be very different than the atmosphere around us. Most of the oxygen will be used up to burn the fuel. The carbon in the fuel burns and becomes carbon dioxide and the hydrogen in the fuel burns and becomes water vapor. If the fuel was methane and the combustion air was totally dry (0% water vapor) the atmosphere in the boiler would be:

73% Nitrogen 18% Water vapor 9% Carbon dioxide

At the high temperatures inside a boiler the relative humidity would be close to zero even though the % moisture by volume would be 18%.

When it is raining or snowing outside the relative humidity is nearly 100%. This is because water vapor from the snow or water droplets will evaporate into the air as long as the RH is less than 100%. When the outside temperature is 10°F and it is snowing, the % moisture in the air is about .2%, even though the relative humidity is near 100%. If we bring this air into our home and heat it to 72°F, the relative humidity drops to 7.59%. The % water vapor is still .2% if all we do is heat the air.

Other Absolute Moisture Scales

The previous examples have shown that % moisture by volume is an absolute scale and does not change with temperature. There are other absolute scales as well:

% Moisture by Volume, %Mv Parts per Million, ppm Humidity Ratio (LB Water/LB Dry Air), W Specific Humidity (LB Water/LB Mixture), q Dew Point Temperature, td

% Moisture by Volume (%Mv):

The % Moisture by Volume can be defined in at least two ways.

 $%M_{v}$ = Number of H₂0 molecules per unit volume $%M_{v}$ = Total number of molecules per unit volume

 $M_v = P_w/P_T$

Pw = Partial pressure
due to water vapor
PT = Total pressure
(usually atmospheric pressure)

Parts Per Million:

Parts per million is just another way of expressing % by volume. One million parts per million is the same as 100%. This scale is generally used when the % by volume is very low. 100ppm is equal to .01% by volume. Parts per million is sometimes expressed by weight instead of by volume. Since water vapor is only 62.2% of the weight of air, .01% by volume would equal 62.2ppm based on weight.

Humidity Ratio:

The humidity ratio is sometimes referred to as the moisture content, or the

mixing ratio. It is the mass of water vapor per unit mass of dry air. The humidity ratio (W) can be calculated if the % moisture by volume (%Mv) is known.

Humidity Ratio =
$$W = .622 \times M_V / (100-M_V)$$

This equation is valid only for the normal mixture of gasses in the atmosphere. When a different mixture of gasses is present as is found inside a boiler flue, the factor .622 must change. This factor is the ratio of the molecular weight of water vapor (18.015) to the average molecular weight of the other gasses (28.965 in the case of air).

$$18.015/28.965 = .622$$

Note that the % moisture by volume scale is totally independent of the molecular weights of the other gases in the mixture, as in a boiler or direct fired oven.

Specific Humidity:

Specific humidity is the ratio of the mass of water vapor to the total mass of the mixture of water vapor and dry air.

The specific humidity (q) can be calculated if the % moisture by volume $(\%M_V)$ is known.

Specific Humidity =
$$q = .622 \times \text{M/}\{(100\text{-}\text{M/V}) + .622 \times \text{M/V}\}$$

The factor .622 is for normal air only. It must be corrected if the average molecular weight of the gasses is different than air.

Dew Point:

As we have shown in previous examples, when air below 212°F is cooled the relative humidity increases. The dew point is the temperature at which the relative humidity reaches 100%. The RH can not exceed 100%, so if we continue to cool the air it will give up moisture in the form of condensation. This is how dew forms, why a glass of ice water gets wet on the outside, and why condensation trails form behind aircraft at high altitudes (it is cold up there).

If the dew point temperature is below 32°F, snow will form instead of rain, or

frost will form instead of dew. Below 32°F the dew point is sometimes called the frost point.

There is a direct correlation between the concentration of water vapor in the air and the dew point temperature. This is also true of the other gasses in the air. If we could cool the air to extremely low temperatures, carbon dioxide would condense into CO₂ snow. By measuring the temperature at which this happens we could determine the concentration of CO₂ in the air. The same is true of the nitrogen and oxygen in the air. Depending on the concentration of a gas we must reach its condensation point (dew point) to get it to condense into a liquid, or its frost point to get it to condense into a solid form.

