A STUDY OF THE EFFECT OF TEMPERATURE AND RELATIVE HUMIDITY ON THE DRYING RATE AND EQUILIBRIUM MOISTURE CONTENT OF HAY

BY

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Introduction

The curing of hay on the farm to retain its maximum feeding value, including minerals and vitamins, is of recognized importance. For several years, agricultural workers have realized that a limiting factor in the production of high quality hay in the Southeastern United States is the difficulty of proper curing. The climatic conditions found in the southern states are among the nations most favorable for the production of hay, but these same conditions make it almost impossible to cure high quality hay in the field.

The average total rainfall for any one month during the hay curing season is not excessive, but numerous light showers at short intervals make the field curing of hay verydifficult. In 1942 a survey of hay losses was made on 215 farms in nine Southwest Virginia counties. The results of the survey showed that 25% of the crop had been lost or damaged. Virginia's annual production of tame hay is about 1,500,000 tons. If the same ratio of loss was applied to the total crop of the state, it would mean that 375,000 tons of the annual hay crop were lost or damaged.

Hay and grain drying by forced ventilation has been practiced successfully by farmers in the Southeast for the past decade. At the close of the 1948 hay drying season, there were 500 driers in operation on Virginia farms.

Available data on the analysis of a number of barn and field dried samples indicate a decided advantage in favor of the barn dried hay, when considering the amount of leaves, green color, carotene, and protein retained.

The design and testing of the drying equipment and forced ventilation systems have become an important part of the research work of the Agricultural Engineering Department, Virginia Agricultural Experiment Station, in cooperation with the U. S. Department of Agriculture.

With the increased use of supplemental heat in forced ventilation drying, a definite need has arisen for data showing the effect of the temperature and relative humidity of the air supply on the drying rate and equilibrium moisture content of hay. The equilibrium moisture content is that moisture content at which no further moisture will be removed from the hay by a particular combination of temperature and relative humidity.

The elementary laws of thermodynamics and heat transfer show that the condition of the drying media has a definite effect on the rate at which a substance may be dried. A thorough investigation showed that the literature on this particular phase of hay drying is very limited; however, a number of articles have been published on closely related subjects, such as the humidity equilibrium of wheat, flour, flaxseed and various other common substances. Of the literature available the most applicable reports were those by Mr. Davis[1], "Supplemental Heat in Mow Drying of Hay - Part Two", and Dexter, Sheldon and Waldron[2], "Equilibrium Moisture Content of Alfalfa Hay".

In Mr. Davis' report the drying rate factor for the 68° F. dew point only was given, and the study by Dexter, Sheldon and Waldron was limited to a constant temperature condition throughout the humidity range. Since practically all hay drying installations operate with varying dry bulb temperatures and varying relative humidities, this investigation was proposed for the purpose of providing data that would constitute an important contribution to the further study and design of hay drying systems.

1. Davis, R. B. Jr., "Supplemental Heat in Mow Drying of Hay - Part Two", U.S.D.A., V.P.I., Agr. Engr. Journal, June 1948

2. Dexter, S. T., Sheldon, W. H., and Waldron, Dorothy I., Michigan State College. "Equilibrium Moisture Content of Alfalfa Hay". Agr. Engr. Journal, July, 1947.

OBJECTIVES

This study was planned and carried out to meet the following objectives:

1. To determine the effect of temperature and relative humidity, within the range of conditions most likely to be encountered, on the drying rate of hay.
2. To determine the equilibrium moisture contents of hay under the above range of temperature and humidity conditions.

MATERIALS AND EQUIPMENT

Constant Temperature Constant Humidity Oven

The samples used in this investigation were dried in a constant temperature constant humidity (CTCH) oven.

This oven, fig. 1, which was constructed in the Farm Electrification Laboratory at V. P. I., was made with 3/8" plywood insulated with an outside covering of 3/4" insulation board. The inside was lined with burlap with a 2" air gap between the plywood and the burlap. The purpose of the burlap lining was to diffuse the air stream as it entered the main chamber from the various conditioning ducts. Each of the four conditioning processes - heating, cooling, humidifying and drying was performed in an individual duct leading from and returning to the main chamber.

The air enclosed in the oven was heated by cone type resistance heaters and cooled by pumping cold water from a can in the refrigeration unit through a cooling coil located in one of the ducts connected to the main chamber. The air was humidified by the evaporation of water from a humidity pan and was dried by circulating it over wire mesh trays containing calcium chloride.

Circulation through each of the ducts was provided by a 6" propellor type fan driven by a 1/20 h.p. electric motor. The fans, as well as the heating elements and liquid pump, were thermostatically controlled. Pilot lights in the electrical circuits indicated the operation of each conditioning process.

The specifications and dimensions for the CTCH oven, as well as those for the forced draft oven, recording thermometer, psychrometer and other equipment used in this investigation are included in the appendix to this report.

PROCEDURE

1. Location. The work pertaining to this project was conducted in the Farm Electrification Research Laboratory at the Virginia Polytechnic Institute.

2. Preparation of Equipment. A careful study of the CTCH oven showed that some minor changes should be made which would render it more applicable to this investigation. A 24-hour recording thermometer was replaced with one using a seven day chart. A one-gallon drip - feed bucket supplying water for the wicks of the wet bulb thermometer and thermostats was replaced with a five-gallon bucket equipped with a sight gage to indicate the level of water in the container. The direction of air movement in the cooling duct was reversed, thereby giving counterflow rather than parallel flow of air with respect to the cooling water. By directing the air stream downward over the cooling coils the condensate was allowed to drip freely from the fins of the coils rather than be retarded by the upward movement of the air stream. The rubber tubing collecting the excess water from the wick of the wet bulb thermostat was located so that it would discharge into the humidity pan. This continuous drip replenished the supply in the pan to the extent that it would last for at least six hours (the frequency of the weighings in the higher humidities) without evaporating completely. An overflow pipe was installed on the pan to prevent flooding.

The CTCH oven and the forced draft oven were operated for approximately two weeks to allow the operator to become familiar with the controls and operating characteristics before any samples were dried. During this trial run period refrigeration difficulties were encountered with the household unit, fig. 2, which necessitated its replacement by the larger unit shown in fig. 3.

3. Collection of Samples. The samples of hay used in this investigation were collected from the alfalfa plots on the V. P. I. Agronomy farm. All of the samples were collected when the plants were either in the partial or full bloom stage. The samples were placed in the drying oven with not more than forty five minutes elapsing between cutting and placing in the drying oven. This investigation was limited to the drying of the natural moisture from the hay, consequently no samples were collected when the plants were wet with dew or rain.

4. Preparation of Samples. Each of the samples consisted of approximately fifty grams of alfalfa and was placed in a cylindrical shaped wire mesh container, 3-1/2 inches in diameter and 5 inches high. The alfalfa plants were cut into five inch lengths so that they would conform to the basket size. The entire plant was used so that a representative proportion between leaves and stems was maintained.

5. Tests Run. Each test of this investigation included four samples of hay. The CTCH oven was regulated until the desired temperature and humidity conditions had become constant before the samples were inserted. After the samples had been in the oven approximately one half hour they were removed momentarily and weighed. The intervals between weighings, after the first half hour, were determined by drying rate, ranging from one-half to six hours.

When the rate of drying had decreased so that each sample did not lose more than 0.02 gram in six hours, the sample was assumed to have reached an equilibrium weight for the temperature and humidity conditions in the oven. When the equilibrium weight for each sample had been determined for the CTCH oven, the samples were removed and placed in the 212° F. forced draft oven and further dried to the equilibrium weight at 212° F. The equilibrium weight for the sample in the 212° F. oven was considered the dry matter content weight for the sample.

The tests of this investigation were conducted in six different series, with a constant dew point temperature maintained for each series. These series were run at 15° F. dew point temperature intervals between a minimum dew point temperature of 55° F. and a maximum of 115° F. The minimum dry bulb temperature used in each series was that temperature as nearly equal to the dew point temperature as could be maintained with the equipment available. This varied for some of the series as shown by the summary on page 8. Using twenty degree dry bulb temperature intervals, the maximum temperature studied was 175 degrees F. The temperatures of the various tests run also are shown on page 8. A total of 22 tests were run.

6. Recording Results. The results of each observation were recorded on data sheets showing the number of the test, the wet bulb, dry bulb and dew point temperatures, date, time of weighing, total number of hours elapsed since placing in the CTCH oven, and the weight to the nearest 0.001 gram. A sample data sheet is shown on page 10. The original data book containing the data from all the tests of this investigation is on file in the Farm Electrification Research office at the Virginia Polytechnic Institute.

SUMMARIES

DEW POINT	WET BULB	DRY BULB	REL. HUM.	INITIAL MOIST.	EQ. MOIST.	H. FACTOR	TEST #
55	62.50	75	51	.791	.1549	12.000	1
55	74.75	115	16	.791	.0732	3.350	8
55	68.00	95	28	.753	.0825	2.650	19
70	80.5	110	29	.777	.0721	4.550	7
70	71.0	74	86	.762	.577	30.120	2
70	84.0	130	18	.754	.0470	1.175	9
70	88.0	150	10	.759	.0495	1.172	10
70	94.0	170	6	.768	.0405	0.762	11
70	76.0	90	52	.769	.1450	4.700	20
85	86.	88	91	.855	.737	57.625	3
85	89.	105	55	.769	.1688	6.375	6
85	100.	165	12	.769	.0422	0.892	12
85	96.	145	19	.756	.0547	0.692	13
85	93.	125	32	.776	.0807	1.115	18
100	101.	104	91	.813	.704	26.125	4
100	108.	160	20	.701	.0312	0.530	14

SUMMARIES, continued

DEW POINT	WET BULB	DRY BULB	REL. HUM.	INITIAL MOIST.	EQ. MOIST.	H. FACTOR	TEST #
100	106.	140	34	.765	.0710	1.137	17
100	103.	120	58	.778	.1086	1.767	21
115	122.	175	22	.746	.0465	0.907	15
115	118.	155	37	.779	.0687	1.090	16
115	117	135	58	.766	.1047	1.587	22
115	116	118	91	.792	.339	12.375	5

TEST #9 DATE STARTED - 7/10/48.......ENDED - 7/11/48 DRY - 130 WET - 84 D.P. - 70

Time of Reading	Total Time	#1	MCR	#2	MCR	#3	MCR	#4	MCR	Remarks
1030	0	110.150	1.0	110.008	1.0	110.353	1.0	110.118	1.0	
1130	1	96.080	.633	97.480	.630	93.210	.465	94.485	.594	
1230	2	86.910	.393	87.455	.335	85.918	.238	85.035	.348	
1330	3	79.890	.210	81.835	.169	82.480	.131	78.859	.188	
1430	4	75.652	.100	78.950	.084	80.665	.074	75.538	.102	
1530	5	73.690	.049	77.612	.045	79.600	.041	73.825	.057	
1730	7	72.248	.011	76.390	.009	78.530	.007	72.070	.012	
2130	11	71.880	.002	76.120	.001	78.310	.0007	71.680	.002	
2330	13	71.830	.0004	76.090	.0002	78.295	.0003	71.628	.0004	
0530	19	71.812	0	76.084	0	78.285	0	71.610	0	Put in 212° F
		71.230		75.495		77.750		70.990		
		71.230		75.495		77.740		70.992		
Eq. Wt.		71.812		76.048		78.285		71.610		
Initial - Eq. Wt.		38.338		33.924		32.068		38.508		
Initial M. C.		.762		.752		.742		.761		Average .754
Eq. M. C.		.045		.051		.045		.047		Average .0470

All of the moisture contents referred to in this thesis were calculated on the wet basis. The following conversion table is included for those who wish to convert to dry basis:

W.B.	D.B.	W.B.	D.B.	W.B.	D.B.	W.B.	D.B.
99	9,900.0	74	284.6	49	96.1	24.	31.5
98	4,900.0	73	270.4	48	92.3	23	29.9
97	3,233.3	72	257.1	47	84.7	22	28.2
96	2,400.0	71	244.8	46	85.2	21	26.5
95	1,900.0	70	233.3	45	81.8	20	25.0
94	1,566.7	69	222.6	44	78.6	19	23.5
93	1,328.6	68	212.5	43	75.4	18	21.9
92	1,150.0	67	203.0	42	72.4	17	20.5
91	1,011.1	66	194.1	41	69.5	16	19.1
90	900.0	65	185.7	40	66.6	15	17.6
89	809.1	64	177.8	39	63.9	14	16.3
88	733.3	63	170.3	38	61.3	13	14.9
87	669.2	62	163.2	37	58.7	12	13.6
86	614.3	61	156.4	36	56.3	11	12.36
85	566.6	60	150.0	35	53.8	10	11.1
84	525.0	59	143.9	34	51.5	9	9.9
83	488.2	58	138.1	33	49.3	8	8.7
82	455.5	57	132.6	32	47.1	7	7.53
81	426.3	56	127.3	31	44.9	6	6.38
80	400.0	55	122.2	30	42.8	5	5.26
79	376.2	54	117.4	29	40.8	4	4.17
78	354.5	53	112.8	28	38.9	3	3.09
77	334.8	52	108.3	27	37.0	2	2.041
76	316.7	51	104.1	26	35.1	1	1.01
75	300.0	50	100.0	25	33.3		

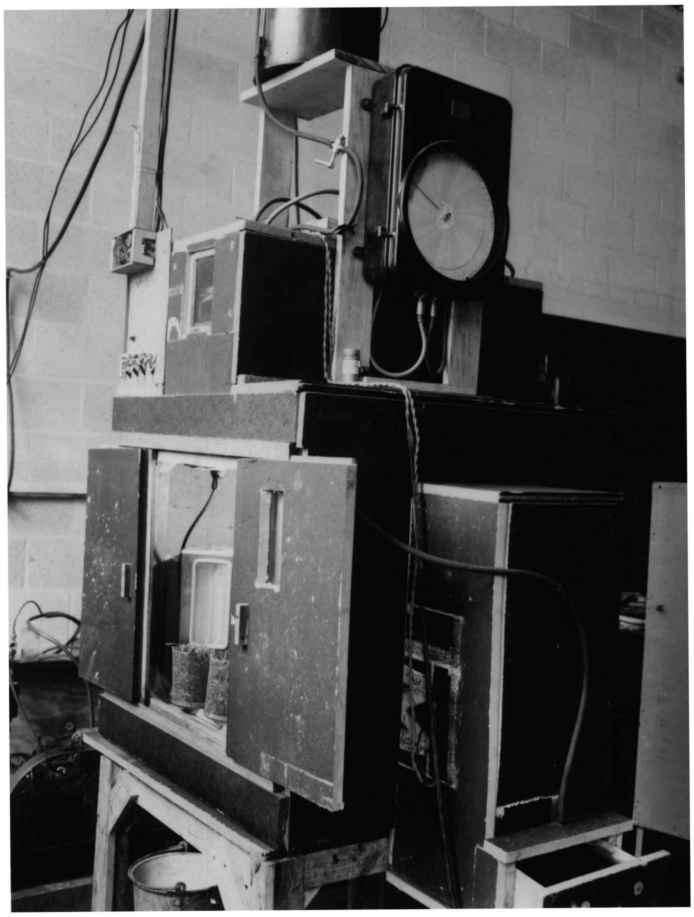


Fig. (1). View of CTCH oven showing; Recording thermometer, upper right; motor aspirated psychrometer, behind wire baskets inside oven; humidity pan, lower right corner, and five gallon reservoir for drip feed to wet bulb thermostats, top. The rectangular projection on the right side of the oven is the humidity conditioning duct.

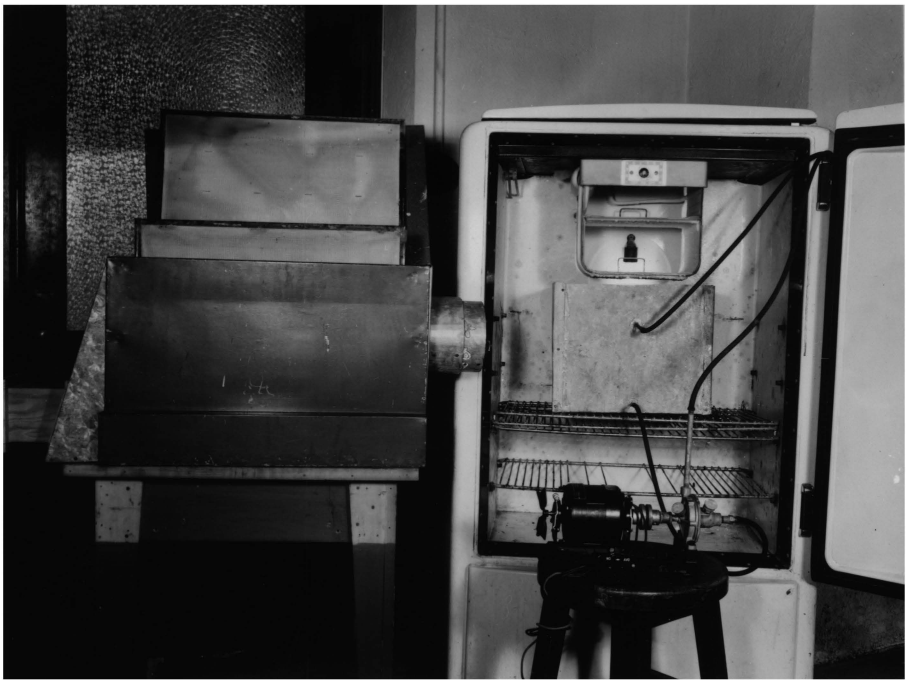


Fig. (2). General Electric household refrigeration unit showing brine tank, motor driven circulating pump, hose for cooling water circulation, and humidifying element. This equipment was replaced because of inadequate capacity.

