

T H E S I S

THE DEVELOPMENT OF A LOW TEMPERATURE

PSYCHROMETRIC CHART

By

William L. Patterson

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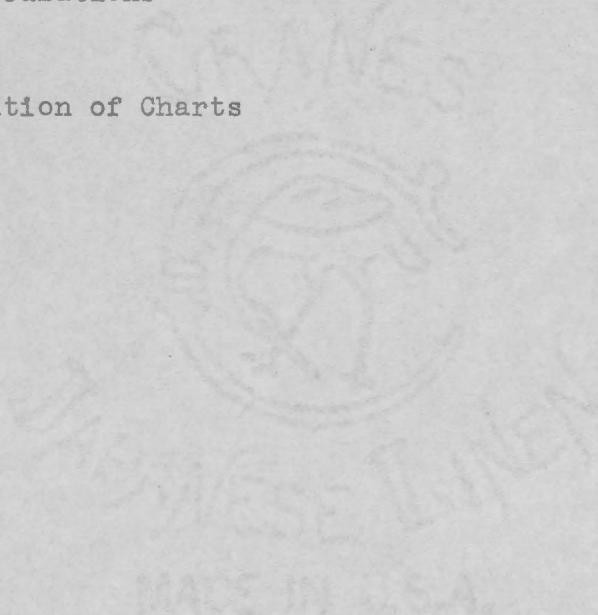
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INTRODUCTION

There has been developed, in the past few years, a specialized engineering field, technically known as air conditioning or the artificial regulation of atmospheric moisture. This has proved to be of great economic importance in many industries, and its theory and application are becoming topics for much discussion. This is especially true where data and charts have been compiled for a definite range of temperatures, thereby rendering them inaccurate for lower or higher temperatures, as the case may be.

With the introduction of very low temperatures in refrigerating and air conditioning, it is evident that a table of values must be compiled that will fill these needs and also tie in with the already existing data for higher temperatures. This thesis differs from already existing material in that it is designed for low temperature air conditioning using -40° F. as a base for calculating data.

GENERAL SURVEY OF THE FIELD

Psychrometric charts and data for making them have been available for many years. In 1911, Willis H. Carrier compiled the data for and published his present psychrometric chart, together with the rational formulae that he used for determining the data. Other psychrometric charts have been made for temperatures as low as 0° F., which have been made from practically the same data.

It was not until this year that a psychrometric chart was made for temperatures below 0° F. Claude A. Bulkley calculated data and made a psychrometric chart for temperatures as low as -40° F., but he plotted his data and constructed his chart to a logarithmic scale.

The laws governing the phenomena of atmospheric moisture are of so much practical and scientific importance that they have been revised and recalculated from rational and empirical formulae until at the present time the data that is available is credited with being reliable. The necessity at the present time, however, is a chart that is entirely reliable at temperatures above and below the freezing point of water, but especially adaptable to very low temperature refrigerating and air conditioning.

PURPOSE

This work is proposed to augment the already available data concerning steam-air mixtures and to set the base of tables of such data at -40° F. instead of at the customary 0° F. It is also purposed to supply reliable data and a chart for use in air conditioning problems involving temperatures between -40° F. and $+40^{\circ}$ F.

THEORY

The data available for low temperatures, say below 0° F., is practically negligible. It is also evident that the psychrometric charts in use today, which have been developed with 0° F. as their base, are unsuitable for use with temperatures below that base. For instance, the total heat curve on the usual psychrometric chart shows the sensible heat in the air above a base temperature of 0° F. plus the latent heat contained in the water vapor at saturation, but does not include the heat of the liquid. This may be used with sufficient accuracy above the freezing point, but when carried below the freezing point this must be considered if the chart is to be entirely accurate.

In considering the interchange of heat occurring in psychrometric phenomena, it is necessary to consider primarily the relative weights of dry air and of water vapor, rather than the usual density-temperature or volumetric relationship. To do this, it is necessary to express moisture content as weight of water vapor per pound of dry air, rather than as weight of water vapor per cubic foot of space.

In developing and constructing a psychrometric chart that is applicable at temperatures below 0° F. as well as at temperatures above 32° F., the author of this thesis, accordingly, has calculated his data and constructed his chart upon that basis.

