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THE MECHANISM OF THE DRYING OF SOLIDS

by

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ABSTRACT

The drying of solids is commercially one of the most important of the unit processes of chemical engineering. Problems involved in the drying of solids are frequently of major practical importance, either because of the desirability of rapid drying, or because of the necessity of drying without injury to the product. There is much published information relative to the construction of driers, and the vapor carrying capacity of air and humidity relations in general are fairly well understood. However, the mechanism of the drying process, that is, the exact manner in which the liquid travels to the surface of the solid and thence out into the air, has been heretofore poorly understood. Since little information was available, the quantitative relations between the rate of drying and the factors affecting it, have been known only approximately at best. The present work describes the mechanism of drying prevailing under different conditions, and with this mental picture of the actual mechanisms, a rational analysis is possible of the quantitative relations between rate of drying and the various factors involved.

The general mechanisms of drying are three: first, evaporation of the liquid from the solid surface, the resistance to internal diffusion of liquid to the surface being great as compared with the resistance to diffusion of the vapor from the solid surface out into the main body of the air; secondly, evaporation of the liquid from the solid surface, the resistance to internal diffusion of liquid to the surface being small as compared with the resistance to diffusion of the vapor away from the surface; and third, evaporation at points within the solid structure, with subsequent diffusion of vapor through the relatively dry surface layer and thence out into the air.

Although the mechanism is found to be different for different solids over similar ranges of liquid content, all very wet solids being dried under constant drying conditions exhibit a "constant rate period" during which the rate of drying is constant. The rate does not continue constant until the solid is dry, but at some definite liquid content called the "critical liquid content" the rate of drying starts to decrease and the range from there to dryness is called the "falling rate period". Obviously, if the initial liquid content is less than the critical, no constant rate period appears.

The mechanism of drying during the constant rate period is apparently always the second of those described above, or "surface evaporation controlling." During this period the surface temperature remains constant, and the rate of diffusion of vapor through the surface gas film controls the rate of drying. When the heat necessary for vaporization is supplied only by conduction through the same surface gas film through which the vapor diffuses, the surface temperature during this period is the wet-bulb temperature of the air. Where heat is supplied in other ways, such as by radiation or by conduction from adjoining dry surfaces of the solid, the surface temperature is higher than the wet-bulb temperature, and the rate of drying is increased. The method of calculating the effect of radiation to the solid is explained, and radiation from surroundings at moderate temperatures is shown to multiply the rate of drying several fold. The quantitative relations between the rate of drying and the ratio of dry to wetted surface are developed, and as an example it is shown that covering one of two equal faces of a thin sheet may reduce its overall rate of drying in the constant rate period by less than 20 per cent.

The liquid concentration gradient across the thickness of a solid slab is shown to be represented by a parabola, when the rate of drying is constant. In cases of drying of a slab having an initial uniform liquid distribution the change is progressive from the uniform distribution towards the parabolic liquid concentration gradient, which is the ultimate or "equilibrium" gradient for the condition of a constant drying rate. Under such conditions the liquid distribution in the slab is continually changing, although the slab temperature and the rate of drying are constant. The equations developed in connection with the liquid concentrations during the constant rate period have been applied to data on clay where it was found possible to calculate the diffusion constant of water in clay from the moisture gradient data.

The falling rate period was found in general to be divisible into two distinct zones. The first of these was called "Zone A" and in the course of the drying followed immediately after the critical point, i.e., after the constant rate period. This zone was characterized by a linear relation between the rate of drying and the average liquid concentration, and the constancy of the overall coefficient of heat transfer from air to solid. Moreover, this coefficient during Zone A was the same as during the constant rate period; and the rate of drying in this period showed no great variation with the thickness of the sample. It was, therefore, concluded that in Zone A evaporation occurred at the solid surface, and that "surface evaporation" was the controlling factor. It is believed that in this zone the decreased rate of evaporation is due to the decrease in the surface area actually wetted.

In "Zone B", the region between "Zone A" and dryness, the rate of vaporization falls off sharply. the rate of drying vs. liquid content curve being convex to the axis of the latter. In this zone the rate of drying is found to vary inversely as the slab thickness, and the overall coefficient of heat flow may or may not decrease below the value found in the constant rate period and "Zone A".