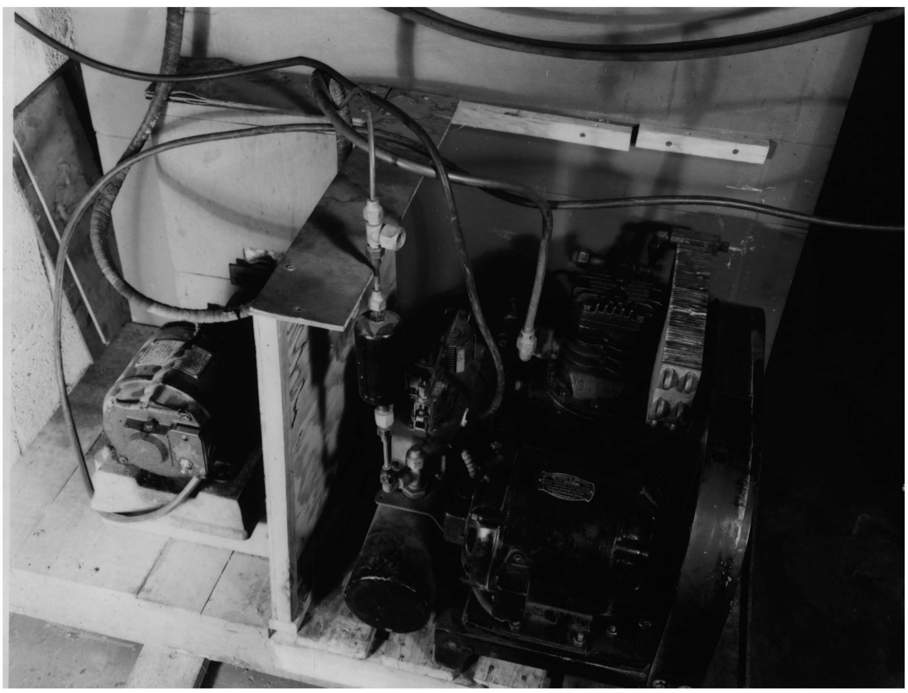


Fig. (3). Frigidaire unit showing compressor, condenser, circulating pump, etc.

Fig. (4). Forced draft oven, analytical balances, and wire mesh containers.

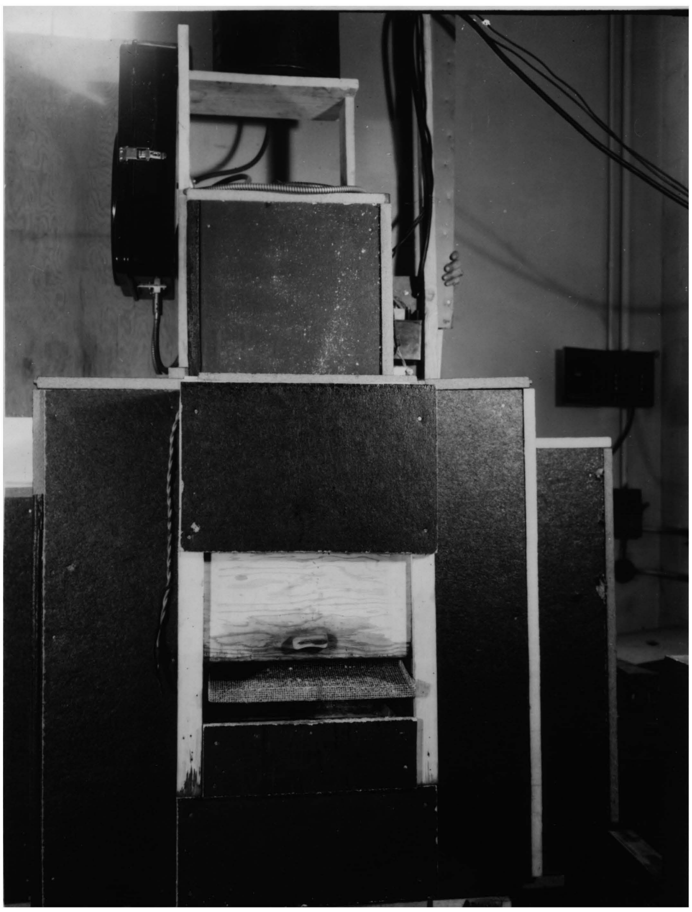


Fig. (5). CTCH oven showing calcium chloride trays.

ANALYTICAL DISCUSSION

Since one of the main facotrs of this investigation was the determination of drying rates under various temperature and humidity conditions, a clear understanding of the mechanism of drying of solids is very essential. Drying usually refers to the removal of a liquid from a solid, the liquid most frequently being water. Drying may be accomplished by various means, such as pressing, centrifuging, absorption, or vaporization of the water content. Since the vaporization process was the only one used in this investigation, the discussion will be limited to drying by this means.

In the initial stages of drying a very wet solid under constant drying conditions, the surface may be completely wet, and if so, the drying process is similiar to the evaporation of water from a free liquid surface. As long as the surface is wholly wet the rate of evaporation is not a function of the water content of the solid and, under constant drying conditions, the rate of drying continues constant. This stage is termed the constant rate period. However, at some definite water content the rate of drying begins to decrease, and the range from this water content to dryness is called the falling rate period. The water content of the solid at the end of the constant rate period and the beginning of the falling rate period is termed the critical water content.

Numerous tests have shown that in drying fully exposed hay the conditions are seldom favorable for constant rate drying.

The falling rate period in general is divisible into two secondary periods or zones, the zone of unsaturated surface drying, and the zone where internal liquid diffusion controls. Drying curves for the falling rate period should approach a straight line when plotted on semi-logarithmic paper[1].

The results of this investigation as recorded on the data sheets similiar to the one on page 10 would have been of very little value in that form. The development of these observed data into a more usable form required several calculations and the plotting of several curves.

The wet and dry bulb temperatures were recorded by the recording thermometer. Knowing these temperatures for each test it was possible to read the relative humidity directly from the psychrometric chart.

The initial moisture content (page 8) of the samples used in this investigation was calculated on the wet basis by the following formula:

$$\text{Initial Moisture Content } \% = \frac{(\text{initial weight} - \text{basket}) - (\text{dry weight} - \text{basket}) \times 100}{(\text{initial weight} - \text{basket weight})}$$

$$= \frac{(\text{initial weight}) - (\text{dry weight})}{(\text{initial weight}) - (\text{basket weight})} \times 100$$

The equilibrium moisture content was calculated on the wet basis by the following formula:

$$\text{Equilibrium M. C.} = \frac{(\text{equilibrium weight}) - (\text{dry weight})}{(\text{equilibrium weight}) - (\text{basket weight})}$$

In preparing the observed data of this investigation for presentation it was desired to express the drying rates in such a manner that they could be compared on a common basis regardless of initial or equilibrium moisture content. If the difference between the moisture content (dry basis) at time T and the equilibrium moisture content (dry basis) is expressed as a percentage of the difference between the initial moisture content (dry basis) and the equilibrium moisture content (dry basis) this common basis for all samples will have been attained. This ratio is called the Moisture Content Ratio (M.C.R.) and is calculated by the following formula:

$$\text{M. C. R.} = \frac{\text{M.C. (d.b.) at time T} - \text{equilibrium M.C. (d.b.)}}{\text{Initial M. C. (d.b.)} - \text{equilibrium M. C. (d.b.)}}$$

This formula for M. C. R. may be reduced to the following form:

$$M. C. R. = \frac{\text{Weight at time T - equilibrium weight}}{\text{Initial weight - equilibrium weight}}$$

For example, a sample of hay with an initial weight of 110.145 grams is dried by air having a given temperature and humidity. The condition of the air is such that the hay will dry to an equilibrium weight of 73.16 grams. When the hay has reached a weight of 78.258 grams it will have a "moisture content ratio" of (78.258 - 73.16) ÷ (110.145 - 73.16) X 100 = 13.7%

In drawing the drying curves for each example of this investigation the M. C. R. was plotted as the ordinate with time as the abscissa. The graph of M. C. R. vs. Time on arithmetic paper indicated a curve of the semi-logarithmic type which when plotted on semi-logarithmic paper approached a straight line. Page 1 (Appendix 1) shows a set of such curves drawn for test #9.

The drying rates given in this report are expressed as H factors. This factor is defined as the time in hours required for the moisture content of fully exposed hay to decrease half way to its equilibrium moisture. The H. factor for each of the four samples was read from the corresponding M.C.R. vs. Time curve; the four values were then averaged to give the H factor for the conditions under which the samples were dried.

The observed and calculated data obtained from this investigation are shown in tabular form on pages 8 and 9.

When the H factors obtained for a particular dew point series were plotted as the ordinate with ΔT (dry bulb - dew point) as the abscissa on arithmetic paper the observed data points indicated a logarithmic curve, which when plotted on logarithmic paper became a straight line. The curves on pages 2, 3, 4, 5 and 6 (Appendix 1) show the location of the observed data points with respect to the calculated curve. The straight line curve was calculated from the observed data by the least squares method. A sample set of calculations made to locate the points on the calculated curve is as follows.

Rather than solve the equation of the line by use of logarithms the process was expedited by plotting the observed data points, measuring their X and Y coordinates arithmetically, and solving these equations as arithmetic equations. The calculated points were then plotted on the logarithmic paper with the use of an arithmetic scale

For the 100° dew point series:

T	Observed H	X(arithmetic)	Y(arithmetic)	XY	X^2
4	26.125	24.0	36.0	864.0	576.00
20	1.767	34.5	18.5	638.25	1,190.25
40	1.137	39.0	15.8	616.20	1,521.00
60	0.530	41.6	10.8	449.28	1,730.56
		Σ 139.1	Σ 81.1	Σ 2,567.73	Σ 5,017.81

$Y = a + bX$ (Normal equation for a straight line)

$\Sigma Y = Na + \Sigma X b$ (1) N = number of observed data points

$\Sigma XY = \Sigma X a + \Sigma X b$ (2)

Substituting in (1) $81.1 = 4a + 139.1\,b$ (3)

Substituting in (2) $2{,}567.73 = 139.1\,a + 5{,}017.81\,b$ (4)

Solving equations (3) and (4) simultaneously

$b = -1.40$

$a = 68.96$

Re-writing the original equation

$Y = 68.96 - 1.4\,X$

Assigning values to X and Y

X	Y
18	43.76
25	33.96
30	26.96

X	Y
35	19.96
40	12.96

When the above values for X and Y were plotted arithmetically on the same sheet as the original observed points, the curve shown on page 5 was easily drawn. The distribution of the observed data points with relation to the calculated curve indicated this to be an acceptable method of plotting the curve.

Since logarithmic paper is considered more of a working tool of the engineer rather than the average layman, the curves on pages 12, 13, 14, 15 and 16 show the H factors vs. Dry bulb temperatures plotted on arithmetic paper for the convenience of those who do not care to use the logarithmic curves. Page 17 shows an accumulation of the five curves shown individually on pages 12, 13, 14, 15 and 16.

Equilibrium Moisture Content

The curves on pages 7, 8, 9, 10 and 11 show the equilibrium moisture content vs ΔT on logarithmic paper. These curves were plotted by the same procedure as previously discussed for the H factor curves and likewise have been drawn on arithmetic paper for those who prefer it to the logarithmic paper.

In preparing the data obtained from this study for presentation it was considered desirable to have the information in a final form that would be the most useful and easiest for the user to interpret. The method of superimposing the final data on a psychrometric chart was selected as the method best meeting the above requirements. Chart 1 (Appendix II) shows the H factor data and Chart 2 the equilibrium moisture data.

[1]For a more complete discussion of the principals of drying the reader is referred to; "Chemical Engineers Handbook", Perry.

Discussion of Results

A study of the H factor curves, page 17, will show that each tends to be asymptotic to a line representing a dry bulb temperature equal to the dew point temperature for that series. This is acceptable because the dry bulb temperature of a given quantity of air can never be less than the dew point temperature. The curve also tends to be asymptotic to a line representing zero H factor. This is also acceptable because the H factor could never be equal to or less than zero.

A further study of these same curves will reveal that the radius of curvature of each successive curve decreases as the dry bulb temperature is increased from the 55° dew point curve to the 115° dew point curve. This characteristic can be explained by the fact that a one degree change in dry bulb temperature in the 55° region will mean a much smaller change in the vapor pressure than a one degree change in the 115° region. The vapor pressure of a liquid may be defined as the pressure of the vapor of that liquid at any given temperature at which the vapor and liquid phases of the substance can exist in equilibrium. The rate of evaporation of the liquid will depend upon the difference between the vapor pressure corresponding to the temperature of the liquid and the actual pressure (atmospheric for this investigation). Therefore, a small change in the dry bulb temperature in the region where it causes the greatest change in vapor pressure will speed up the drying process more than the same temperature change in a region where it causes a lesser change in vapor pressure. This would tend to make the drying curve for the 115° series fall more rapidly than the one for the 55° series.

A study of the equilibrium moisture content curves on arithmetic paper, pages 18, 19, 20, 21 and 22 will show each curve to be asymptotic, within the ranges studied in this investigation, to a line representing a dry bulb temperature equal to the dew point temperature for its series and to a line representing zero moisture content. This, as in the case of the H factor curves, can be explained by the fact that the dry bulb temperature of a given quantity of air can never be less than the dew point temperature. To obtain an equilibrium moisture content of zero would require higher temperatures and lower humidities than those used in this study and which would be impractical for actual use. Therefore, it can be assumed that zero equilibrium moisture content can never be attained in a practical situation and the curve becomes asymptotic to this line. By comparing the curves for the various dew point series it will be noticed that the same general type curve prevails throughout the dew point range studied.

A study of chart (1) will show that an increase in the dry bulb temperature will cause the lines of constant H Factor to move into regions of higher relative humidity. Further inspection also will show that the constant H lines tend to straighten as higher dry bulb temperatures are used. This characteristic can be explained by the vapor pressure principal as discussed earlier in this report.

The lines of constant EMC on chart (2) tend to follow the relative humidity lines in the regions of comparatively low dry bulb temperatures and to curve into the higher R. H. regions as the dry bulb temperatures are increased. This also can be explained by the vapor pressure principal.

The H factor values determined by this investigation compare very closely with those obtained by Mr. Davis in preliminary studies and reported in his article "Supplemental Heat in Mow Drying of Hay - Part Two".

The data obtained from this investigation can be used as a parameter in projected formulae such as the one presented by William V. Hukill, Senior Agricultural Engineer, Division of Farm Buildings and Rural Housing, Bureau of Plant Industry, Soils, and Agricultural Engineering, U. S. Department of Agriculture, in his article "Basic Principles in Drying Corn and Grain Sorghum". In Mr. Hukill's formula,

$$G = \frac{Q \times 60 \times \Delta T \times Sa \times H}{0.01 \times \Delta M \times V}$$

G is pounds of dry matter in a layer of corn one unit deep.

Q is volume of air in pounds per minute.

ΔT is maximum temperature drop that may occur in the air.

Sa is the specific heat of air at constant pressure which may be taken. as 0.24 BTU per pound per degree.

H is the time in hours required for fully exposed grain to reach half way to its equilibrium moisture.

ΔM is the total possible change in moisture content of the grain which is equivalent to the initial moisture minus the equilibrium moisture (% dry basis).

V is the latent heat of drying, BTU per pound of water.

Mr. Davis, in his work at V. P. I. and as stated in his report "Supplemental Heat in Mow Drying of Hay, Part Two", shows that this same formula can be used in hay drying calculations. The data this investigation has provided can be used with the above mentioned formula to determine the amount of hay that can be dried to safe storage conditions in a given length of time by a given quantity of air, knowing its temperature and relative humidity.