METHOD USED

Much of the already available data has as its base 0° F., and it is impossible to use these values as a part of the data for temperatures with -40° F. as a base without involving negative values. Therefore, the base was changed, and all data was calculated from existing authentic formulae, which will be fully explained.

Upon looking up the experimental information on which to base the calculations, it was found that values differed slightly, but not enough to affect results materially.

In the preparation of data for making up this psychrometric chart, calculations were only made for five-degree intervals, which are sufficient for plotting curves. In constructing this chart and making calculations, the following fundamental data were employed:

1. Standard barometric pressure equals 29.92 inches of mercury equals 14.7 pounds per square inch equals 2116.8 pounds per square foot.

2. Absolute temperature equals t plus 459.6° F.

Data below, quoted by Bureau of Standards and in the International Critical Tables, were used. Taken at 60° F. and atmospheric pressure.

3. Weight of dry air in pounds per cubic foot equals 0.076393.

4. Specific heat of dry air at constant pressure equals 0.24114.

5. Change in specific heat per degree F. rise equals -0.000009.

6. Specific heat of water vapor at constant pressure equals 0.44266.

7. Change in specific heat per degree F. rise equals -0.00018.

8. Latent heat of water vapor, B. T. U. per pound equals 1057.8.

9. Change in latent heat per degree F rise equals -0.5557.

10. Specific heat of ice in B. T. U. per pound per degree F., at any temperature, t ,

equals $0.5052 \text{ plus } 0.001861(t - 32)$

INTERPRETATION OF DATA

Column 1. The specific heat of ice in B. T. U. per pound per degree F. at any temperature is found from the formula, S equals 0.5052 plus $0.001861(t - 32)$.

Column 2. The heat of the liquid above -40° F. which is the heat of the ice for temperatures below 32° F. is calculated from the instantaneous specific heats of ice at the temperature in question. The total heat added to a pound of ice when its temperature is raised from one five-degree interval to another was determined by the average specific heat in that interval.

Column 3. The latent heat of fusion of ice is practically constant.

Column 4. The latent heat of vaporization of water was figured for all temperatures using the Bureau of Standards' value of 1057.8 B. T. U. per pound at 60° F. and atmospheric pressure, with the change per degree F. rise equals -0.5557 .

Column 5. The total heat per pound of liquid including the heat of sublimation was found by adding the heat of the liquid, the latent heat of fusion, and the latent heat of vaporization.

Column 6. The volume in cubic feet of one pound of dry air was found from the thermodynamic relation, PV equals BT , where P equals pressure in pounds per square foot, V equals volume in cubic feet, B equals

universal constant for air equals 53.34, and T equals absolute temperature, t plus 459.6.

Column 7. The weight of moisture necessary to saturate one pound of dry air was calculated from a formula derived by William S. Kent:

$$W \text{ equals } \frac{KH}{2.036 P - H} \quad \text{where}$$

W equals maximum weight in pounds of water vapor that one pound of pure air can contain.

K equals ratio of the weight of a volume of saturated steam to an equal volume of dry air at the same temperature and pressure.

H equals elastic force or tension of water vapor or saturated steam corresponding to temperature t.

P equals pressure in pounds per square inch.

2.036 equals constant of the equation.

Tables of values for K and H are given in Kent's Handbook, tenth edition, page 661.

Column 8. The volume of moisture in cubic feet necessary to saturate one pound of dry air was calculated from the thermodynamic relation, PV equals MBT. M being the weight of water vapor found in Column 7, and B, the universal constant for vapor within the range of temperature given. B equals 85.70.

Column 9. The volume of one pound of dry air plus the volume of water vapor necessary to saturate one

pound of dry air.

Column 10. The total heat in B. T. U. in the moisture necessary to saturate one pound of dry air is the product of the total heat per pound of moisture at that temperature and the weight in pounds of moisture necessary to saturate a pound of dry air at that temperature.

Column 11. The heat content per pound of dry air was found by using -40° F. as a base and the specific heat of dry air as given by the Bureau of Standards.