For the analysis of data on drying by this mechanism, the solution of the fundamental diffusion equation

$$\frac{\partial^2 v}{\partial x^2} = \frac{1}{K}\frac{\partial v}{\partial \theta}$$

for the case of an infinite slab is used in the form

$$= \frac{4}{\pi}\left[e^{-(\pi/2)^2\tau} \sin\frac{x\pi}{2R} + \frac{1}{3} e^{-9(\pi/2)^2\tau} \sin\frac{3x\pi}{2R} + \frac{1}{5} e^{-25(\pi/2)^2\tau} \sin\frac{5x\pi}{2R} + \ldots\ldots\ldots\ldots\ldots \right]$$

where v = free liquid concentration per unit volume

x = distance of the point from the sheet surface

θ = time

K = diffusion constant

$$\Delta = \frac{\text{free liquid concentration}}{\text{initial free liquid concentration}}$$

R = thickness of half the slab

$\tau = K\theta/R^2$

The above equation gives the theoretical liquid distribution at any time in a slab where internal liquid diffusion controls the drying and the surface resistance to vapor removal is negligible.

Moreover, if we let

$$E = \frac{\text{total free liquid}}{\text{initial total free liquid}}$$

then

$$E = \frac{1}{1xR}\int_{0}^{R} \Delta \, dx$$

$$\therefore E = \frac{8}{\pi^2}\left[e^{-(\pi/2)^2\tau} + \frac{1}{9} e^{-9(\pi/2)^2\tau} + \frac{1}{25} e^{-25(\pi/2)^2\tau} + \ldots\ldots\ldots\ldots\ldots\ldots\ldots \right]$$

which is the theoretical drying equation when internal diffusion controls. This equation was found valuable in the correlation of data on the drying of soap, clay, and wood and should apply to the drying of similar slow-drying materials. The corresponding equation for finite surface resistance is also derived.

Depending on the material and the drying conditions"Zone A" may or may not appear between the constant rate period and "Zone B". Thus, the rate of internal diffusion and consequently the rate of drying in "Zone B" is independent of outside conditions, and if the average liquid content falls to that value where the rate of internal liquid diffusion is equal to the rate of drying in the constant rate period, before the surface liquid concentration falls to such a value as to cause the wetted surface area to decrease, then no "Zone A" appears. An increase in air velocity will increase the rate during the constant rate period and consequently increase the average water content at the point where the rate of internal diffusion is equal to the rate of drying during the constant rate period. Such a change in air velocity may thus eliminate "Zone A", and if the initial liquid content is low enough, may also eliminate the constant rate period.

When internal liquid diffusion becomes controlling in the case of a porous solid there is a tendency for the locus of evaporation to retreat from the surface, as evidenced by an increase in the overall coefficient of heat flow from air to solid. Thus, throughout the falling rate period in the case of paper pulp, the actual evaporation occurs at points within the solid structure, as evidenced by a continued decrease in the overall coefficient of heat transfer. Under such conditions it is evident that forced air convection is of little value in speeding up the rate of drying. With the fine-grained colloidal clay the overall coefficient of heat transfer remained constant during "Zone B", indicating that the evaporation occurred at the surface as during the constant rate period and "Zone A".

PART I

INTRODUCTION

A. - INTRODUCTION

"Drying" is generally taken to mean the removal of water from a solid, although in some cases the removal from solids of liquids other than water is called drying, and in still other cases the removal of water from solids may be termed filtration, dewatering, centrifuging, or absorption. The term is, therefore, loosely used, though in general engineering practice is used to denote the removal of water from a system or structure, with the limitation that the amount of water present be relatively small. Drying, so defined, may be accomplished by absorption, freezing, vaporization, mechanical separation, or by chemical means. The most important method in commercial work is the vaporization of the water present with the subsequent removal in a stream of gas of the vapor formed. When the gas used is air, the process is called "air drying" and in industrial practice is the common method of removing small amounts of water from solids.

Drying operations are important in the manufacture of most non-metallic products and drying is one of the most important and widely used of the so-called "unit processes of Chemical Engineering."

Drying is of major importance in the manufacture of pulp, paper, textiles, ceramic products, soap, lumber, sugar, rubber, dried foods, low grade fuels, leather, etc. The drying problem is often that of how to remove the necessary water as quickly as possible and with the least expense, but in many cases, such as in the drying of lumber and clay products, the major problem is the removal of the water without distortion or cracking in the product.