The following example is given to illustrate the use of the generalized drying formula and the data presented on Charts (1) and (2). Alfalfa hay with a moisture content of 40% wet basis, or 66.7% dry basis (Conversion Table, Page (11), is to be dried on a mow hay drier. The air supply will have a dry bulb temperature of 90° F. and a relative humidity of 50% and will be blown through the hay at the rate of 15 c.f.m. per sq. ft. of mow floor area. Drying will be considered complete when the moisture content in the top layer reaches 20% (dry basis). How much hay can be dried under these conditions in four days?

The first step will be to compute the moisture content ratio desired in the top layer. Chart (2) shows that air with a 90° dry bulb and a 50% relative humidity will dry hay to an equilibrium content of 13% wet basis or 14.9% dry basis. The moisture content ratio in the layer will be

$$\frac{20 - 14.9}{66.6 - 14.9} = \frac{5.1}{51.7} \quad .0985 \quad \text{or} \quad 9.85\%$$

The conditions stated in the problem give the value of the constants to be substituted into the formula. The values are as follows:

$Q = 15$ c.f.m. $\div$ 13.85 $ft^3/\#$ = 1.084 #/min/ft^2 floor area

$\Delta T = 90 - 75 = 15°$ F

$Sa = 0.24$

H at 90° dry bulb and 50% relative humidity from Chart (2) = 6.75

$\Delta M = 66.6 - 20 = 46.6$

V = 1150 BTU/#. Using steam table value

By substituting in Mr. Hukill's equation:

$$G = \frac{(1.084)\ (60)\ (15)\ (0.24)\ (6.75)}{(0.01)\ (46.6)\ (1150)}$$

G = 2.95 pounds of dry hay per depth unit per square foot of mow area.

To determine the number of time units in four days when a time unit is 6.75 hours:

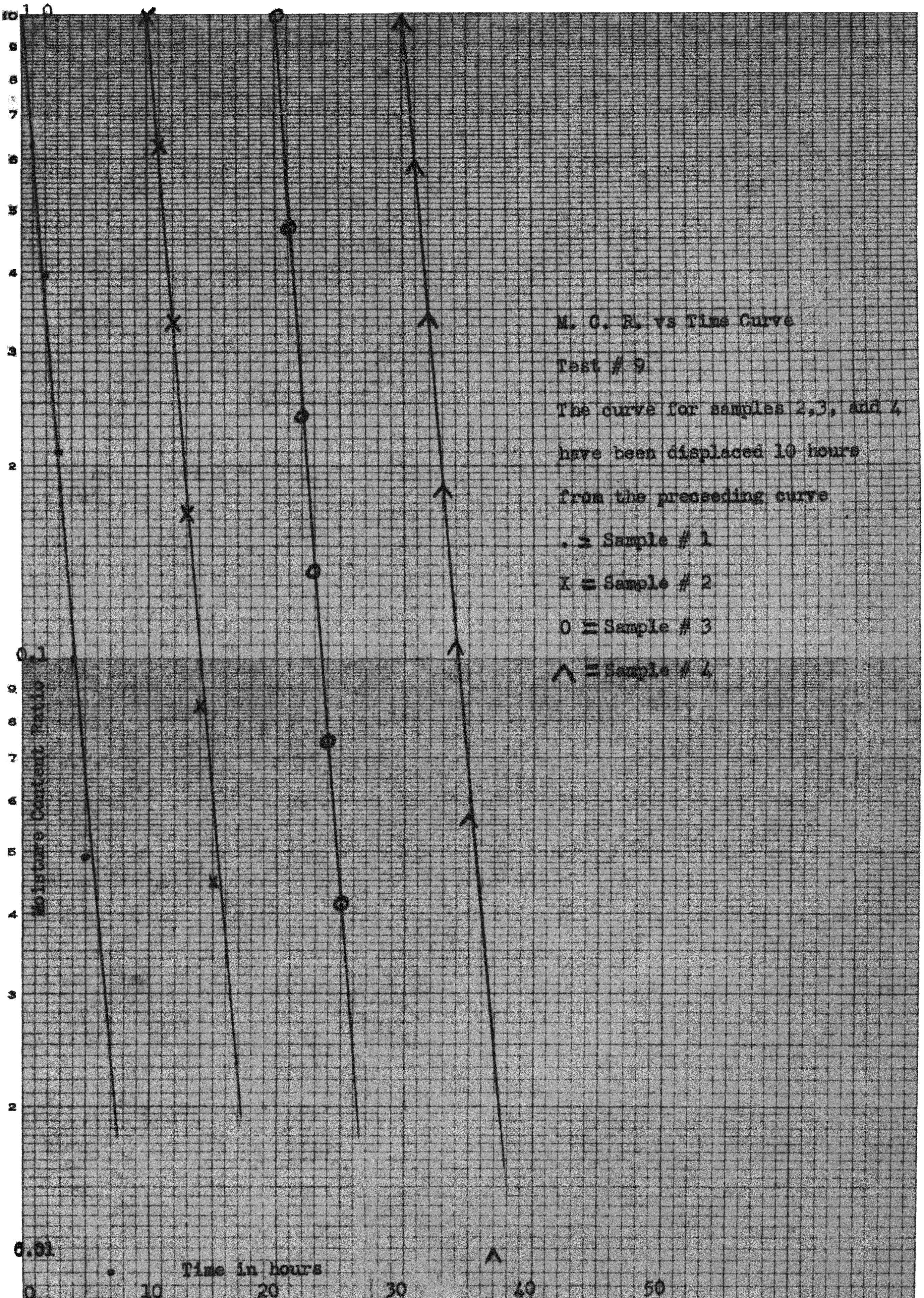
(4) (24) $\div$ 6.75 = 14.23 time units.

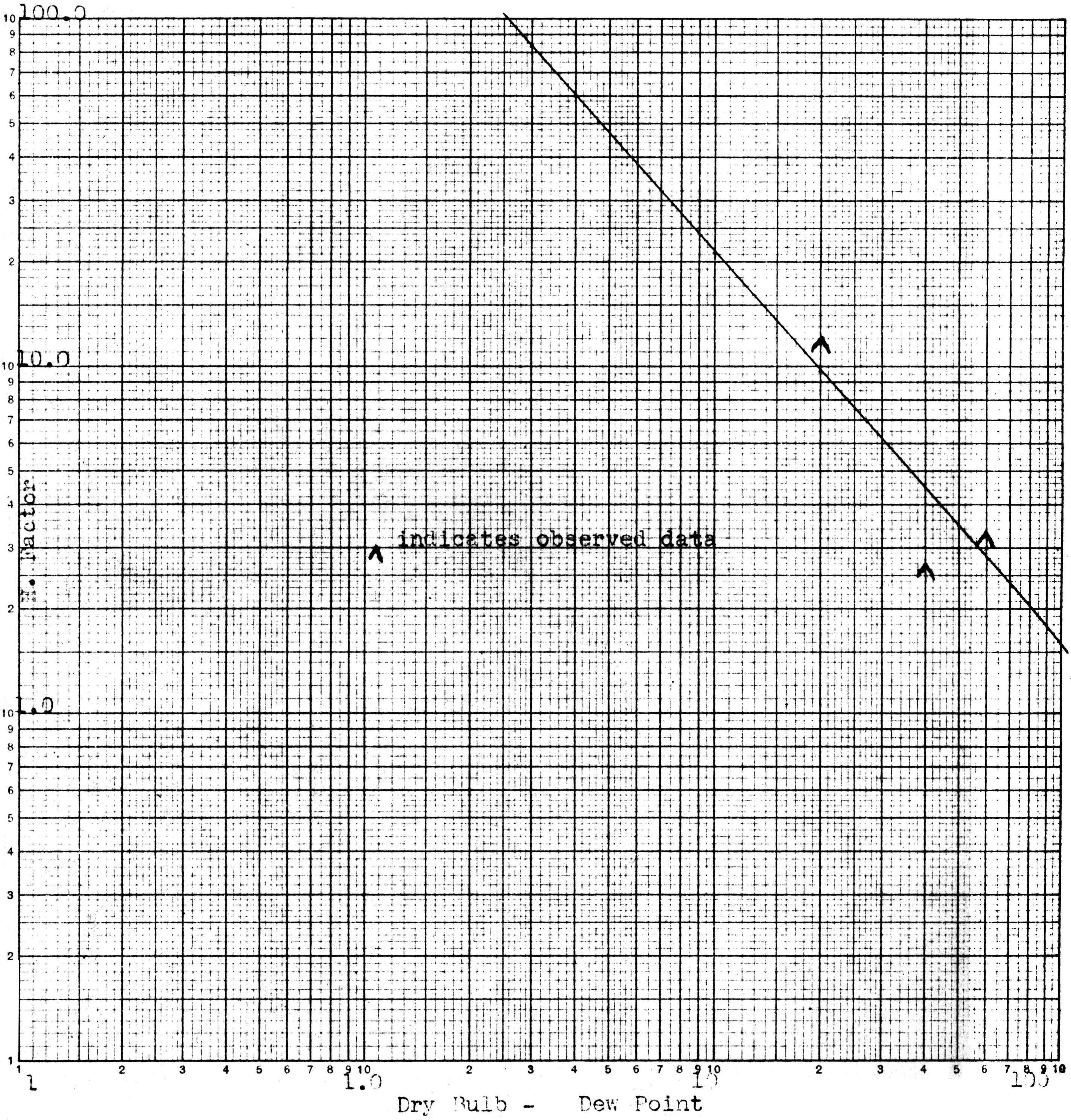
From fig. 6 of Mr. Davis' article "Supplemental Heat in Mow Drying of Hay - Part II", we can see that hay 21 depth units deep will dry to a moisture content ratio of 9.9 in 14.2 time units. 21 depth units will contain (21) (2.95) or 62# of dry hay per square foot of mow area. The total amount that could be dried in four days would be 62 times the mow floor area in square feet.

Suggestions for Further Study

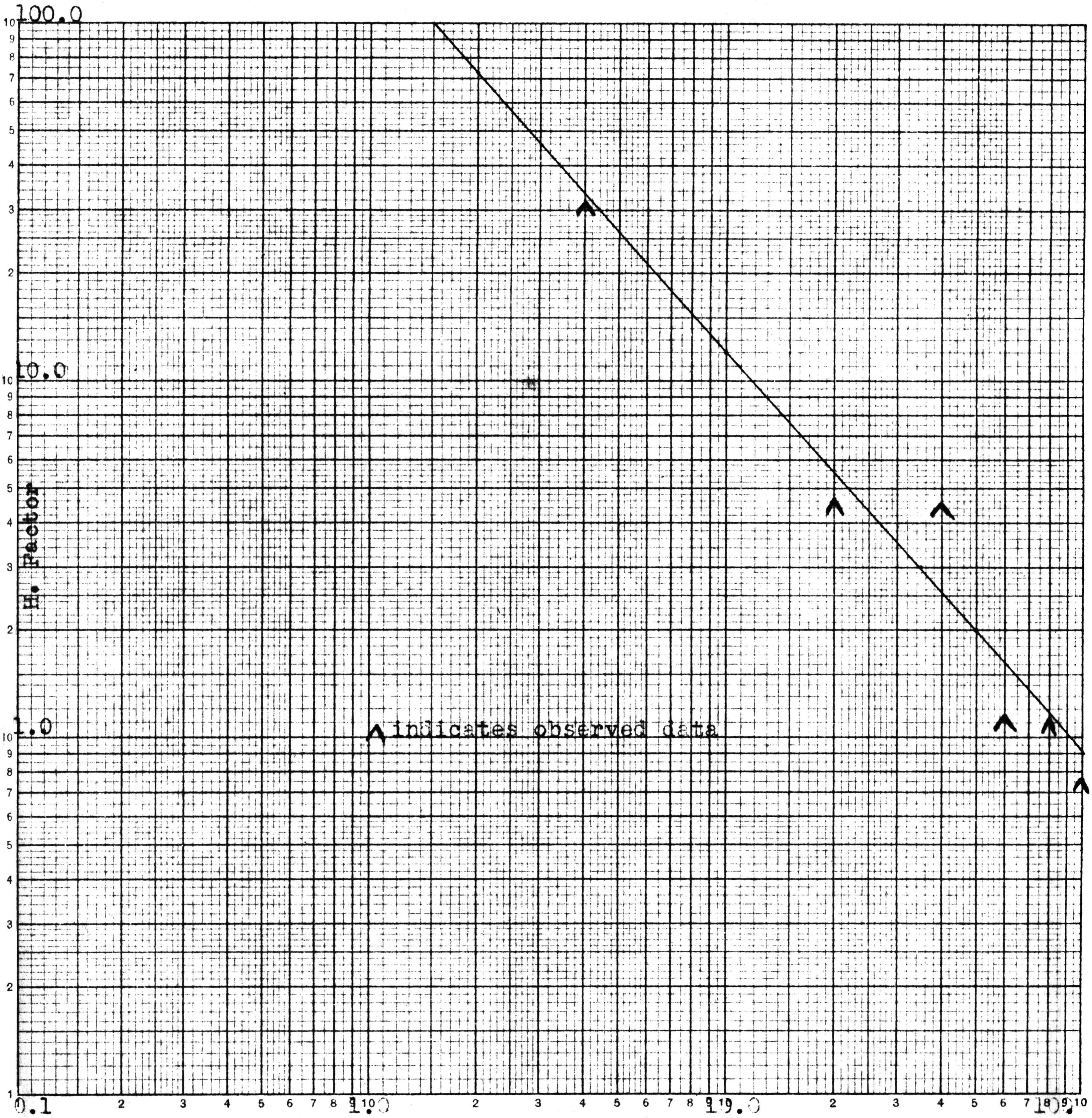
It is believed that this study was reasonably complete insofar as the rates of drying and equilibrium moisture contents of alfalfa are concerned. However, it is suggested that this same type of investigation be conducted for the clovers and grasses. It may be found, after a few preliminary tests, that their drying characteristics are very similiar to alfalfa. If this is true, the data presented in this report will also be applicable to those hay crops.

It is also suggested that if the equipment is available for securing the desired temperature and humidity conditions additional tests be run for the 55° dew point series of this investigation. This would help to locate the drying curves for this series in a more positive manner than the system used in this study, treating similiar curves of all the series as a family of curves. It is believed that this treatment was permissible, and additional points on the curve would either verify or disapprove this supposition.