The boiling points of the major components of air at atmospheric pressure are:

Water Vapor	H ₂ 0	212°F
Carbon Dioxide	CO ₂	-108°F
Oxygen	O ₂	-297°F
Nitrogen	N_2	-321°F

These temperatures are also the temperature at which a 100% concentration of the gas would liquify (dew point temperature).

When the concentration of a gas in a mixture is less than 100% the liquidization temperature becomes lower.

The point of this discussion is that there is nothing special about the way water vapor behaves compared to other gasses in the atmosphere except that the dew point and frost point of water vapor can occur at ordinary ambient temperatures.

Figure 4 gives the dew/frost point temperatures for low concentrations of moisture in the air.

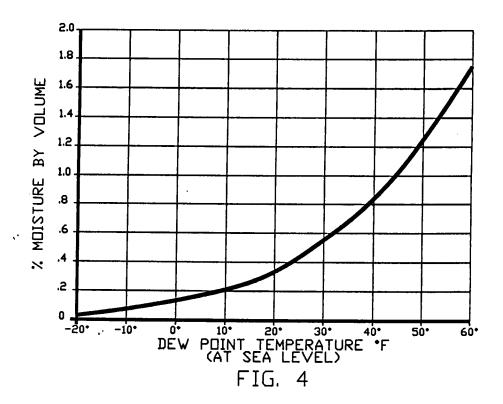
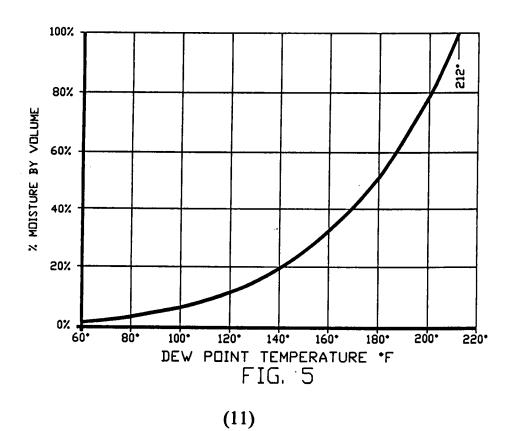


Figure 5 gives the dew point temperature for medium and high concentrations of moisture in air.



The dew point can be determined from the % moisture by volume by using a graph of the saturation pressure (Ps) of water vapor (as in Figure 2) or a table of Ps vs temperature.

Example:

If the % moisture by volume is 25 %, what is the dew point temperature?

First find the partial pressure of water vapor (Pw).

At atmospheric pressure and 25%M $_{V}$, Pw = 25% of 14.7 PSI or 3.68 PSI. At the dew point RH = 100% so Pw must equal Ps.

Go to Figure 2 and find Ps at 3.68 PSI and read the corresponding temperature from the graph (150°F).

Dew point is not quite an absolute scale. Dew point does change with pressure, and atmospheric pressure changes with altitude. The atmospheric pressure in Denver, Colorado is only 12.2 PSI (5200 ft. above sea level). At sea level water boils @ 211.9 °F. In Denver water boils at 203 °F. These two temperatures are dew point temperatures corresponding to 100% moisture by volume, but they are different due to the change in total pressure.

Comparison of Absolute Moisture Scales

Values for five different moisture scales are tabulated in **Table 1** - **Moisture/Humidity Scales** (found on pages 15 thru 20). This table can be used to convert from one moisture scale to another.

Table 1 can also be used to convert to or from relative humidity (RH) at temperatures below 212°F.

Example 1:

If the relative humidity (RH) is 50% and the temperature is 76°F, what is the % moisture by volume (%Mv)?

First find the temperature of 76°F in the dew point column. Then look across to the %Mv column and find 3%. This tells us that 100% RH at 76°F (dew point

temperature) is 3% moisture by volume (%M_v). 50%RH corresponds to 50% of 3% or 1.5%M_v.