In view of the importance of the subject it is surprising that so little has been published regarding the mechanism of drying. The literature abounds with articles on drying and drying equipment, but the theoretical articles are usually found to deal with the moisture carrying capacity of the air used, and humidity relations in general, rather than the mechanism of the transfer of water from solid to air.

Equilibrium and Free Water Content

Before discussing the mechanism of the drying process, the terms "free water" and "equilibrium water content" will be defined. Most solids retain appreciable amounts of water when left in contact with other than dry air for indefinite lengths of time. An equilibrium is reached and the amount of water retained depends on the humidity and temperature of the air. Thus, when a wet solid is being dried in air at a definite amd constant humidity, the water content of the solid can not be reduced below a definite value called the equilibrium water content. Any excess of water above this equilibrium water content may be defined as "free" water. Thus, in terms of the nomenclature to be used, T represents the total water concentration, per unit of dry solid; T_E is the equilibrium water content; and $T-T_E$ is the free water concentration. The quantitative relations between T_E and the air humidity and temperature will be discussed in another section.

Classifications of Drying Mechanisms

In the drying of a solid of appreciable thickness by air or other gas, two general mechanisms are possible. These are (a) the diffusion of liquid from the interior to the solid surface, followed by vaporization of the liquid at the surface, and diffusion of the vapor of the liquid into the surrounding gas; or (b) vaporization of the water at points within the solid structure, followed by diffusion of water vapor through the porous solid to the surface and out into the air. Both groups may be further divided into those cases where the resistance to internal diffusion of liquid is very small or very great as compared with the resistance to removal of the vapor. Four general cases may be noted:

I. Evaporation at the solid surface; resistance to internal diffusion of liquid great as compared with the resistance to removal of vapor from the surface.

II. Evaporation at the solid surface; resistance to internal diffusion of liquid small as compared with the resistance to removal of vapor.

III. Evaporation in the interior of the solid; resistance to internal diffusion of liquid small as compared with the total resistance to removal of vapor.

IV. Evaporation in the interior of the solid; resistance to internal diffusion of liquid great as compared with the total resistance to removal of vapor.

B. Diffusion of Liquid through Solid

The first general mechanism of air drying described above is the diffusion of liquid through the solid to the solid surface where evaporation takes place, followed by diffusion of vapor into the main body of the air. A more or less stagnant gas film on the solid surface presents a resistance to the passage of vapor from the surface into the gas. This "gas-film" resistance will be discussed more fully later. However, in the drying process described, the gas-film or surface resistance to diffusion of vapor, and the resistance to diffusion of liquid through the solid to the surface constitute the "over-all" resistance to transfer of liquid from the interior of the solid to the main body of the gas. Thus, in a case where the surface resistance is entirely negligible as compared to the interior resistance to liquid diffusion, variables affecting the latter will affect the over-all drying rate to the same degree, and laws governing the internal diffusion of liquid will apply equally well to the drying process as a whole.

Assuming Newton's fundamental law of diffusion, and using the principle of a material balance, it is possible to derive relations between the time, liquid concentration, position, diffusion constant, etc.

A complete derivation of the equation for diffusion of liquid in a slab is given in Appendix II and the resulting solution is

$$\Delta = \frac{4}{\pi}\left[e^{-\left(\frac{\pi}{2}\right)^2 T} \sin\frac{x\pi}{2R} + \frac{1}{3} e^{-9\left(\frac{\pi}{2}\right)^2 T} \sin\frac{3x\pi}{2R} + \frac{1}{5} e^{-25\left(\frac{\pi}{2}\right)^2 T} \sin\frac{5x\pi}{2R} + \ldots \right] \quad (1)$$

where $\Delta = \dfrac{\text{free liquid concentration per unit volume}}{\text{initial free liquid concentration per unit volume}}$

x = distance from surface

R = half thickness of slab

$T = \dfrac{K\theta}{R^2}$

θ = time

K = diffusion constant divided by density.