M. C. R. vs Time Curve
Test # 9
The curve for samples 2,3, and 4
have been displaced 10 hours
from the preceeding curve
. = Sample # 1
X = Sample # 2
O = Sample # 3
^ = Sample # 4
Moisture Content Ratio
Time in hours
1.0
0.1
0.01
0
10
20
30
40
50

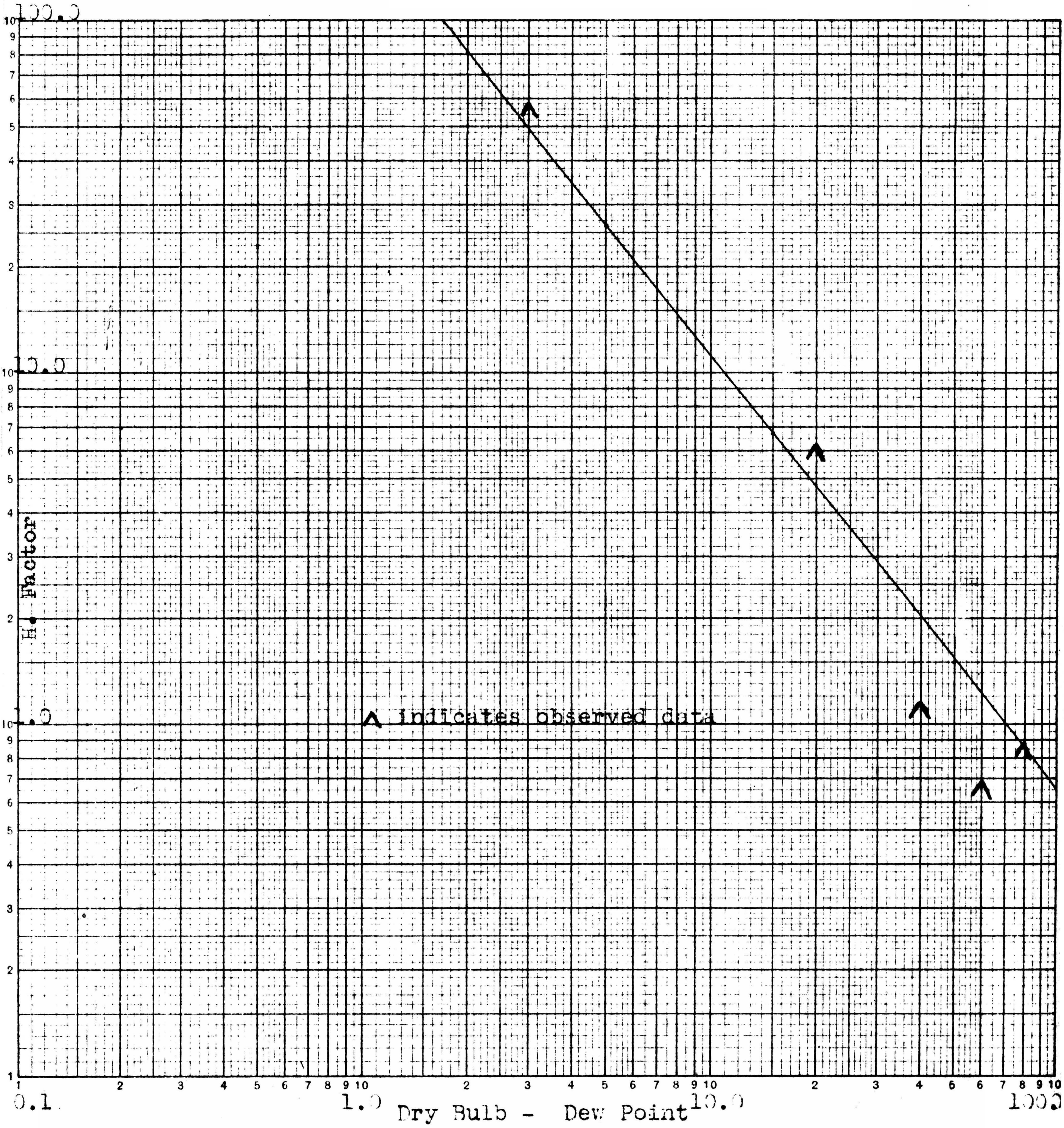

100.0
10.0
1.0
Factor
indicates observed data
Dry Bulb - Dew Point

55° Dew Point



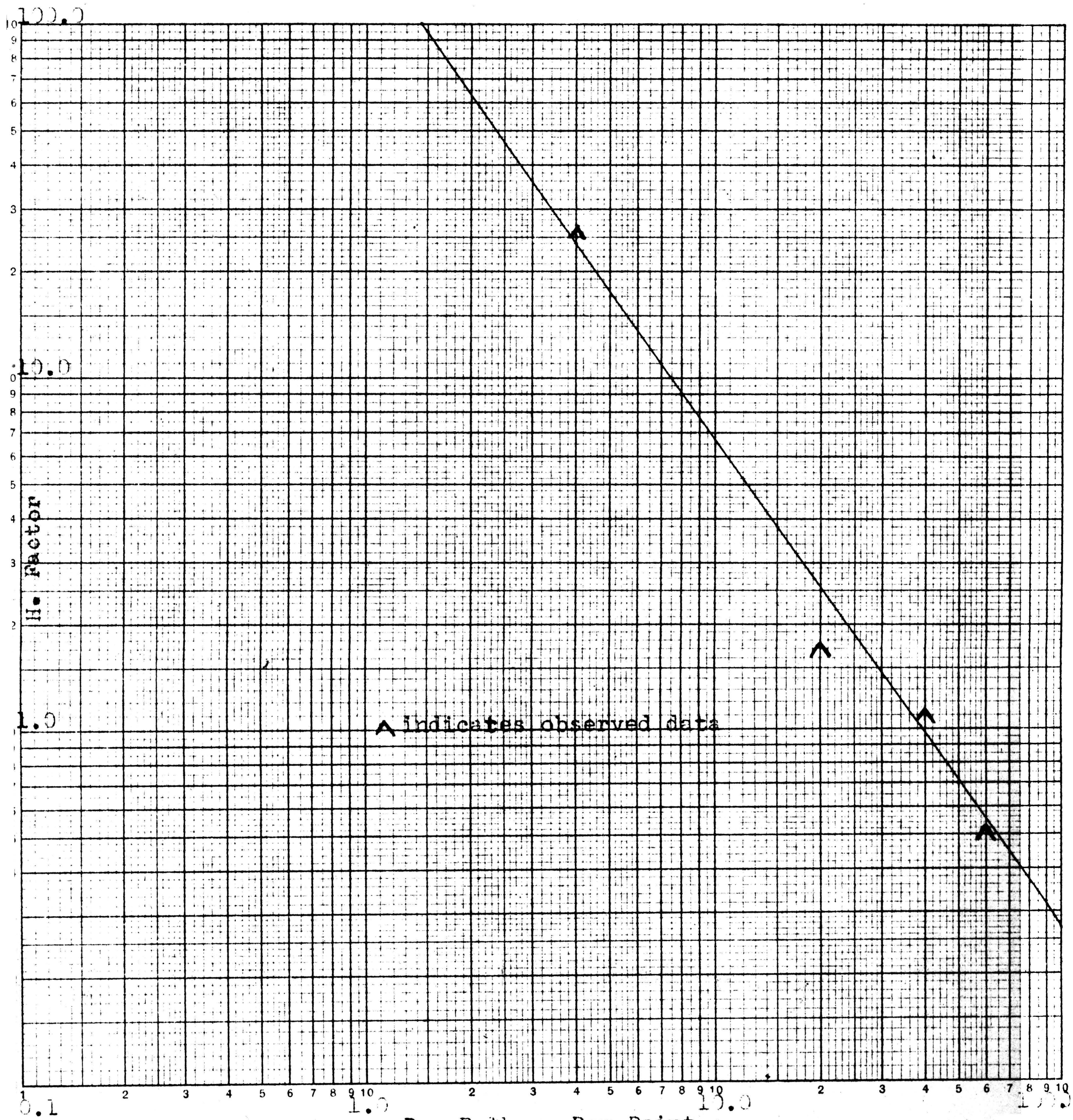
Dry Bulb - Dew Point

70° Dew Point



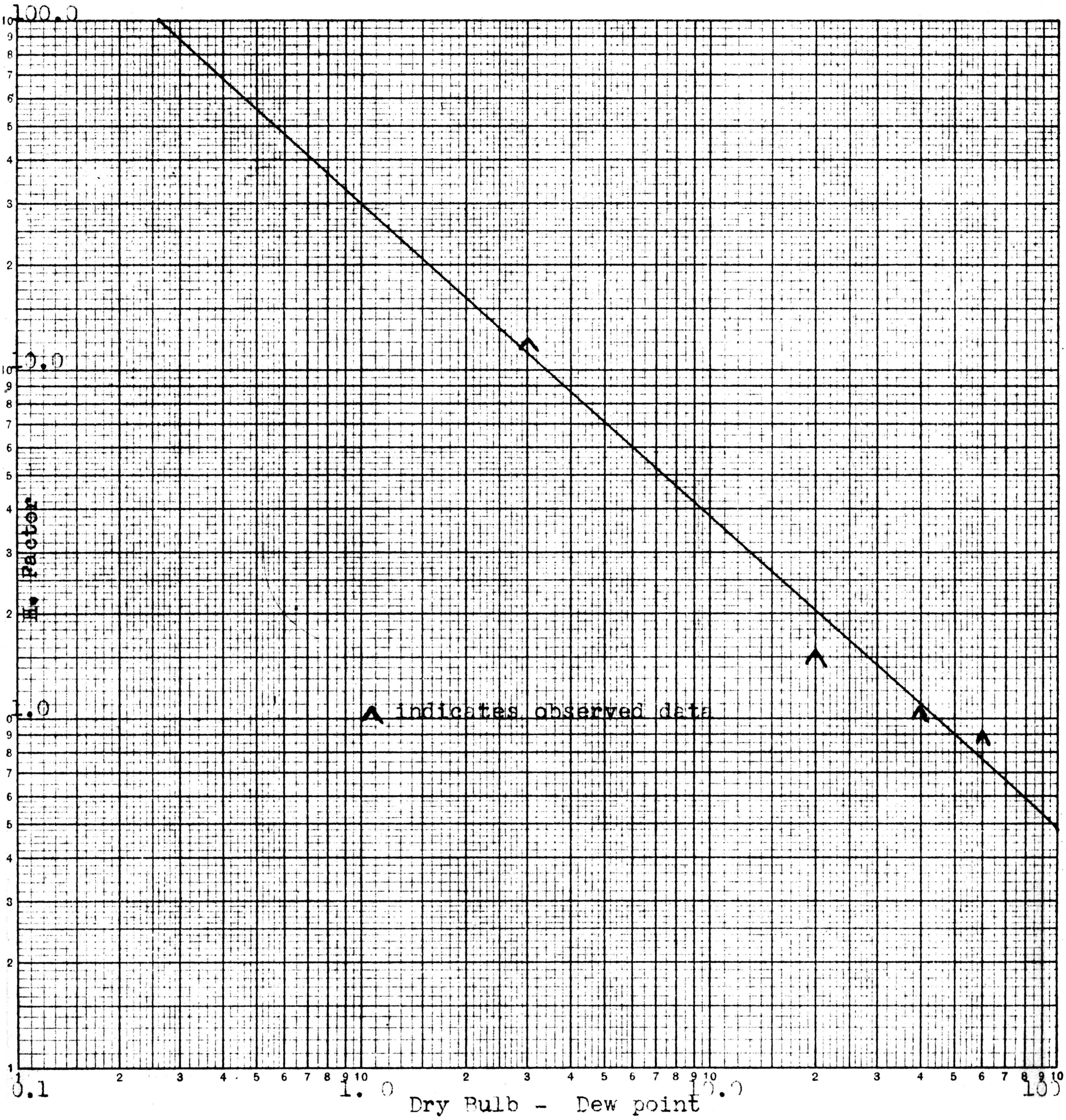
100.0
10.0
1.0
H. Factor
^ indicates observed data
0.1
1.0
10.0
100.0
Dry Bulb - Dew Point