Column 12. The total heat above -40° F. contained in one pound of dry air with moisture to saturate it is the sum of the heat in one pound of dry air and the heat of the moisture required to saturate one pound of dry air at that temperature.

Column 13. The amount of moisture contained in one pound of saturated air was obtained by a ratio. That is, the amount of moisture necessary to saturate one pound of dry air, is to the amount of moisture in one pound of the mixture, as the sum of one pound of dry air and the moisture necessary to saturate it is to 1.

Column 14. The amount of air in one pound of saturated air equals 1 minus the amount of moisture in the mixture.

Column 15. The grains of moisture necessary to saturate one pound of dry air equals the product of the number of grains in a pound and the weight of water

vapor necessary to saturate one pound of dry air. 7,000 grains per pound were used in these calculations.

Column 16. The grains of moisture per cubic foot of saturated air was also calculated from a ratio. The volume of one pound of dry air plus volume of moisture necessary to saturate it, divided by the weight of one pound of dry air plus weight of moisture necessary to saturate it, gives the cubic feet per pound of the saturated air. The reciprocal of this gives the pounds of saturated air per cubic foot. This value multiplied by the weight of moisture in one pound of saturated air multiplied by 7,000 gives the grains of moisture per cubic foot of saturated air.

Temperature in Degrees F.	DATA			
	1. Specific Heat of Ice B.T.U. per Pound	2. Heat of One Pound of Liquid Above -40° F. B.T.U. per Pound	3. Latent Heat of Fusion of Ice B.T.U. per Pound	4. Latent Heat of Vaporiza- tion of Moisture B.T.U. per Pound
40	-----	181.90	-----	1068.8
35	-----	176.90	-----	1071.6
32	0.5052	31.50	143.4	1073.2
30	0.5016	30.50	143.4	1074.3
25	0.4922	28.02	143.4	1077.1
20	0.4829	25.59	143.4	1079.9
15	0.4773	23.19	143.4	1082.8
10	0.4643	20.84	143.4	1085.8
5	0.4550	18.55	143.4	1088.2
0	0.4457	16.30	143.4	1091.0
-5	0.4360	14.10	143.4	1093.8
-10	0.4271	11.95	143.4	1096.6
-15	0.4178	9.84	143.4	1099.4
-20	0.4085	7.78	143.4	1102.1
-25	0.3992	5.76	143.4	1104.9
-30	0.3899	3.79	143.4	1107.7
-35	0.3806	1.87	143.4	1110.5
-40	0.3713	0.00	143.4	1113.2

Tempera- ture in Degrees F.	5. Total Heat per Pound of Liquid Including Heat of Sub- limation in B. T. U.	6. Volume of One Pound of Dry Air in Cubic Feet	7. Weight of Moisture Nec- essary to Satur- ate One Pound of Dry Air in Pounds	8. Volume of Mois- ture Nec- essary to Sat- urate One Pound of Dry Air in Cubic Feet
40	1250.70	12.59	0.00517	0.1045
35	1248.50	12.47	0.00422	0.0849
32	1248.10	12.39	0.00374	0.0744
30	1248.20	12.34	0.00343	0.0679
25	1248.42	12.22	0.00275	0.0539
20	1248.89	12.09	0.00220	0.0426
15	1249.29	11.96	0.00177	0.0339
10	1249.74	11.83	0.00141	0.0268
5	1250.15	11.70	0.00112	0.0210
0	1250.70	11.58	0.000898	0.0168
-5	1251.30	11.45	0.000711	0.0130
-10	1251.95	11.33	0.000561	0.0102
-15	1252.64	11.20	0.000442	0.0079
-20	1253.28	11.08	0.000342	0.0061
-25	1254.06	10.95	0.000264	0.0046
-30	1254.89	10.83	0.000201	0.0035
-35	1255.77	10.70	0.000150	0.0026
-40	1256.60	10.57	0.000109	0.0018