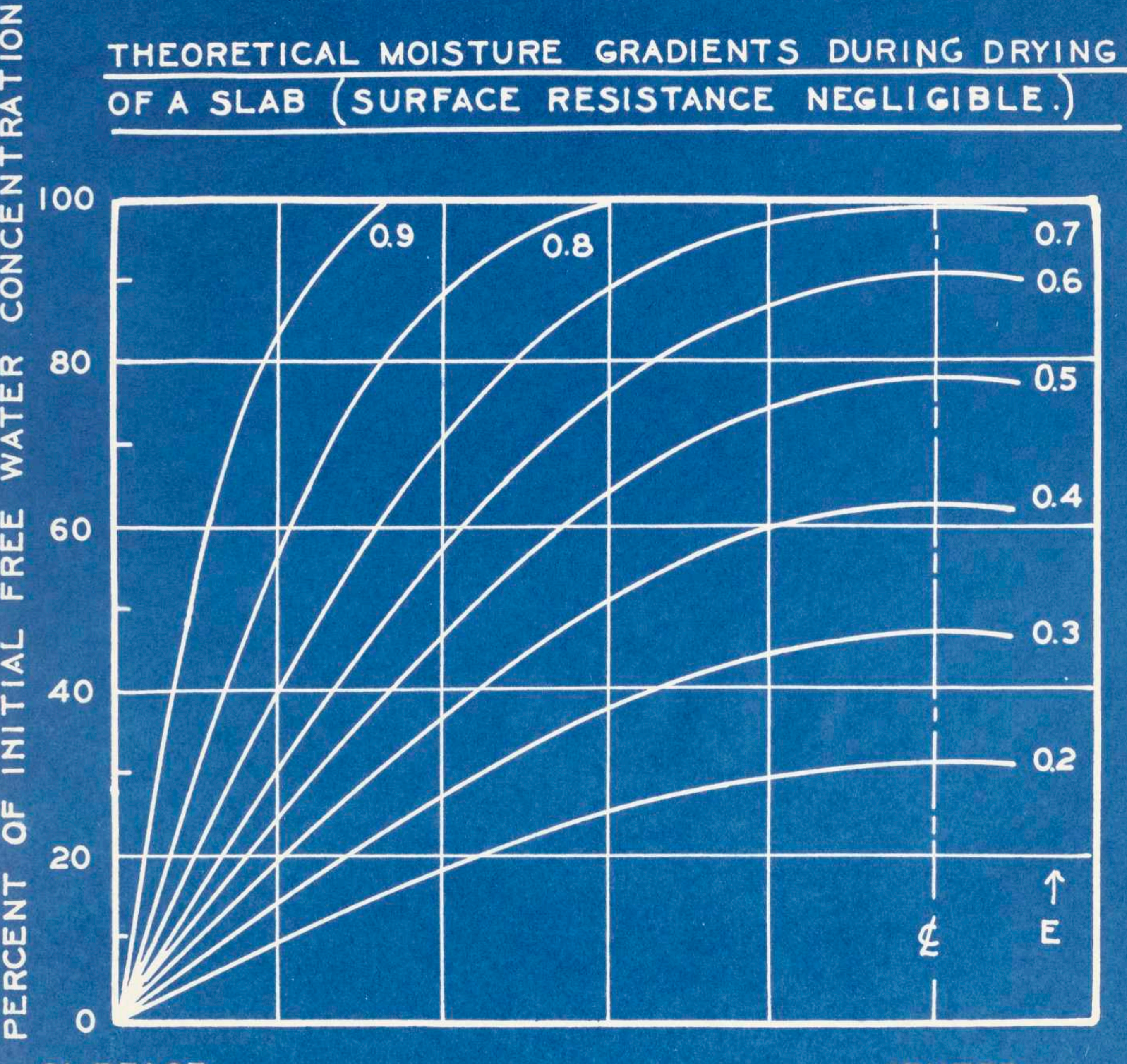
Δ represents the free liquid concentration at any point between the slab faces, as a fraction of the initial free liquid concentration, which is assumed to be uniform through the slab. The assumptions involved in the derivation of this equation are:

1. The validity of Newton's law of diffusion.
2. The constancy of the diffusion constant.
3. A uniform liquid concentration throughout the solid at the start.
4. That the diffusion is wholly normal to the surface plane.
5. That evaporation takes place at the surface and that the surface resistance to vapor

diffusion may be considered negligible, i.e., that the liquid concentration on the surface falls to zero immediately after the start of the drying.

Fig. I shows graphically the relations stated by equation (1). The per cent of the initial free water concentration, which is 100 times the variable Δ, is shown plotted against the location in the slab of the point considered. The various curves represent the relations at different stages in the drying process, as indicated by the values of E noted on the plot. E represents the ratio of the total free water content of the slab to the initial total free water content, and is, therefore, equal to the area under the moisture gradient curve at any time, divided by the area under the moisture distribution curve at the start of the drying. Since the first term of the series in equation (1) becomes large compared with the later terms when E is less than 0.7, the moisture gradients may be seen to be represented by sine curves on Fig. I for such values of E.