85° Dew Point

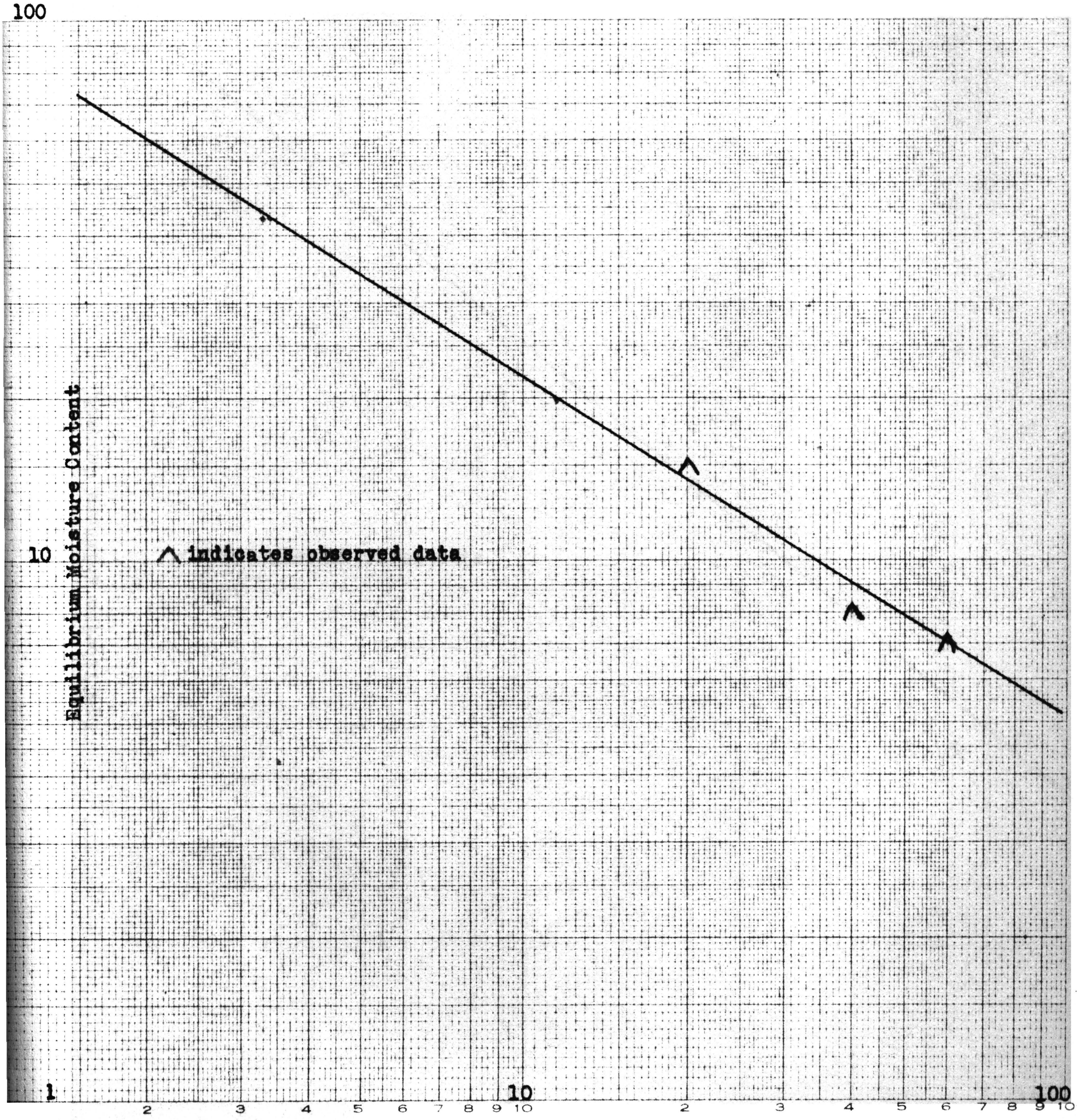


Dry Bulb - Dew Point

100° Dew Point

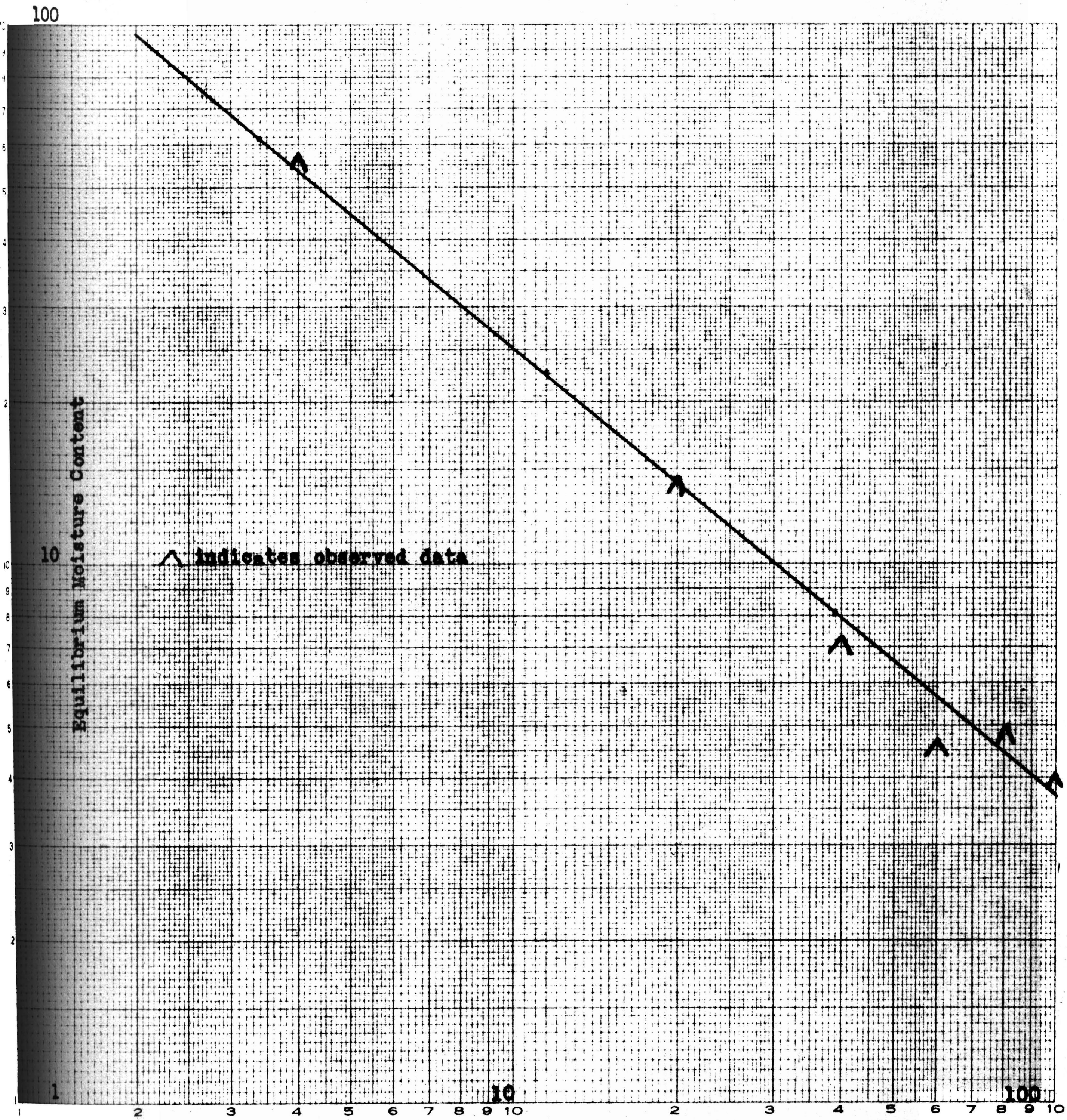


115° Dew Point



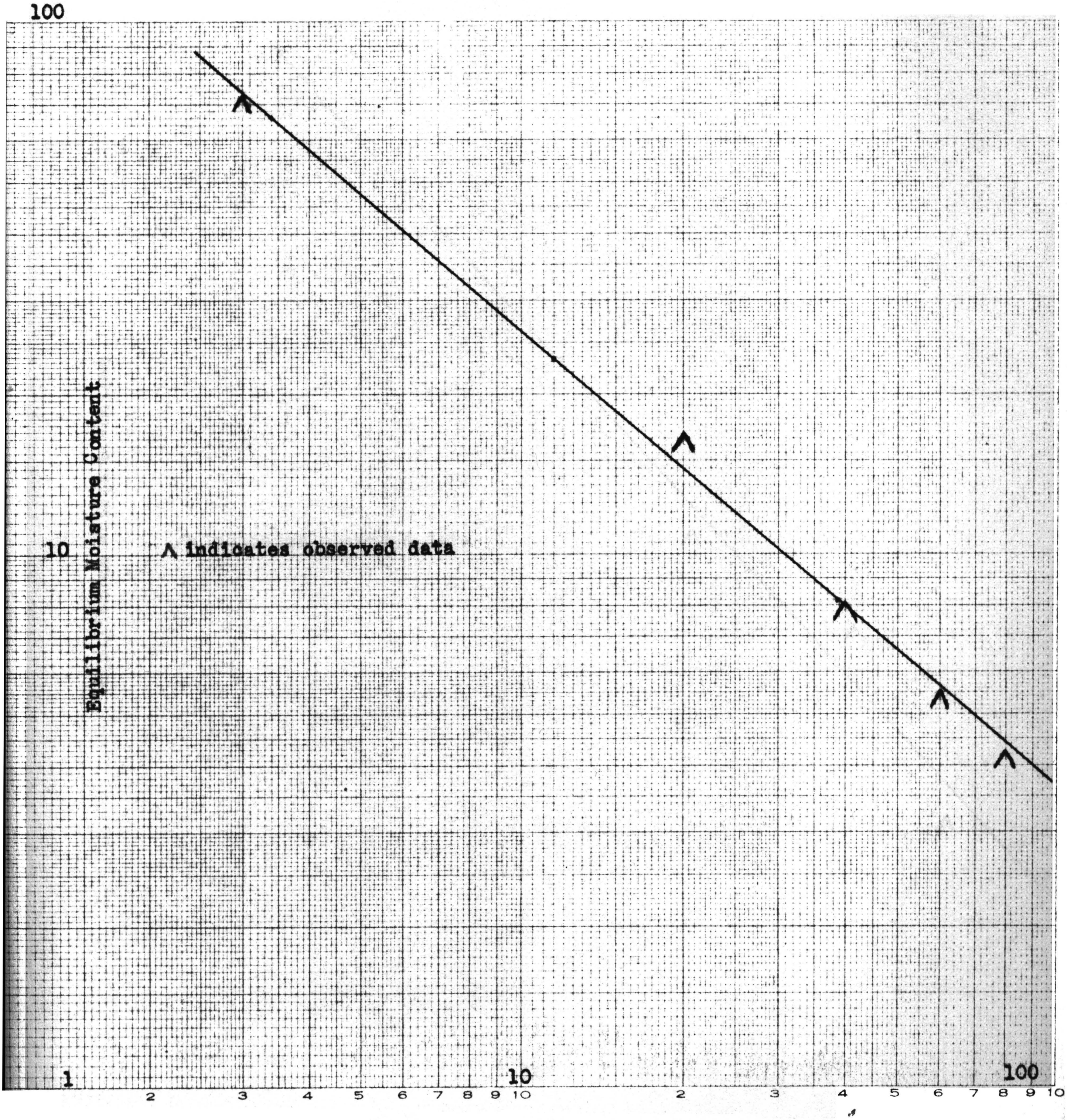
Dry Bulb - Dew Point

55° Dew Point

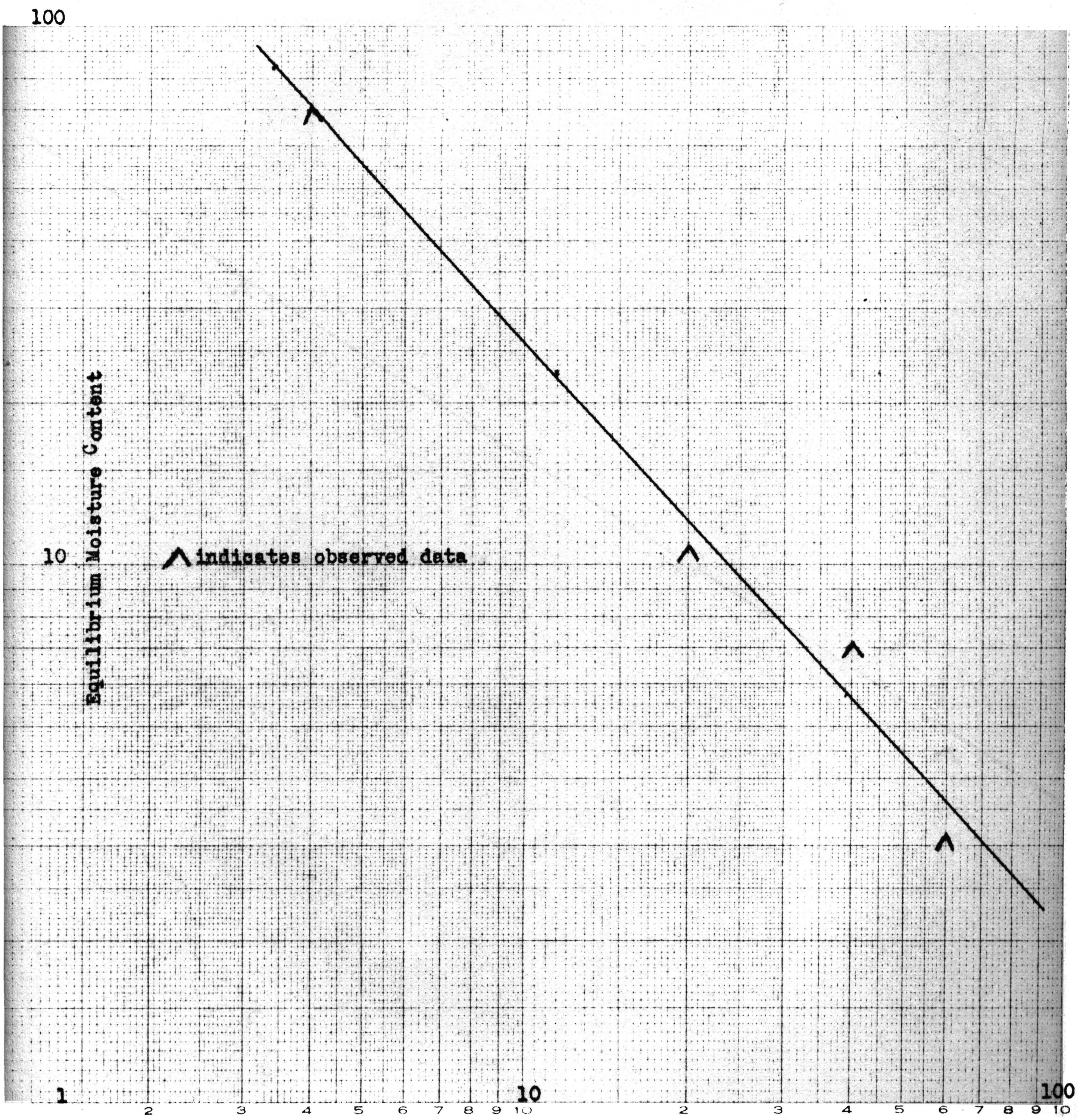


Dry Bulb - Dew Point

70° Dew Point

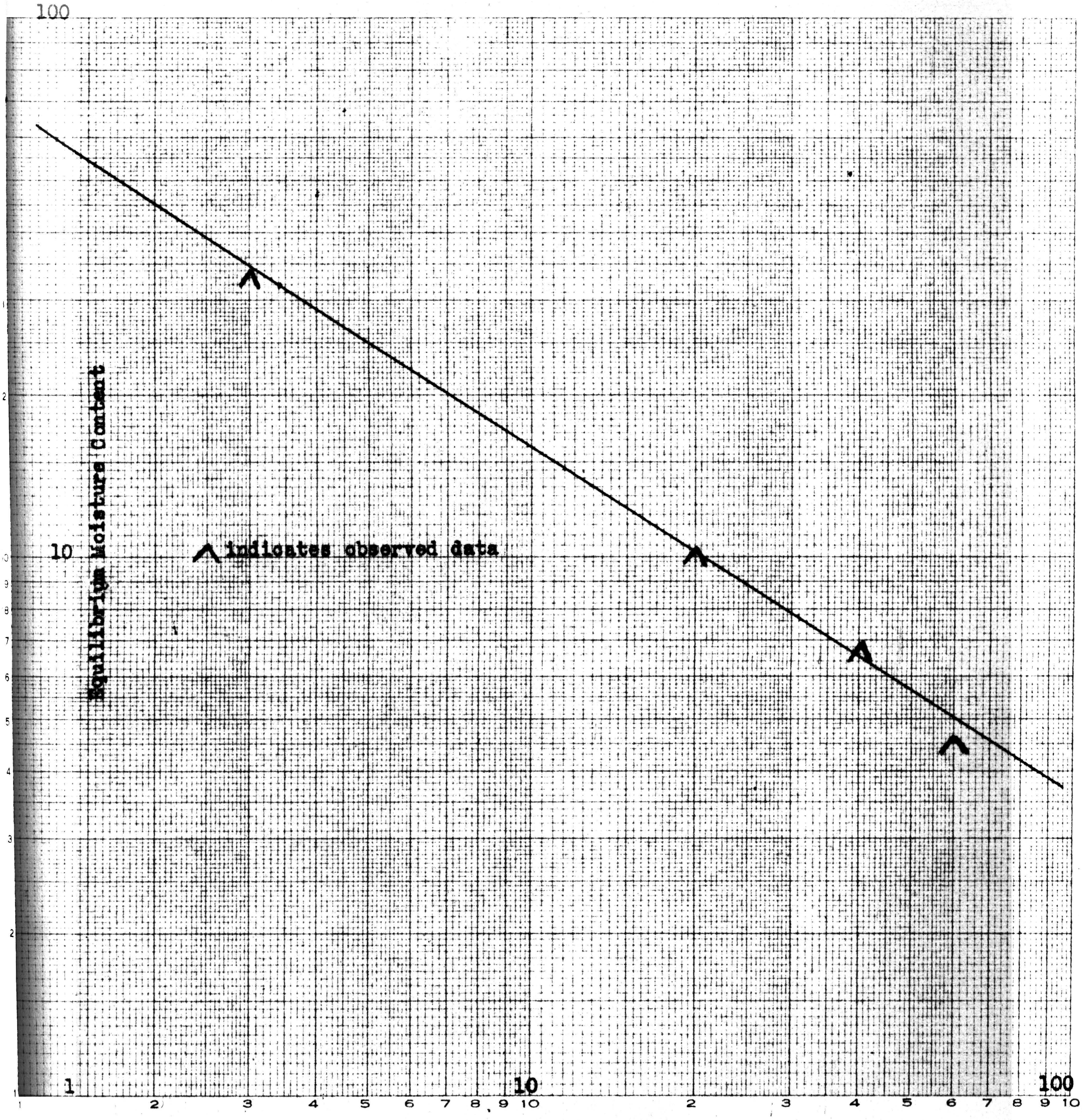


Dry Bulb - Dew Point
85° Dew Point



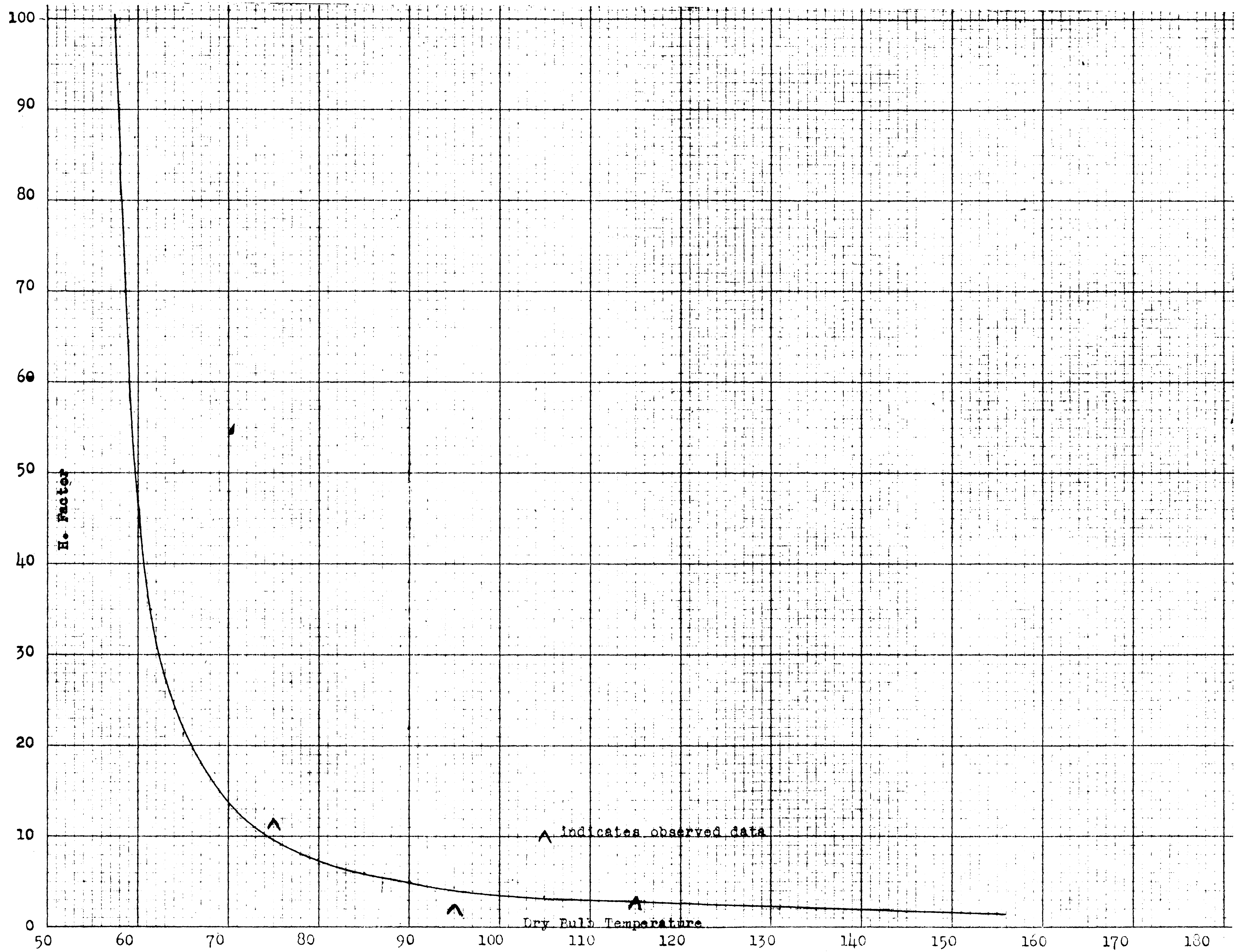
Dry Bulb - Dew Point

100° Dew Point