Tempera- ture in Degrees F.	9. Volume of One Pound of Dry Air Plus Mois- ture to Saturate It in Cubic Feet	10. Total Heat in Moisture Necessary to Saturate One Pound of Dry Air B. T. U.	11. Heat Con- tent Per Pound of Dry Air B. T. U.	12. Total Heat Above -40°F. Contained in One Pound of Dry Air Sat- urated with Moisture B. T. U.
40	12.70	6.4661	19.29	25.7561
35	12.57	5.2686	18.08	23.3486
32	12.46	4.6678	17.36	22.0278
30	12.41	4.2812	16.88	21.1612
25	12.27	3.4331	15.67	19.1031
20	12.13	2.7430	14.47	17.2130
15	11.99	2.2112	13.27	15.4812
10	11.85	1.7621	12.06	13.8221
5	11.72	1.4001	10.85	12.2501
0	11.60	1.1231	9.64	10.7631
-5	11.464	0.8896	8.44	9.3296
-10	11.340	0.7023	7.234	7.9365
-15	11.208	0.5536	6.028	6.5616
-20	11.086	0.4286	4.823	5.2516
-25	10.955	0.3310	3.617	3.9480
-30	10.834	0.2522	2.411	2.6632
-35	10.703	0.1884	1.206	1.3944
-40	10.572	0.1370	0.000	0.1370

Tempera- ture in Degrees F.	13. Amount of Moisture in One Pound of Mixture - Pounds	14. Amount of Air in One Pound of Mixture - Pounds	15. Grains of Moisture Necessary to Saturate One Pound of Dry Air - Grains	16. Grains of Moisture Per Cubic Foot of Saturated Air - Grains
40	0.00514	0.99486	36.19	2.85
35	0.00420	0.99580	29.54	2.36
32	0.00372	0.99628	26.18	2.09
30	0.00341	0.99659	24.01	1.96
25	0.00274	0.99726	19.25	1.56
20	0.00219	0.99781	15.40	1.26
15	0.00176	0.99824	12.39	1.03
10	0.00140	0.99860	9.87	0.821
5	0.00111	0.99889	7.84	0.663
0	0.000897	0.999103	6.28	0.541
-5	0.000710	0.999290	4.98	0.434
-10	0.000560	0.999440	3.93	0.346
-15	0.000441	0.999559	3.09	0.275
-20	0.000341	0.999659	2.39	0.215
-25	0.000263	0.999737	1.85	0.168
-30	0.000200	0.999800	1.41	0.129
-35	0.000149	0.999851	1.05	0.097
-40	0.000108	0.999892	0.76	0.072

SAMPLE CALCULATIONS

(Equations on pages 7 to 10)

Column 1. - at -40°

S equals $0.5052 \text{ plus } 0.001861(-40 - 32)$
equals 0.3713.

Column 2. - at -35°

$0.00 \text{ plus } 5 \frac{(0.3806 \text{ plus } 0.3713)}{2}$ equals 1.87.

Column 3. - This is practically the same for
all temperatures.

Column 4. - at $+40^{\circ}$

$1057.8 \text{ plus } 20 \times 0.5557$ equals 1068.8.

Column 5. - at -40°

Sum of corresponding values in columns 2, 3, 4.

Column 6. - at $+40^{\circ}$

PV equals BT, $2116.8V$ equals 53.34×419.6 ,
V equals 10.57

Column 7. - at -40°

W equals $\frac{0.6072 \times 0.0054}{2.036 \times 14.7 - 0.0054}$ equals 0.000109.

Column 8. - at -40°

V equals $\frac{0.000109 \times 85.70 \times 419.6}{2116.8}$ equals 0.0018.

Column 9. - at -40°

Sum of corresponding values in Columns 6 and 8.

Column 10. - at -40°

Product of corresponding values in Columns 5
and 7.

Column 11. - at -35°

$$5 \times 0.24114 \text{ equals } 1.206$$

Column 12. -

Sum of corresponding values in Columns
10 and 11.