We have derived the theoretical equation for moisture distribution at any time in a slab where internal diffusion of liquid water is the process controlling the drying. Knowledge of the total free water left, or of the variable E, is, however, of greater practical interest. Equation (1) gives the



THEORETICAL MOISTURE GRADIENTS DURING DRYING OF A SLAB (SURFACE RESISTANCE NEGLIGIBLE.)

moisture gradient for any value of τ, and these might be plotted and the corresponding value of E determined by graphical integration. However, since

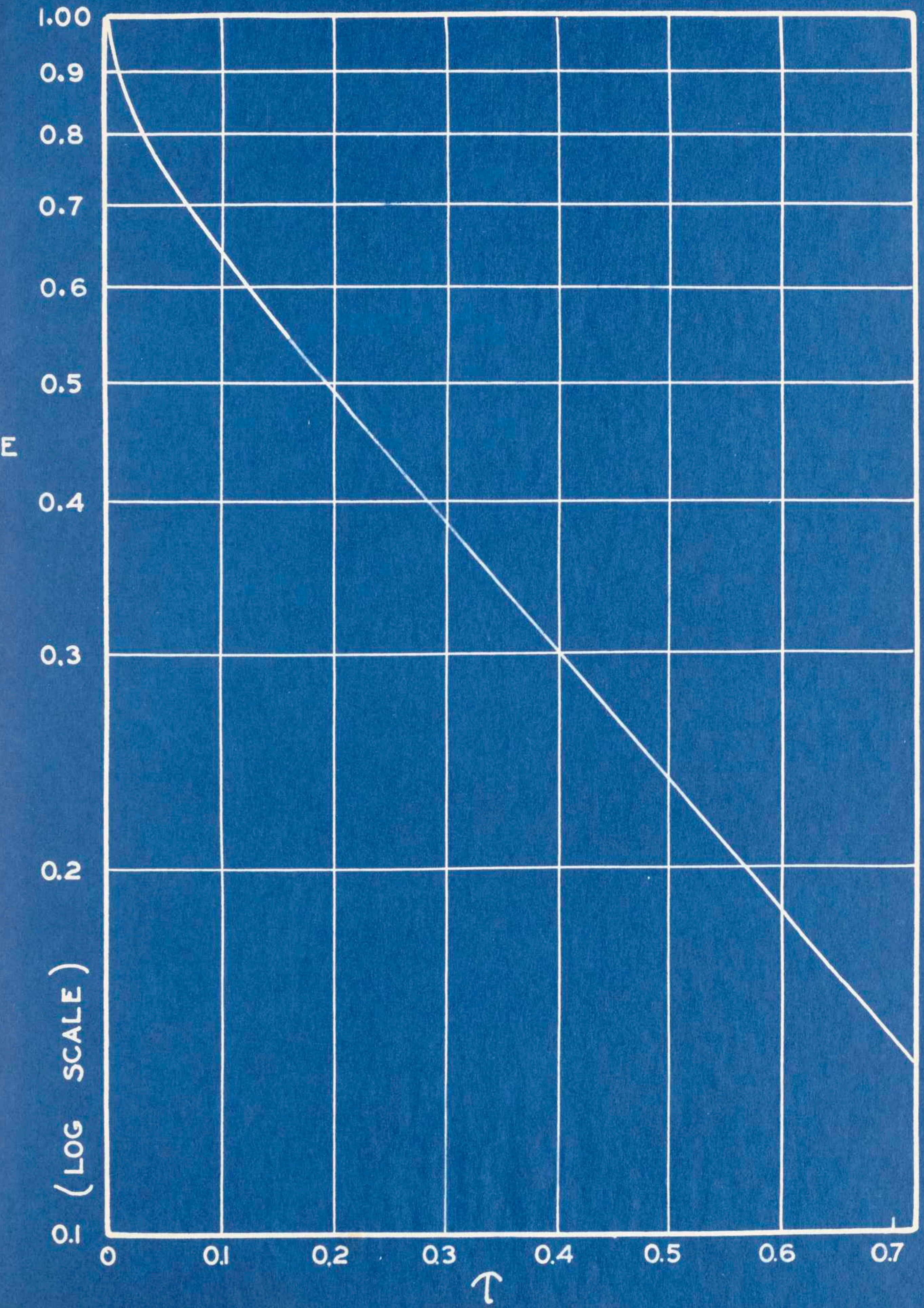
$$E = \frac{1}{1\times R}\int_{o}^{R} \Delta \, dx$$