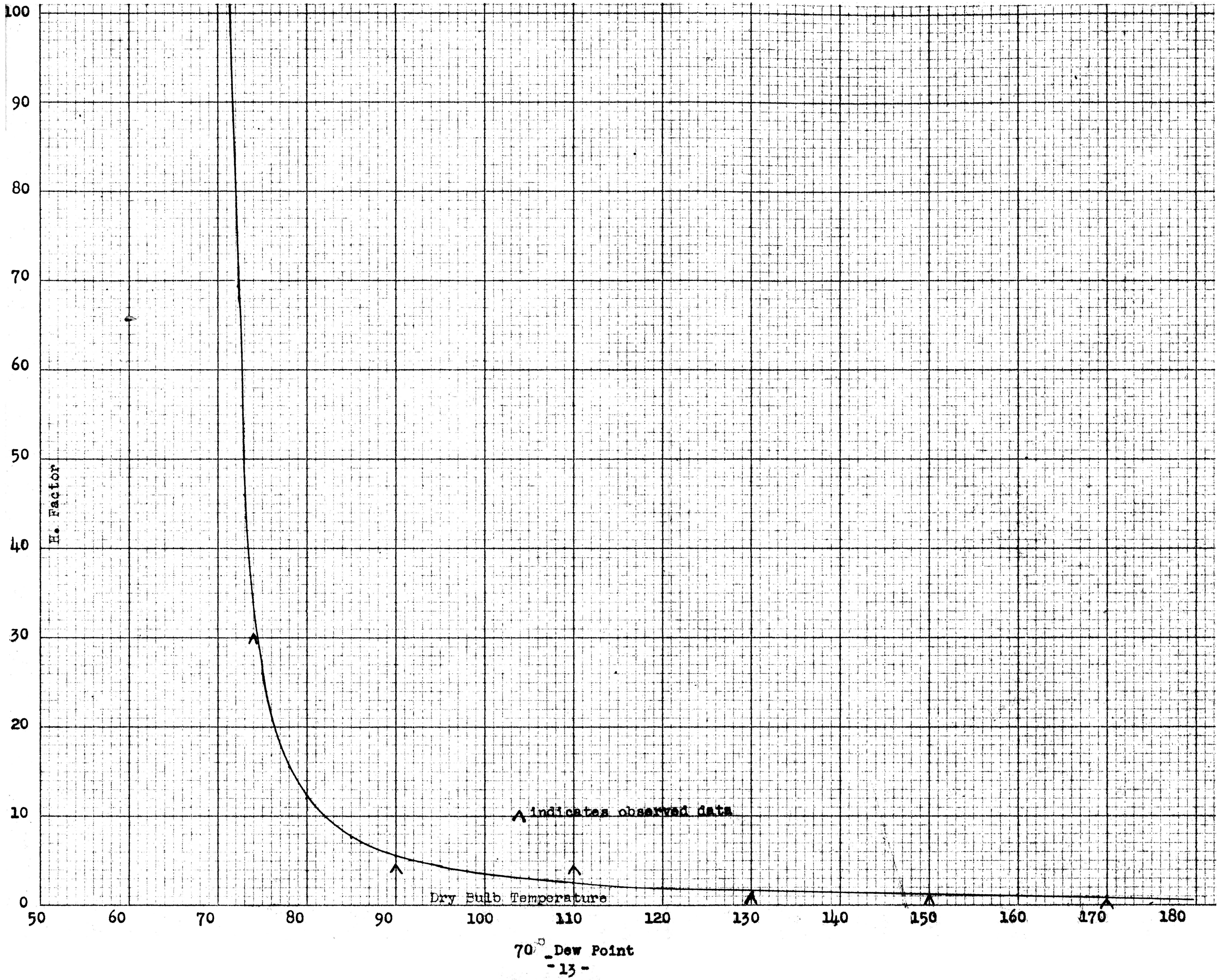
Dry Bulb - Dew Point

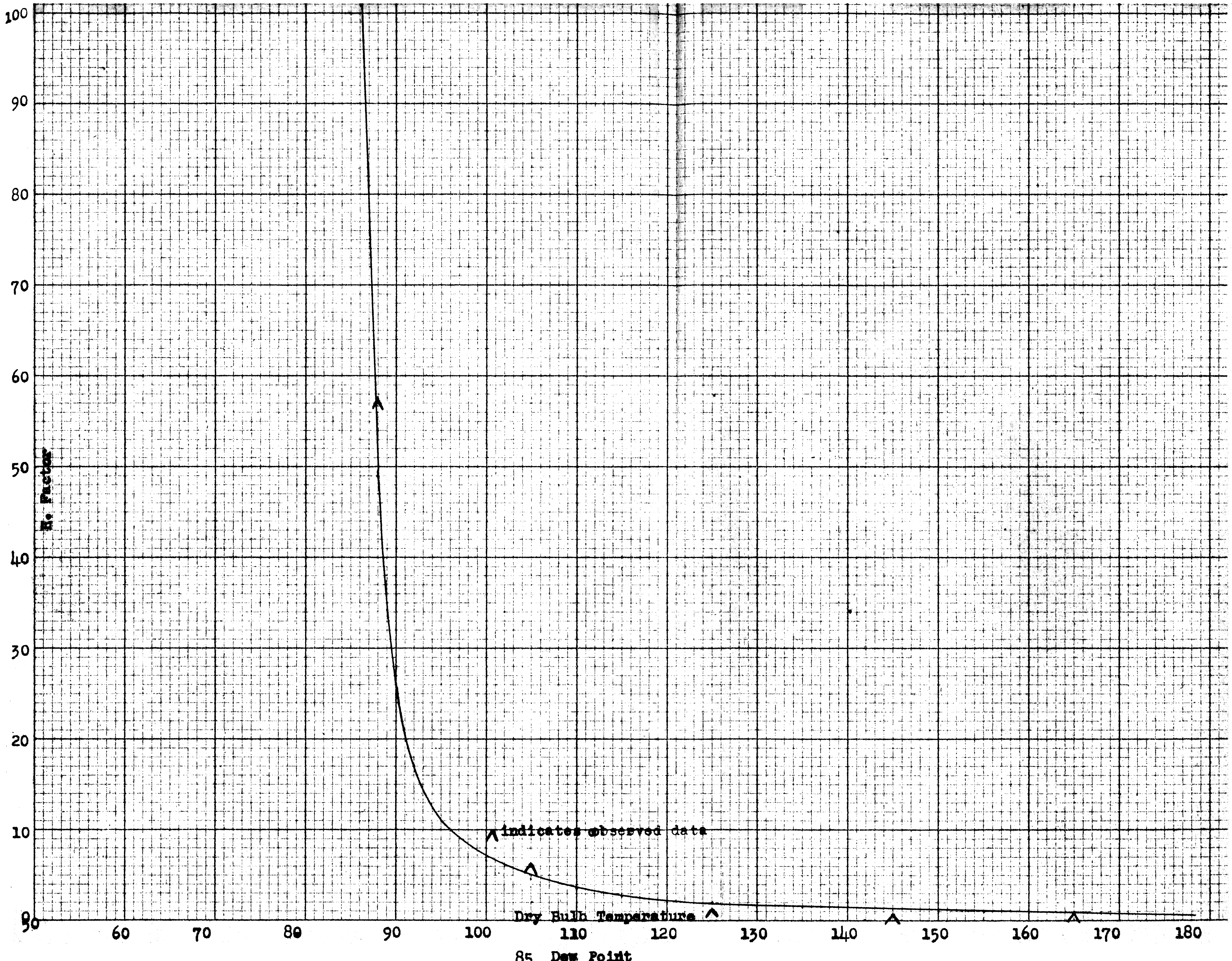
115° Dew Point

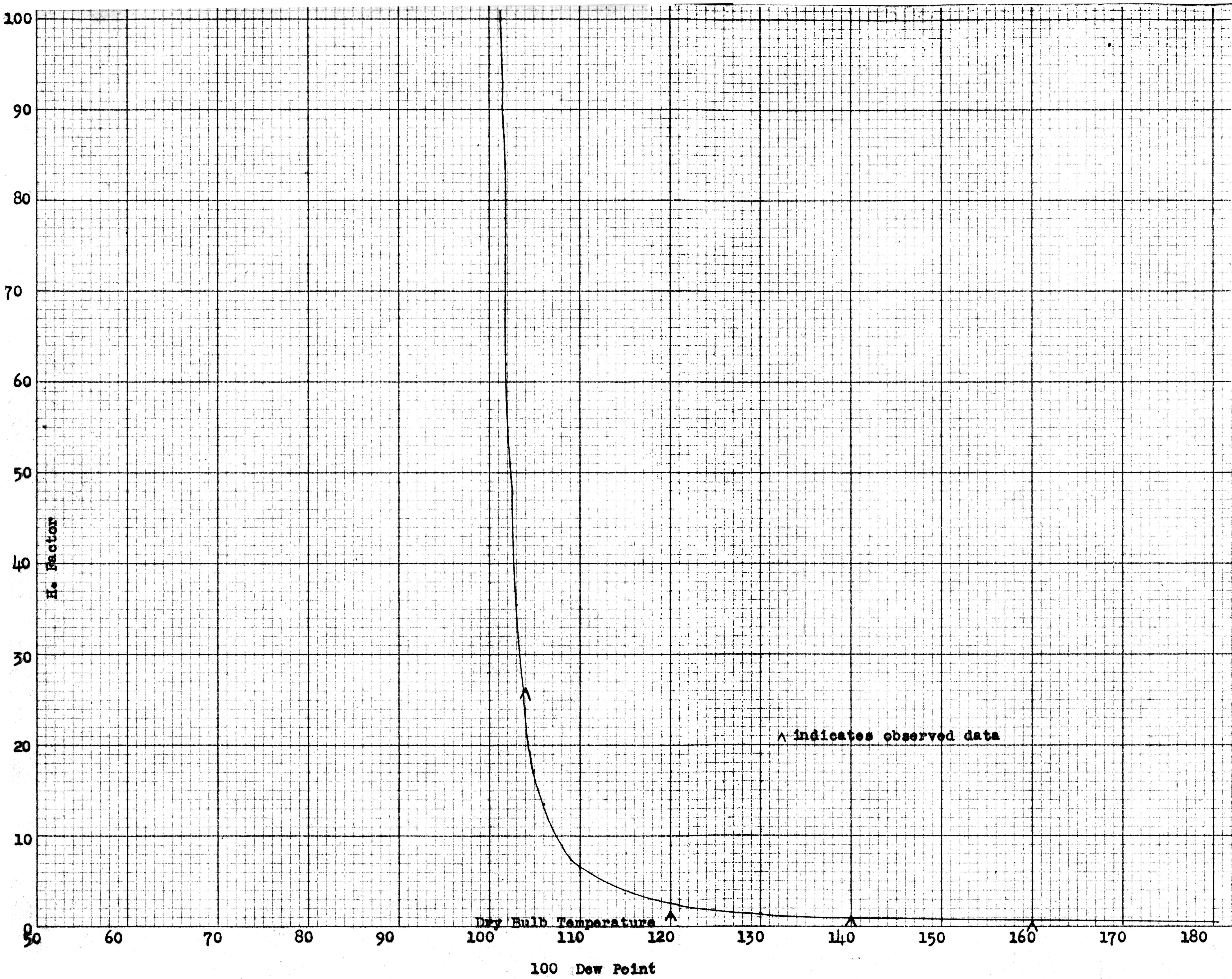


100
90
80
70
60
50
40
30
20
10
0
H. Factor
indicates observed data
Dry Bulb Temperature
50
60
70
80
90
100
110
120
130
140
150
160
170
180

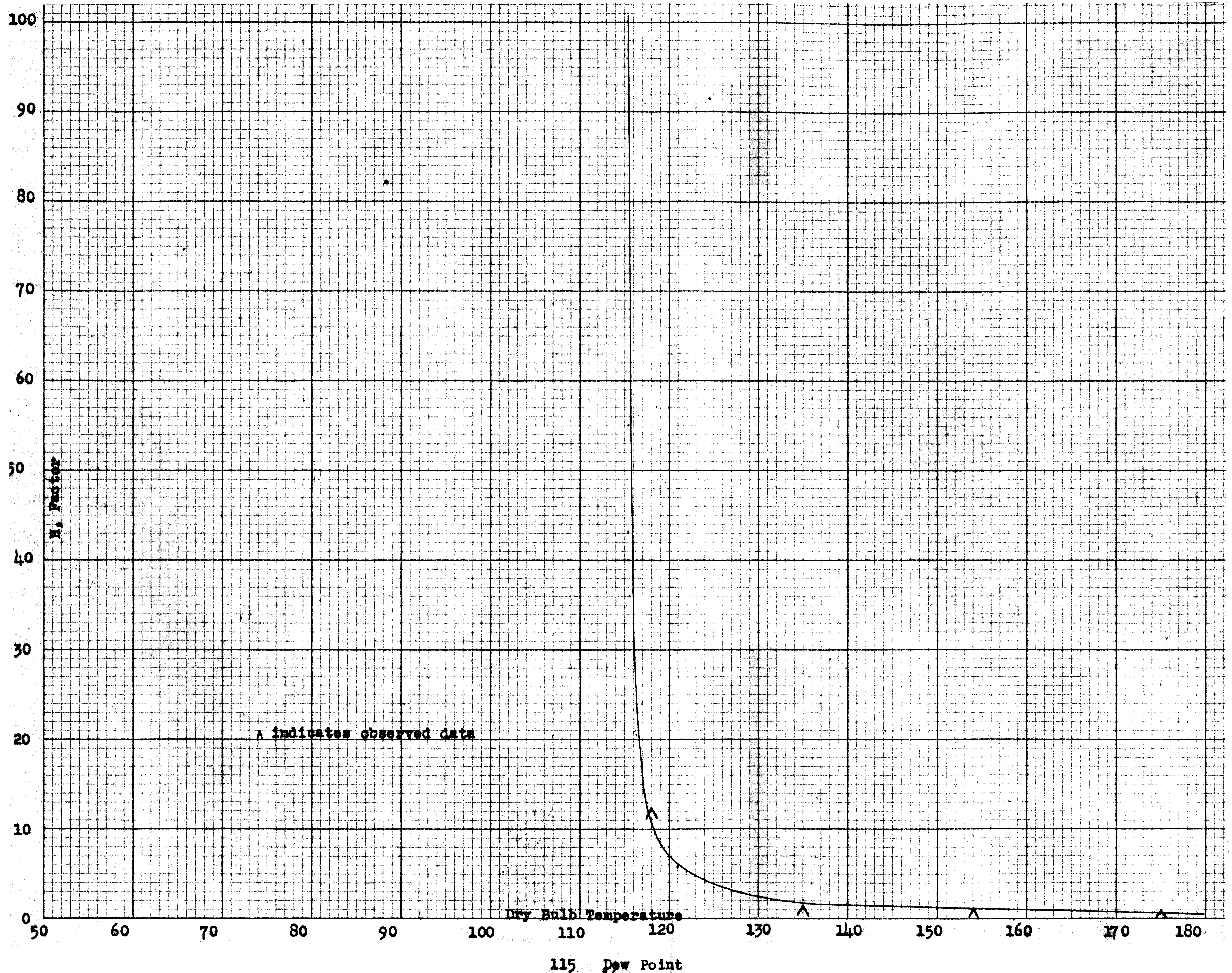
55 Dew Point


H. Factor
Dry Bulb Temperature
indicates observed data
0
10
20
30
40
50
60
70
80
90
100
50
60
70
80
90
100
110
120
130
140
150
160
170
180
70° _ Dew Point