Column 13. - at $+40^{\circ}$

$$\frac{0.00517}{x} \text{ equals } \frac{1.00517}{1}, \quad x \text{ equals } 0.00514.$$

Column 14. - at $+40^{\circ}$

$$1 - \text{Value in Column 13, } 1 - 0.00514 \text{ equals } 0.99486.$$

Column 15. - at $+40^{\circ}$

$$7,000 \text{ times corresponding value in Column 7} \\ 7,000 \times 0.00517 \text{ equals } 36.19.$$

Column 16. - at $+40^{\circ}$

$$\text{Grains equal } \frac{1}{\frac{12.70}{1.00517}} \times 7,000 \times 0.00517$$

$$\text{equal } 2.85.$$

PSYCHROMETRIC CHART

FROM -40° TO 40°

W.L. PATTERSON

GRAINS OF MOISTURE PER CU. FT. "D"

25

20

15

10

5

0

VOLUME IN CU. FT. 1° DRY AIR "C"

10

0

0

0

0

-40

-35

-30

-25

-20

-15

-10

-5

0

5

10

15

20

25

30

35

40

DRY BULB TEMPERATURES °F

GRAINS OF MOISTURE PER POUND OF DRY AIR "A"

26

24

22

20

18

16

14

12

10

8

6

4

2

0

0

1° STU PER LB. AIR SAT. WITH MOISTURE "B"

12

10

8

6

4

2

0

0

TOTAL HEAT ABOVE 40°

WET BULB TEMPERATURES

-35

-30

-25

-20

-15

-10

-5

0

5

10

15

20

25

30

35

40

45

50

55

60

65

70

75

80

85

90

95

100

105

110

115

120

125

130

135

140

145

150

155

160

165

170

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180

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985

990

995

1000

1005

1010

1015

1020

1025

1030

1035

1040

1045

1050

1055

1060

1065

1070

1075

1080

1085

1090

1095

1100

1105

1110

1115

1120

1125

1130

1135

1140

1145

1150

1155

1160

1165

1170

1175

1180

1185

1190

1195

1200

1205

1210

1215

1220

1225

1230

1235

1240

1245

1250

1255

1260

1265

1270

1275

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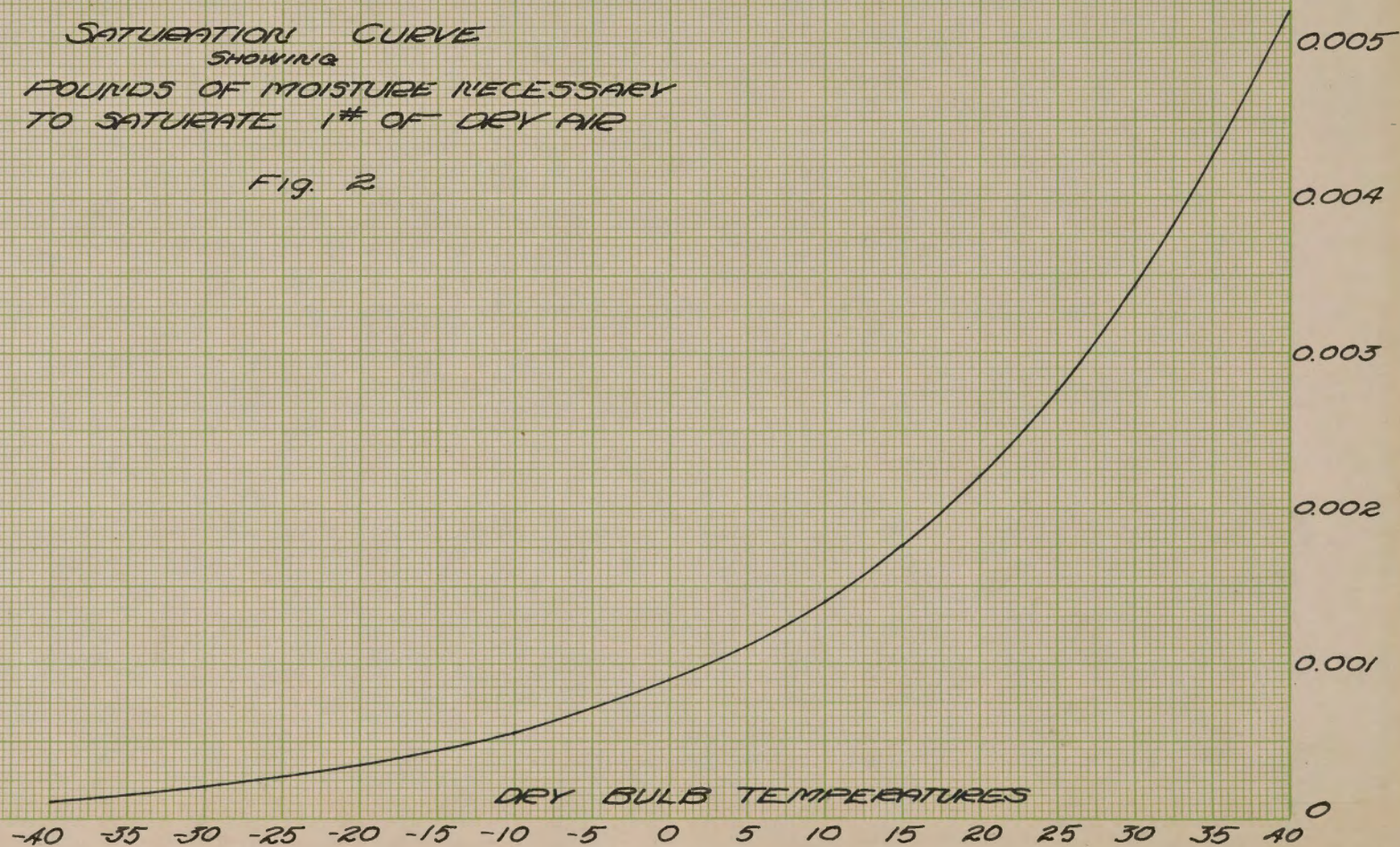
1360