$$\therefore E = \frac{4}{\pi R}\int_{o}^{R}\left[e^{-\left(\frac{\pi}{2}\right)^{2}\tau} \sin\frac{\pi x}{2R} + \frac{1}{3}\, e^{-9\left(\frac{\pi}{2}\right)^{2}\tau} \sin\frac{3\pi x}{2R} + \cdots\cdots\cdots \right] dx$$

$$E = \frac{8}{\pi^{2}}\left[e^{-\left(\frac{\pi}{2}\right)^{2}\tau} + \frac{1}{9}\, e^{-9\left(\frac{\pi}{2}\right)^{2}\tau} + \frac{1}{25}\, e^{-25\left(\frac{\pi}{2}\right)^{2}\tau} + \cdots\cdots\cdots \right] \qquad (2)$$

which is the theoretical drying equation when internal diffusion is controlling. From its derivation it is seen to be subject to the same limitations as equation (1).

Fig. 2 shows equation (2) plotted on semi-log paper, as E vs. τ. Since $\tau = \frac{K\theta}{R^{2}}$, equation (2) or Fig. 2 obviously represents the relation between E and θ for any given slab. We would expect that if the fundamental assumptions are valid, experimental data obtained under conditions where the surface resistance was negligible, would indicate a similar relation between E and θ.


1.00
0.9
0.8
0.7
0.6
0.5
E
0.4
0.3
0.2
(LOG SCALE)
0.1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
τ

W.K.Lewis[1], assuming a linear moisture gradient from surface to center line, derived an equation for the drying of a solid under conditions of negligible surface resistance, which may be written, using the symbols defined above:

$$\log E = - \frac{C_1 \theta}{R^2} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

where C_1 is a constant. If the relation between E and θ, as determined by this equation, were plotted on semi-log paper as in Fig. 2, a straight line would result, passing through $E = 1$ at $\theta = 0$. The theoretical relation is linear on Fig. 2 at low values of E, but curves sharply between $E = 0.7$ and $E = 1.0$. The linear portion, if continued, would cut the E axis at $E = 0.81$. Both the theoretical equation (2) and Lewis' equation (3) show the drying time to be directly proportional to the square of the slab thickness, R. The discrepancy between the shapes of the two curves at large values of E is probably mainly due to Lewis' assumed linear moisture gradient from surface to center line being impossible at values of E greater than 0.5, since the assumptions specify a free water concentration of zero at the surface.