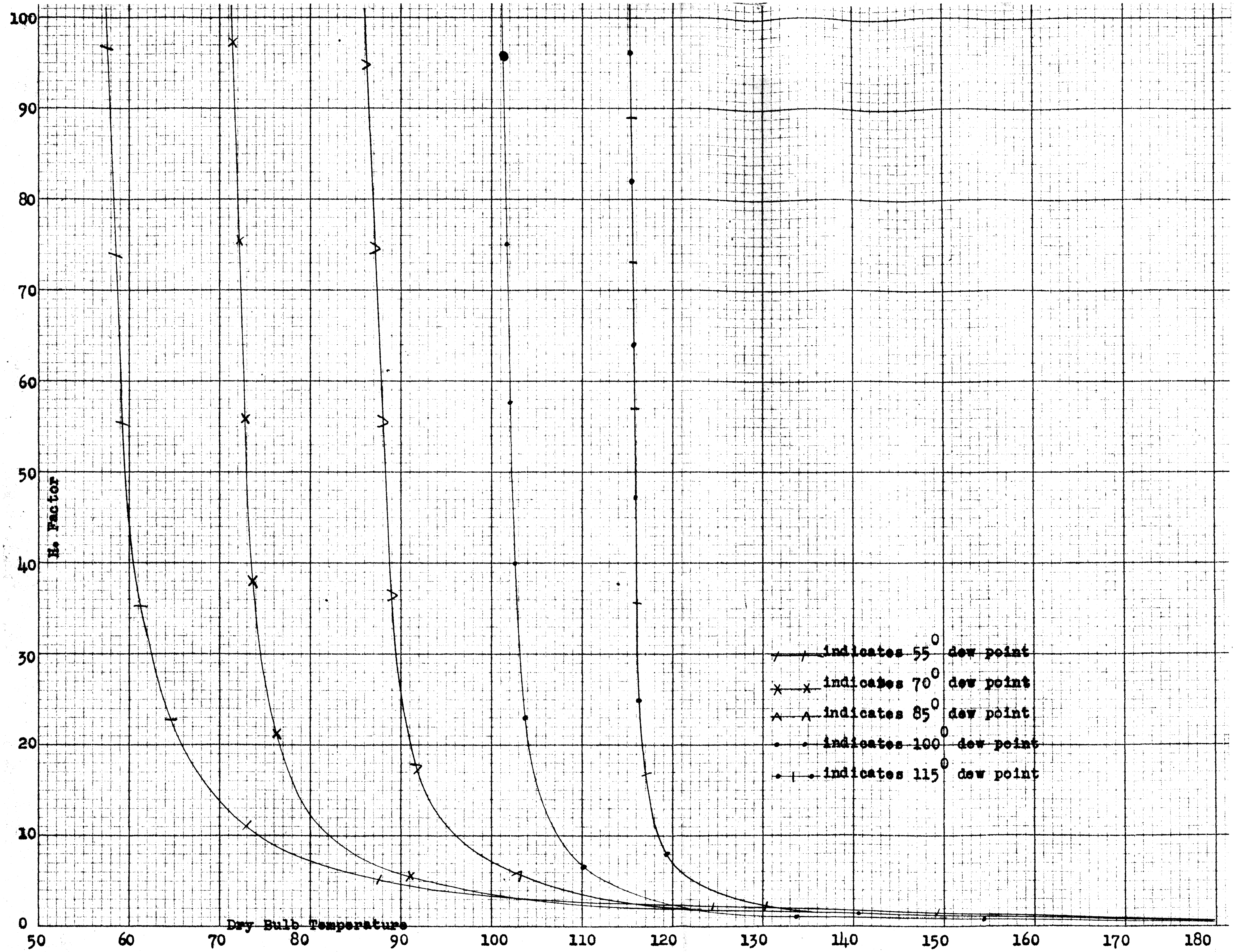

H. Factor
indicates observed data
Dry Bulb Temperature
85 Dew Point
100
90
80
70
60
50
40
30
20
10
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180

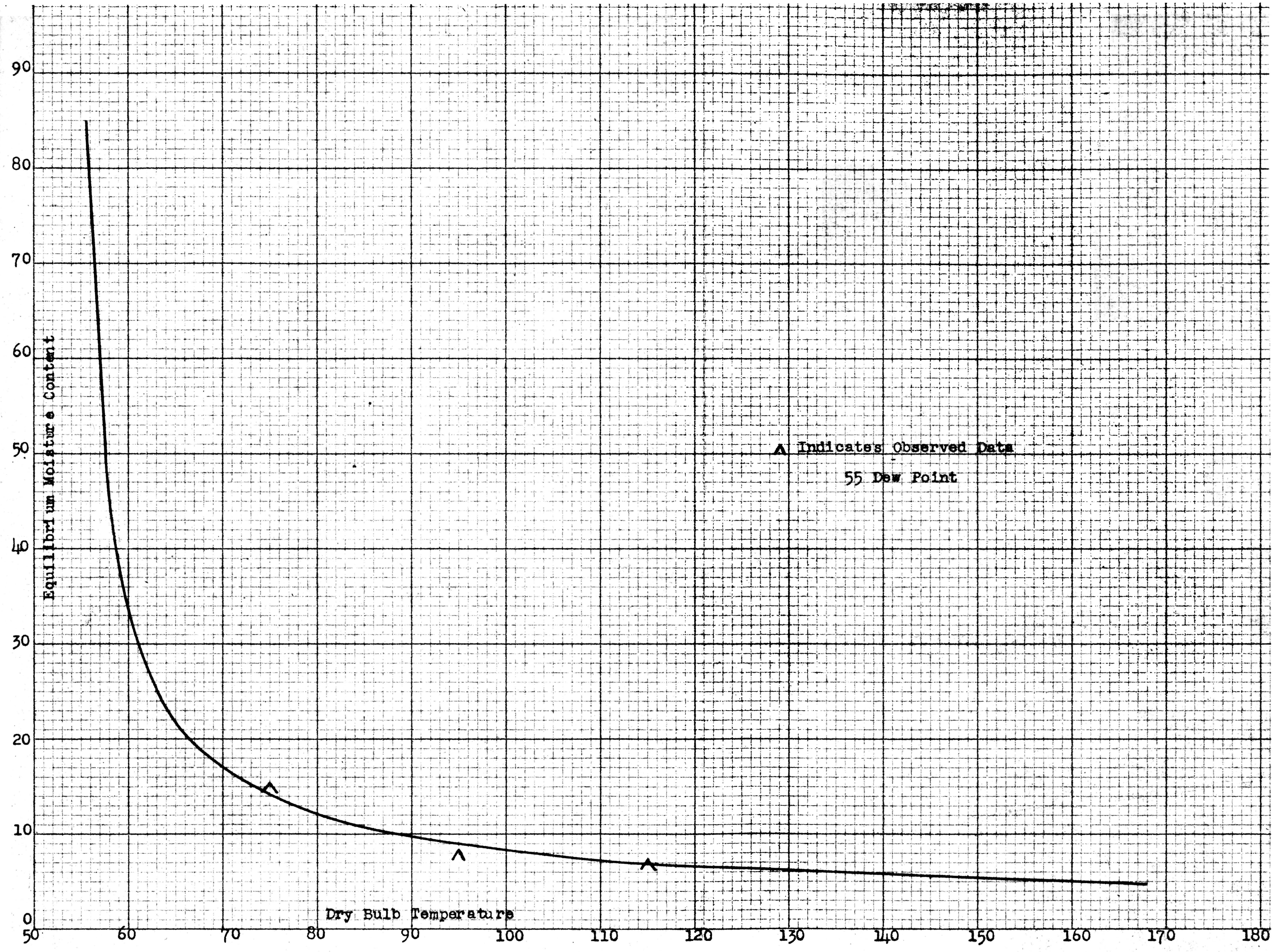


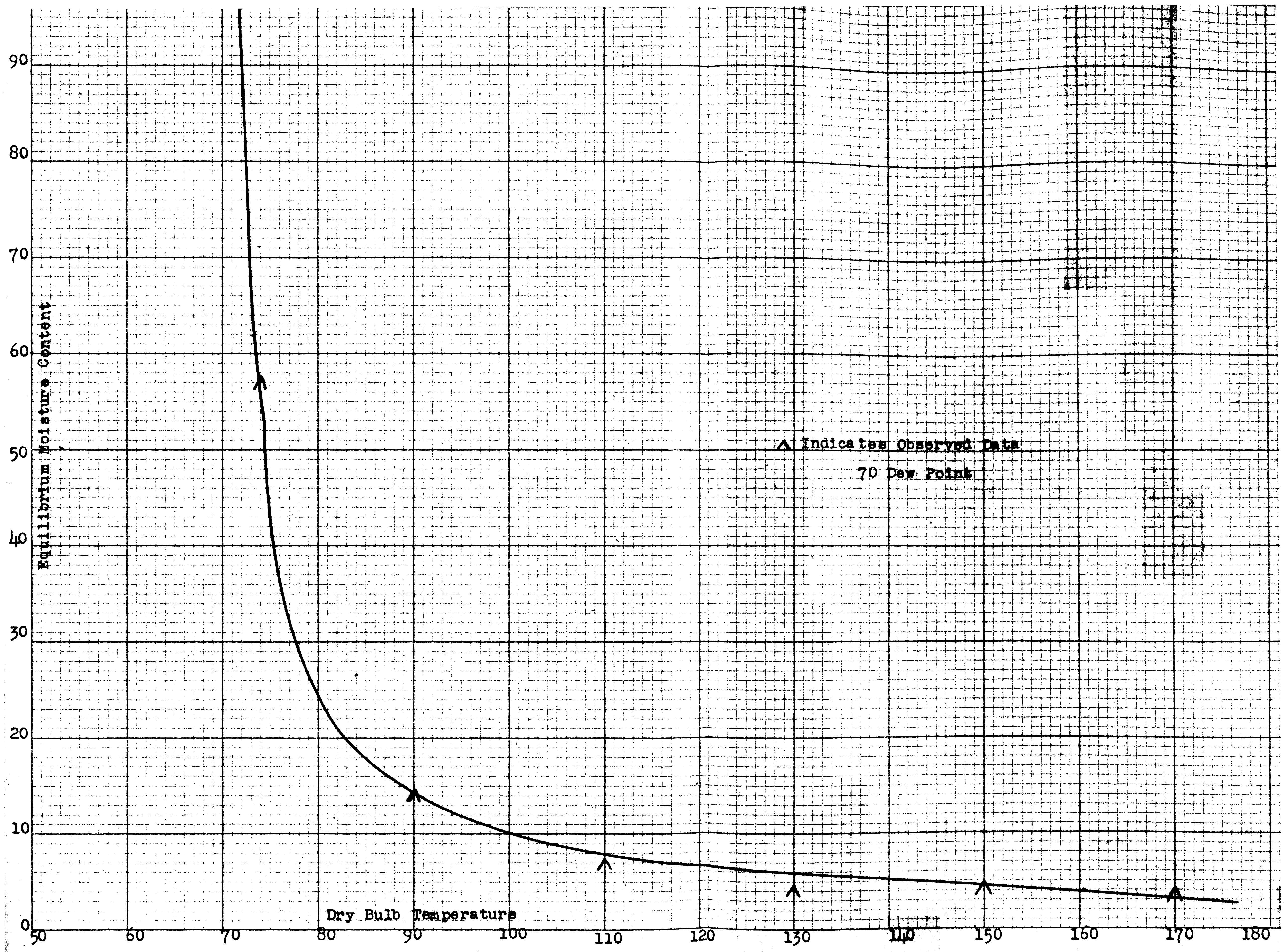
H. Factor
100
90
80
70
60
50
40
30
20
10
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Dry Bulb Temperature
∧ indicates observed data
100 Dew Point



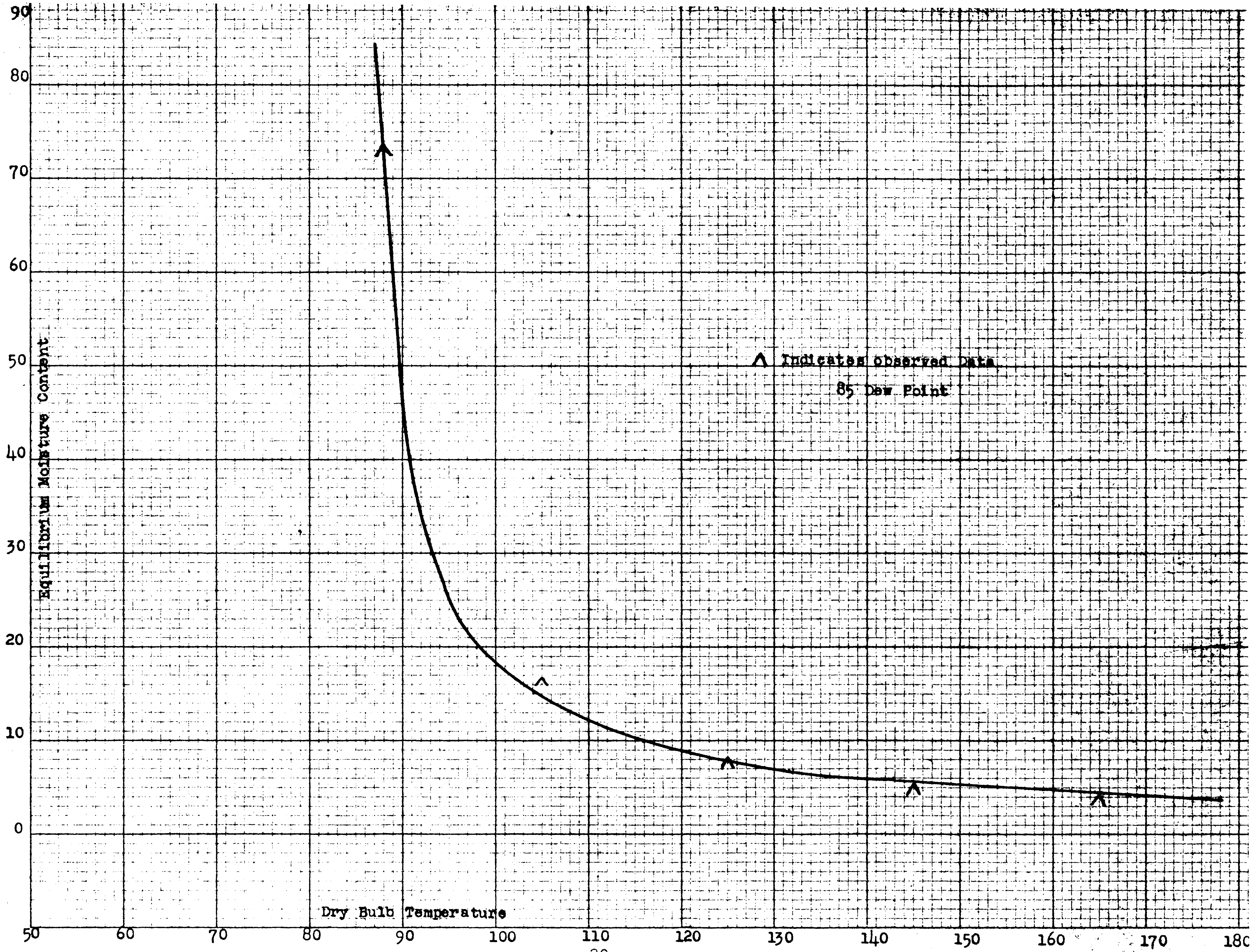
100
90
80
70
60
50
40
30
20
10
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180
H_1 Factor
∧ indicates observed data
Dry Bulb Temperature
115 Dew Point

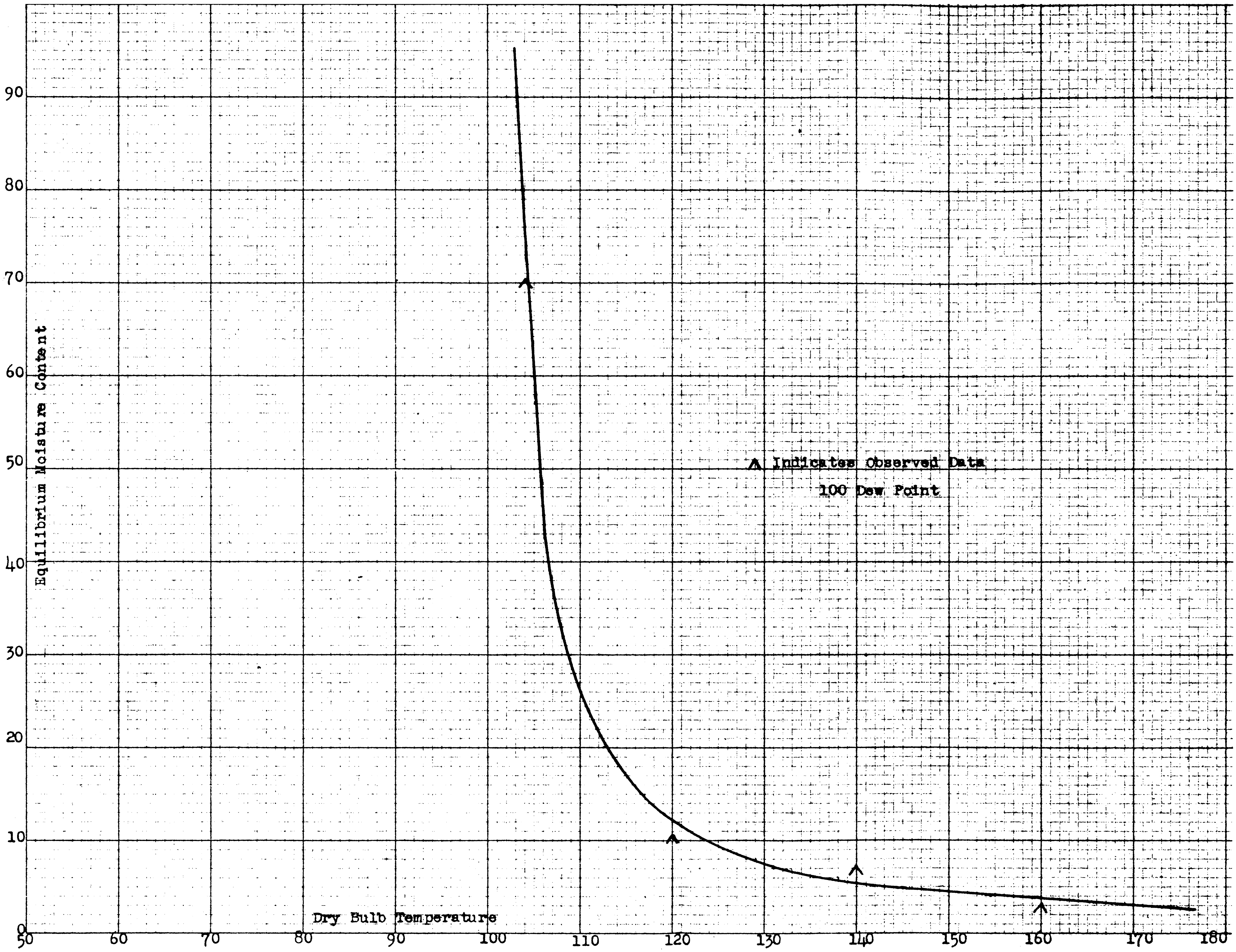

H. Factor
Dry Bulb Temperature
indicates 55° dew point
indicates 70° dew point
indicates 85° dew point
indicates 100° dew point
indicates 115° dew point
0
10
20
30
40
50
60
70
80
90
100
50
60
70
80
90
100
110
120
130
140
150
160
170
180