Example 2:

If the % moisture by volume is 4% and the temperature is 107°F, what is the RH?

First find the temperature of 107°F in the dew point column. Then look across to the %Mv column and find 8% moisture by volume. Since 8% is the moisture level @ 100%RH @ 107°F, 4%Mv corresponds to 50%RH.

Each moisture scale that we have discussed is preferred by people that work in specific disciplines.

Relative Humidity (RH):

When dealing with human comfort at normal ambient temperatures relative humidity is the preferred scale. Weather forecasters (meteorologists) and heating, ventilating and air conditioning engineers (HVAC) use relative humidity regularly.

% Moisture by Volume (M):

This scale is the most intuitive of the absolute scales. People who work in the areas of combustion and pollution control engineering, routinely measure flue gas constituents in % moisture by volume. Because of the linear nature of this scale it is easy to display and easy to regulate using normal set point P.I.D. controllers. For these reasons %Mv is also used in the areas of food processing, product drying, and product humidifying.

Humidity Ration (W):

This scale is preferred by people who work with product drying processes since it can be directly used in energy calculations. This scale is also commonly used as the vertical axis on most psychometric charts. Because this scale is very non linear and goes thru many orders of magnitude, it is a difficult scale to display or use in a control mode. Since it is simple to convert between scales, %Mv is used for display and control of the moisture level, and then converted to humidity ratio for calculations.

Dew Point Temperature (td):

This scale is widely used by people who are concerned with the possibility of water condensing in pipes carrying compressed air or other gasses. Dew point is also used by those working with sampling systems for the same reason. Condensation in lines can be avoided by maintaining the working fluid at a temperature well above its dew point or by drying a fluid to a dew point well below the lowest temperature to which it will be exposed.

Parts Per Million (ppm):

This scale is generally used as a measure of extremely low moisture levels. 100ppm is equivalent to .01% moisture by volume.

TABLE 1 - MOISTURE/HUMIDITY SCALES

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Mv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
0	0	0	-460°F	0
.1	.000623	.000622	-4°F	1,000
.2	.00125	.00124	10°F	2,000
.3	.00187	.00187	18°F	3,000
.4	.00250	.00249	24°F	4,000
.5	.00313	.00312	28°F	5,000
.6	.00375	.00374	32°F	6,000
.7	.00438	.00437	36°F	7,000
.8	.00502	.00499	39°F	8,000
.9	.00565	.00562	42°F	9,000
1.0	.00628	.00624	45°F	10,000
2.0	.0127	.0125	64°F	20,000
3.0	.0192	.0189	76°F	30,000
4.0	.0259	.0253	85°F	40,000
5.0	.0327	.0317	92°F	50,000
6.0	.0397	.0382	98°F	60,000
7.0	.0468	.0447	103°F	70,000
8.0	.0541	.0513	107°F	80,000
9.0	.0615	.0579	111°F	90,000
10.0	.0691	.0646	115°F	100,000

TABLE 1 - MOISTURE/HUMIDITY SCALES (CONTINUED)

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Mv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
11.0	.0769	.0714	118°F	110,000
12.0	.0848	.0782	121°F	120,000
13.0	.0929	.0850	124°F	130,000
14.0	.101	.0919	127°F	140,000
15.0	.110	.0989	130°F	150,000
16.0	.118	.106	132°F	160,000
17.0	.127	.113	134°F	170,000
18.0	.137	.120	136°F	180,000
19.0	.146	.127	139°F	190,000
20.0	.155	.135	141°F	200,000
21.0	.165	.142	143°F	210,000
22.0	.175	.149	144°F	220,000
23.0	.186	.157	146°F	230,000
24.0	.196	.164	148°F	240,000
25.0	.207	.172	150°F	250,000
26.0	.219	.179	151°F	260,000
27.0	.230	.187	153°F	270,000
28.0	.242	.195	154°F	280,000
29.0	.254	.203	156°F	290,000
30.0	.267	.210	157°F	300,000