1365

1370

SATURATION CURVE
SHOWING
POUNDS OF MOISTURE NECESSARY
TO SATURATE 1# OF DRY AIR

Fig. 2



INTERPRETATION OF CHARTS: Figure 1.

"A" - The upper curved line "A" is the saturation line. It is plotted with grains of moisture per pound of dry air as ordinates and the dry-bulb temperature as the abscissa. All points on this line represent conditions where the wet-bulb and dry-bulb thermometers have the same reading.

The curved lines below the saturation line are the relative humidity lines. To draw these it was necessary to read the grains of moisture for each point or five-degree interval on the saturation line and multiply these values by the different percents of relative humidity and plot the resulting data. Lines drawn through these points gave the relative humidity lines.

The wet-bulb temperatures are shown on the saturation curve, and the constant wet-bulb temperature lines are those straight lines that slope downward to the right of the saturation curve. These lines were drawn by the use of a formula derived by Mr. Carrier for determining the maximum wet-bulb depression.

The formula is:

$$t \text{ equals } t' \text{ plus } \frac{R'(W' - W)}{C_{pa} \text{ plus } C_{ps}W}$$

in which

t equals dry-bulb temperature

t' equals wet-bulb temperature

R' equals latent heat of vaporization at t'

W equals weight of water vapor actually contained in one pound of dry air at saturation at temperature t'.

W equals weight of water vapor actually contained in one pound of dry air.

C_{ps} equals mean specific heat of water vapor between temperatures t and t' .

C_{pa} equals mean specific heat of air at constant pressure between temperatures t' and t .

This will give the intercept t where W equals 0.

The line drawn through this point and the corresponding wet-bulb temperature on the saturation curve gives the constant wet-bulb temperature line.

"B" - This curve represents the total heat above -40°F. contained in one pound of dry air plus moisture to saturate it, and is to be referred to figures at the bottom and left side of the chart.

"C" - This curve represents the volume in cubic feet of one pound of dry air between temperatures of -40°F. and $+40^{\circ}\text{F.}$, referred to the vertical scale at the left side of the chart.

"D" - This curve shows the grains of moisture or water vapor per cubic foot of saturated mixture, referred to figures at the left side of the chart.

Figure 2. This figure shows the saturation line between temperatures of -40°F. and $+40^{\circ}\text{F.}$, plotted with pounds of water vapor necessary to saturate one pound of dry air as ordinates rather than as grains of moisture.

This curve is for convenience in reading the pounds of moisture at the saturation point since most of

the data connected with air conditioning deals with
pounds instead of grains of moisture.

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

Name W. R. Woolrich

Title Professor Mech Eng.