Equilibrium Moisture Content
Dry Bulb Temperature
Indicates Observed Data
55 Dew Point
0
10
20
30
40
50
60
70
80
90
50
60
70
80
90
100
110
120
130
140
150
160
170
180

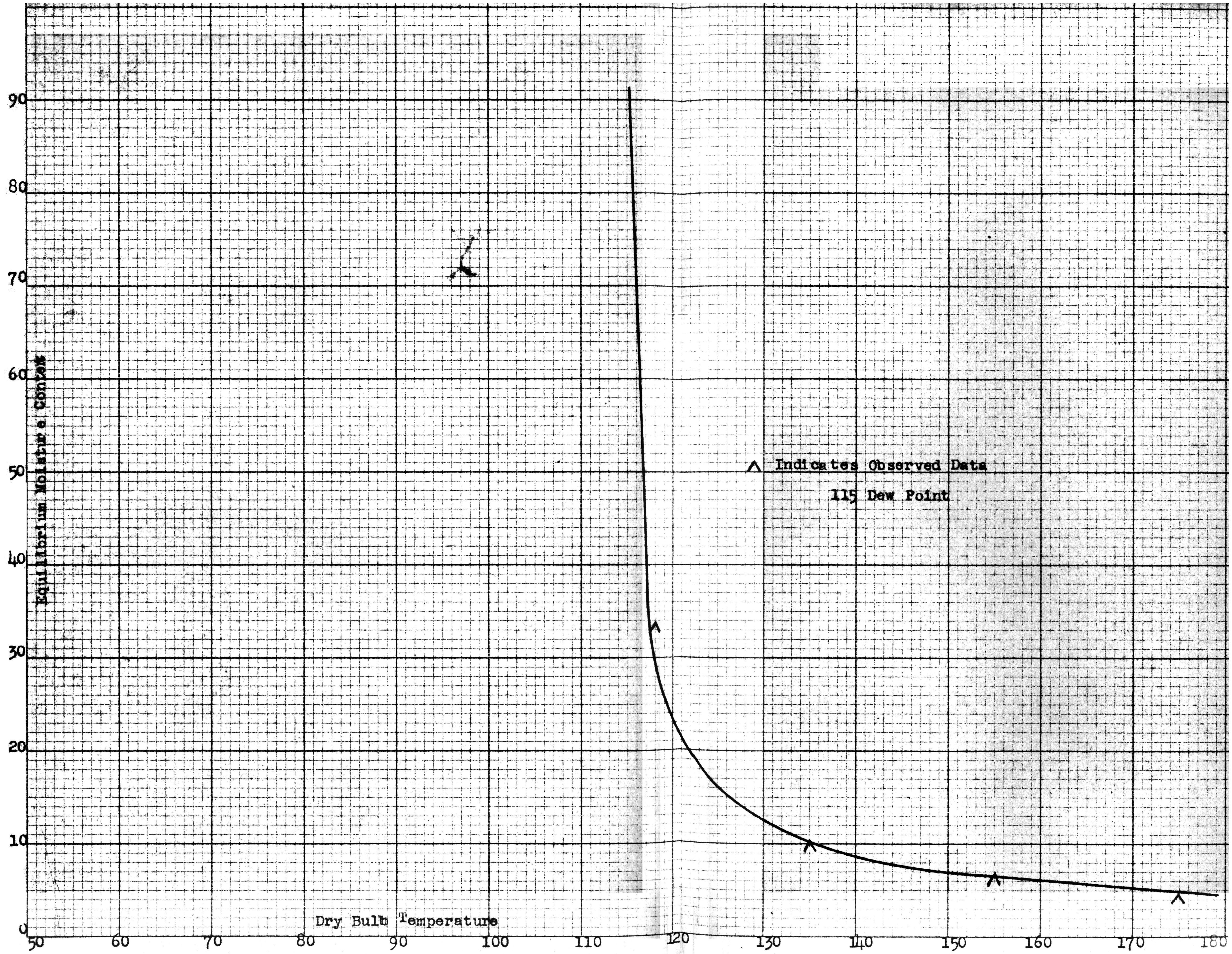


Equilibrium Moisture Content
Dry Bulb Temperature
Indicates Observed Data
70 Dew Point
90
80
70
60
50
40
30
20
10
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180

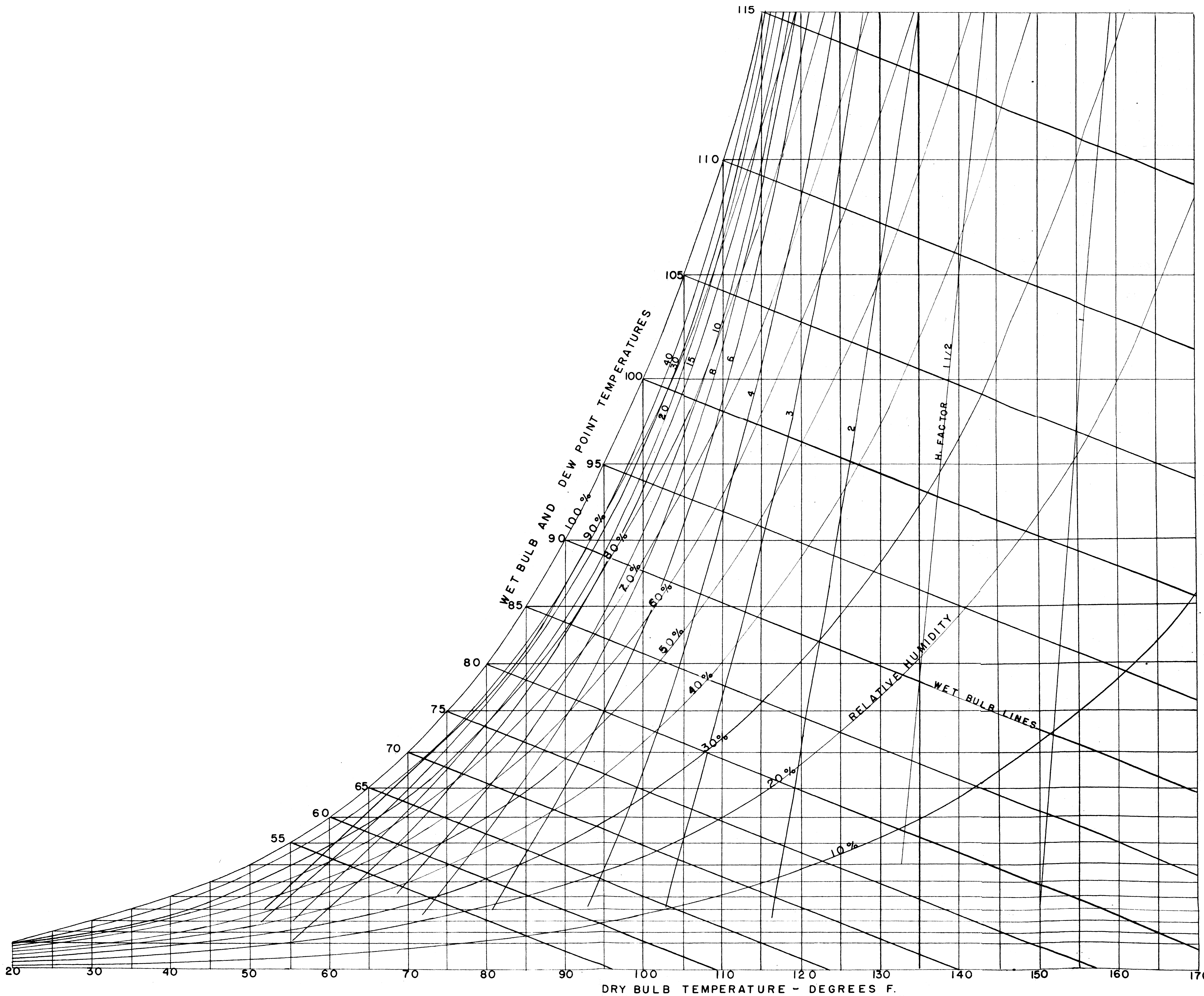

Equilibrium Moisture Content
Dry Bulb Temperature
Indicates observed Data
85 Dew Point
90
80
70
60
50
40
30
20
10
0
50
60
70
80
90
100
110
120
130
140
150
160
170
180



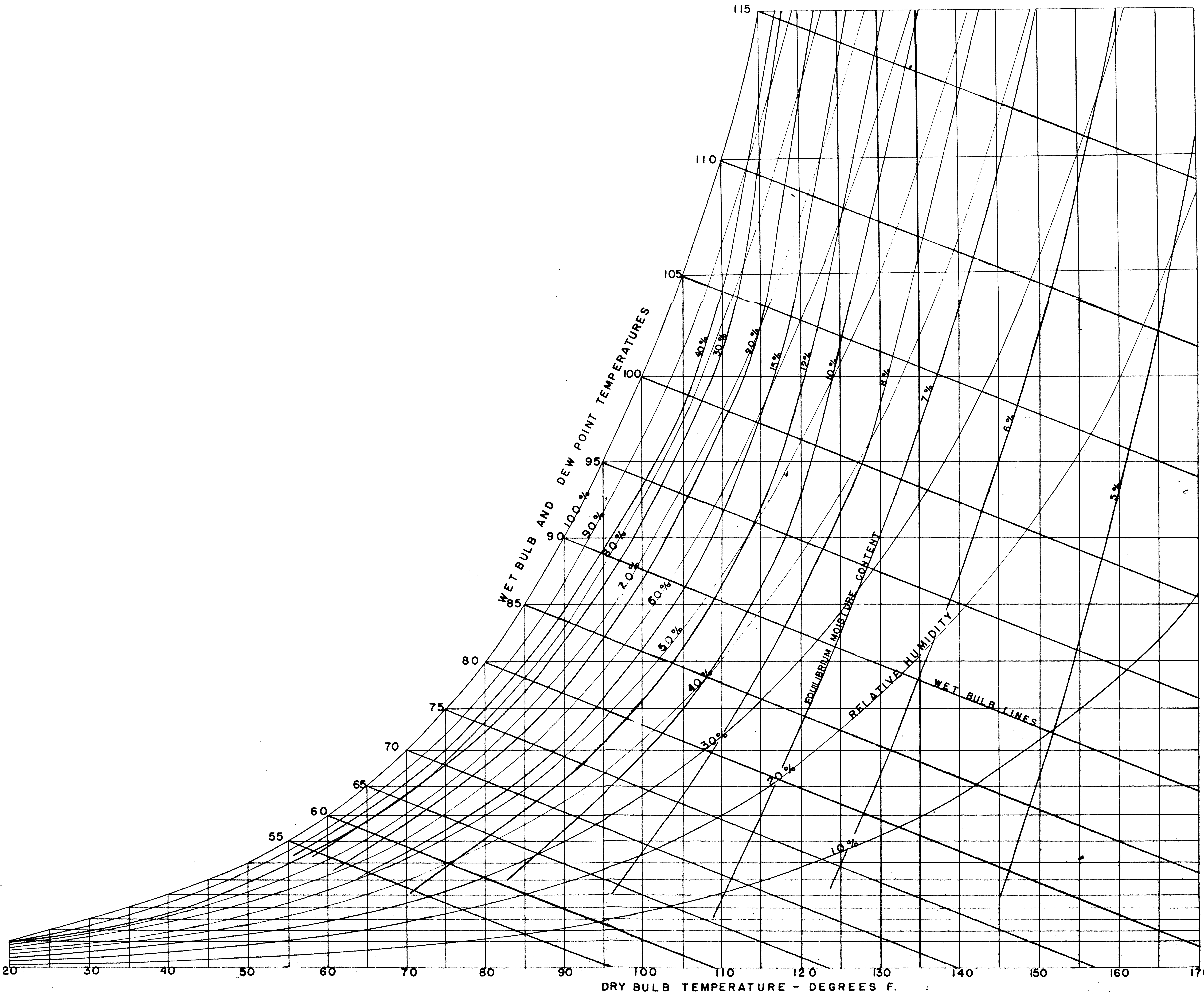
Equilibrium Moisture Content
Dry Bulb Temperature
^ Indicates Observed Data
100 Dew Point
0
10
20
30
40
50
60
70
80
90
50
60
70
80
90
100
110
120
130
140
150
160
170
180



90
80
70
60
50
40
30
20
10
0
Equilibrium Moisture Content
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Dry Bulb Temperature
Λ Indicates Observed Data
115 Dew Point



WET BULB AND DEW POINT TEMPERATURES
115
110
105
100
95
90
85
80
75
70
65
60
55
100 %
90%
80%
70%
60%
50%
40%
30%
20%
10%
RELATIVE HUMIDITY
WET BULB LINES
H. FACTOR
40
30
20
15
10
8
6
4
3
2
1 1/2
1
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
DRY BULB TEMPERATURE - DEGREES F.



WET BULB AND DEW POINT TEMPERATURES
115
110
105
100
95
90
85
80
75
70
65
60
55
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
DRY BULB TEMPERATURE - DEGREES F.
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
RELATIVE HUMIDITY
EQUILIBRIUM MOISTURE CONTENT
40%
30%
20%
15%
12%
10%
8%
7%
6%
5%
WET BULB LINES

APPENDIX III

FORCED DRAFT OVEN

Specifications:

Manufacturer: American Instrument Company
Silver Springs, Maryland

Number : 4- 148A

Serial No. : D 20064

Volts : 220

Cycles : 60

Phase : Single

Min. Operating Temperature: Room temperature

Max. Operating Temperature: 260° C.

Consumption of electrical energy at various switch settings:

"High"	2000 watts
"Medium"	1000 watts
"Low"	500 watts

All settings are controlled by an Aminco "Quickset"

Bimetal Thermometer

Outside overall dimensions: 41" long, 25" wide, 34" high

Inside dimensions: 19", 19", 19"

CTCH OVEN

Dimensions and Specifications:

Inside: 30" x 30" x 24" high (Main Chamber)

Ducts : 8" x 12"

Humidity pan: 9" x 12" x 4" deep
heating element 750 watt

C Cl_2 trays: 5" x 12" x 3/4" deep

Heating elements: 500 watts

REFRIGERATION UNIT

Make: Frigidaire

Type: Vapor compression

Motor: Frigidaire

110 - 220 volts

60 cycles

single phase

4.1 - 2.05 amps

1/4 h.p.

1760 r.p.m.

Repulsion - induction

SAMPLE CONTAINERS

Type: 16 mesh wire screen

Shape: Cylindrical

Size: 3-1/2" diam. x 5" high

Hinged type sheet metal bottom

PSYCHROMETER

Motor aspirated

Volts: 110

Cycles: 60

Amps.: 0.4

Catalogue number: 573

Manufacturer: J. P. Fries and Sons, Baltimore, Maryland

Serial Number: 220 - 39

Temperature Range: 0 - 130° F.

Relative Humidity Range: 0 - 100

RECORDING THERMOMETER

Manufacturer: The Bristol Company
Waterbury, Conn.

Model: 340M

Chart: 621

Pens: 2

Serial No. 104730

Clock: 7 day

Range: -20 to 110° F.

Bulb: Gas filled, 8" #29968

Accuracy: - 2°

ANALYTICAL BALANCES

Manufacturer: Central Scientific Company

Accurate to within 0.001 gram