TALE 1 - MOISTURE/HUMIDITY SCALES (CONTINUED)

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Мv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
31.0	.279	.218	158°F	310,000
32.0	.293	.226	160°F	320,000
33.0	.306	.235	161°F	330,000
34.0	.320	.243	162°F	340,000
35.0	.335	.251	163°F	350,000
36.0	.350	.259	165°F	360,000
37.0	.365	.268	166°F	370,000
38.0	.381	.276	167°F	380,000
39.0	.398	.285	168°F	390,000
40.0	.415	.293	169°F	400,000
41.0	.432	.302	170°F	410,000
42.0	.450	.311	171°F	420,000
43.0	.469	.319	1 72 °F	430,000
44.0	.489	.328	173°F	440,000
45.0	.509	.337	174°F	450,000
46.0	.530	.346	175°F	460,000
47.0	.552	.355	176°F	470,000
48.0	.574	.365	177°F	480,000
49.0	.598	.374	1 78 °F	490,000
50.0	.622	.383	179°F	500,000

TABLE 1 - MOISTURE/HUMIDITY SCALES (CONTINUED)

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Mv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
51.0	.647	.393	1 8 0°F	510,000
52.0	.674	.403	181°F	520,000
53.0	.701	.412	1 82 °F	530,000
54.0	.730	.422	182°F	540,000
55.0	.760	.432	183°F	550,000
56.0	.792	.442	184°F	560,000
57.0	.824	.452	185°F	570,000
58.0	.859	.462	1 8 6°F	580,000
59.0	.895	.472	187°F	590,000
60.0	.933	.483	187°F	600,000
61.0	.973	.493	188°F	610,000
62.0	1.01	.504	189°F	620,000
63.0	1.06	.514	190°F	630,000
64.0	1.11	.525	190°F	640,000
65.0	1.16	.536	191°F	650,000
66.0	1.21	.547	192°F	660,000
67.0	1.26	.558	192°F	670,000
68.0	1.32	.569	193°F	680,000
69.0	1.38	.581	194°F	690,000
70.0	1.45	.592	195°F	700,000

TABLE 1 - MOISTURE/HUMIDITY SCALES (CONTINUED)

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Mv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
71.0	1.52	.604	195°F	710,000
72.0	1.60	.615	196°F	720,000
73.0	1.68	.627	197°F	730,000
74.0	1.77	.639	197°F	740,000
75.0	1.87	.651	198°F	750,000
76.0	1.97	.663	198°F	760,000
77.0	2.08	.676	199°F	770,000
78.0	2.21	.688	200°F	780,000
79.0	2.34	.701	200°F	790,000
80.0	2.49	.713	201°F	800,000
81.0	2.65	.726	201°F	810,000
82.0	2.83	.739	202°F	820,000
83.0	3.04	.752	203°F	830,000
84.0	3.27	.766	203°F	840,000
85.0	3.52	.779	204°F	850,000
86.0	3.82	.793	204°F	860,000
87.0	4.16	.806	205°F	870,000
88.0	4.56	.820	206°F	880,000
89.0	5.03	.83	206°F	890,000
90.0	5.60	.848	207°F	900,000
95.0	11.8	.922	209°F	950,000

TABLE 1 - MOISTURE/HUMIDITY SCALES (CONTINUED)

% Moisture By Volume	Humidity Ratio	Specific Humidity	Dew Point Temperature	Parts Per Million
%Мv	W <u>LB H2O</u> LB Dry Air	q <u>LB H2O</u> LB Mixture	td	ppm (volumetric)
91.0	6.29	.863	207°F	910,000
92.0	7.15	.877	208°F	920,000
93.0	8.26	.892	208°F	930,000
94.0	9.74	.907	209°F	940,000
96.0	14.9	.937	210°F	960,000
97.0	20.1	.953	210°F	970,000
98.0	30.5	.968	211°F	980,000
99.0	61.6	.984	211°F	990,000
100.0	∞	1.00	212°F	1,000,000