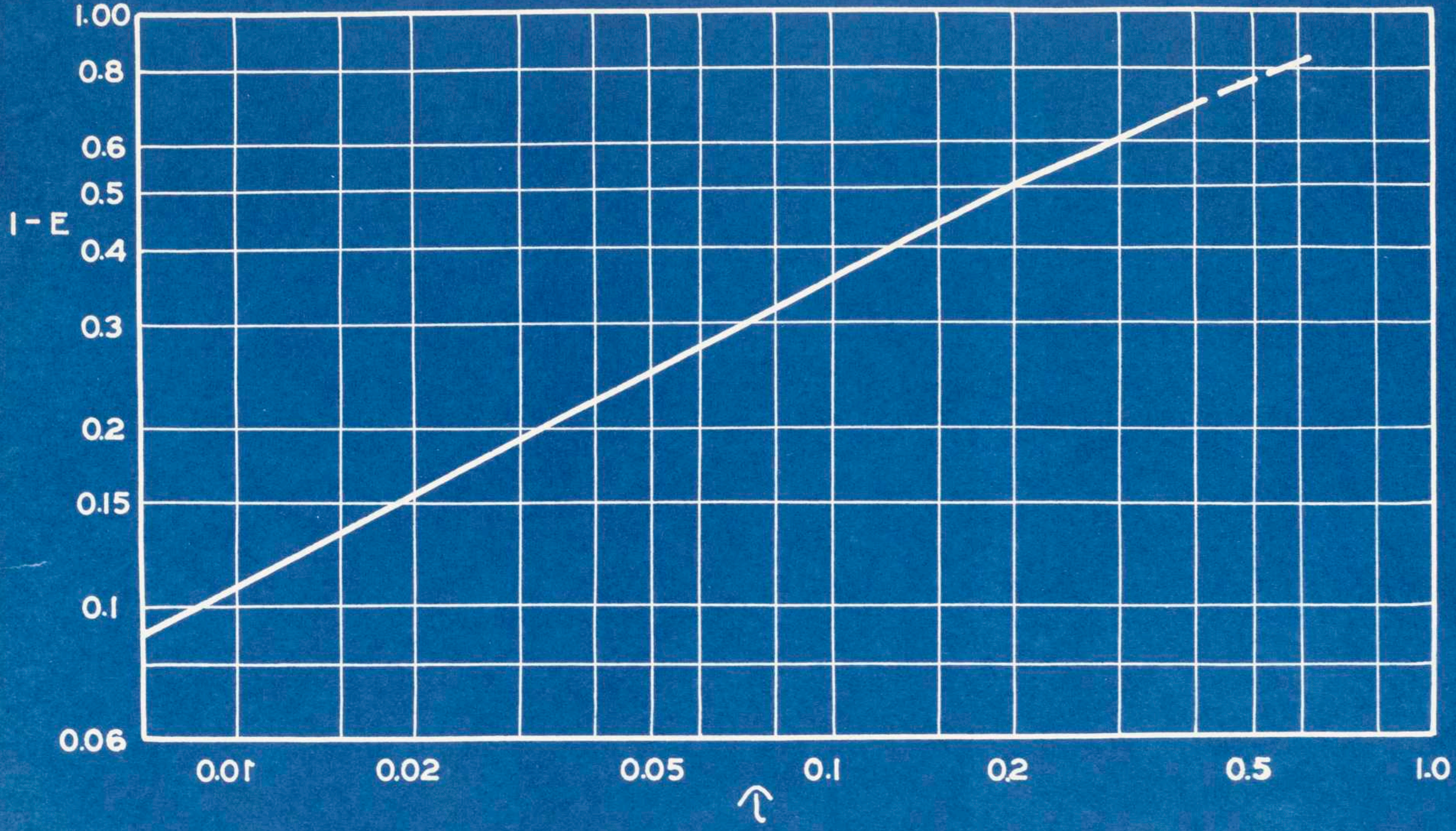
This limitation of Equation (3) was realized by Lewis, who derived another equation[2] for conditions of negligible surface resistance, which in the symbols defined above may be written

$$(T_o - T)^n = \frac{C\theta}{R^2}$$

or

$$(1-E)^n = \frac{c'\,\theta}{R^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3a)$$

where C and c' are constants, and n is a constant approximately equal to 2. The theoretical equation (2) may be compared with this equation by plotting 1-E as calculated from equation (2) vs τ, on logarithmic paper. This has been done ~~shown~~ as shown in Fig. 3, and it is seen that a linear relation results, as called for by equation (3a), over a wide range of values of E. Moreover, between E = 0.9 and E = about 0.4, the slope is very nearly 0.5, corresponding to a value of 2 for n in equation (3a). Lewis' equation (3a) is, therefore, seen to compare closely with equation (2) for the drying of a slab under conditions of negligible surface resistance, during the period in which the first 60% of the free water is being removed. Since E approaches zero as the drying proceeds, the curve on Fig. 3 must approach 1-E=1 as an asymptote at large values of τ. Equation (3a) is similarly limited to values of 1-E less than unity.


1.00
0.8
0.6
0.5
1 - E
0.4
0.3
0.2
0.15
0.1
0.06
0.01
0.02
0.05
0.1
0.2
0.5
1.0
τ

Theoretical Equation for Rate of Drying (Surface Resistance Negligible).

Since the rate of drying is often found to be a convenient basis for the analysis of experimental data on drying, the theoretical equation for the drying rate may be noted here. By differentiating equation (2) with respect to τ

$$\frac{dE}{d\tau} = -2\left[e^{-\left(\frac{\pi}{2}\right)^2 \tau} + e^{-9\left(\frac{\pi}{2}\right)^2 \tau} + e^{-25\left(\frac{\pi}{2}\right)^2 \tau} + \ldots\ldots\ldots \right] \qquad (4)$$

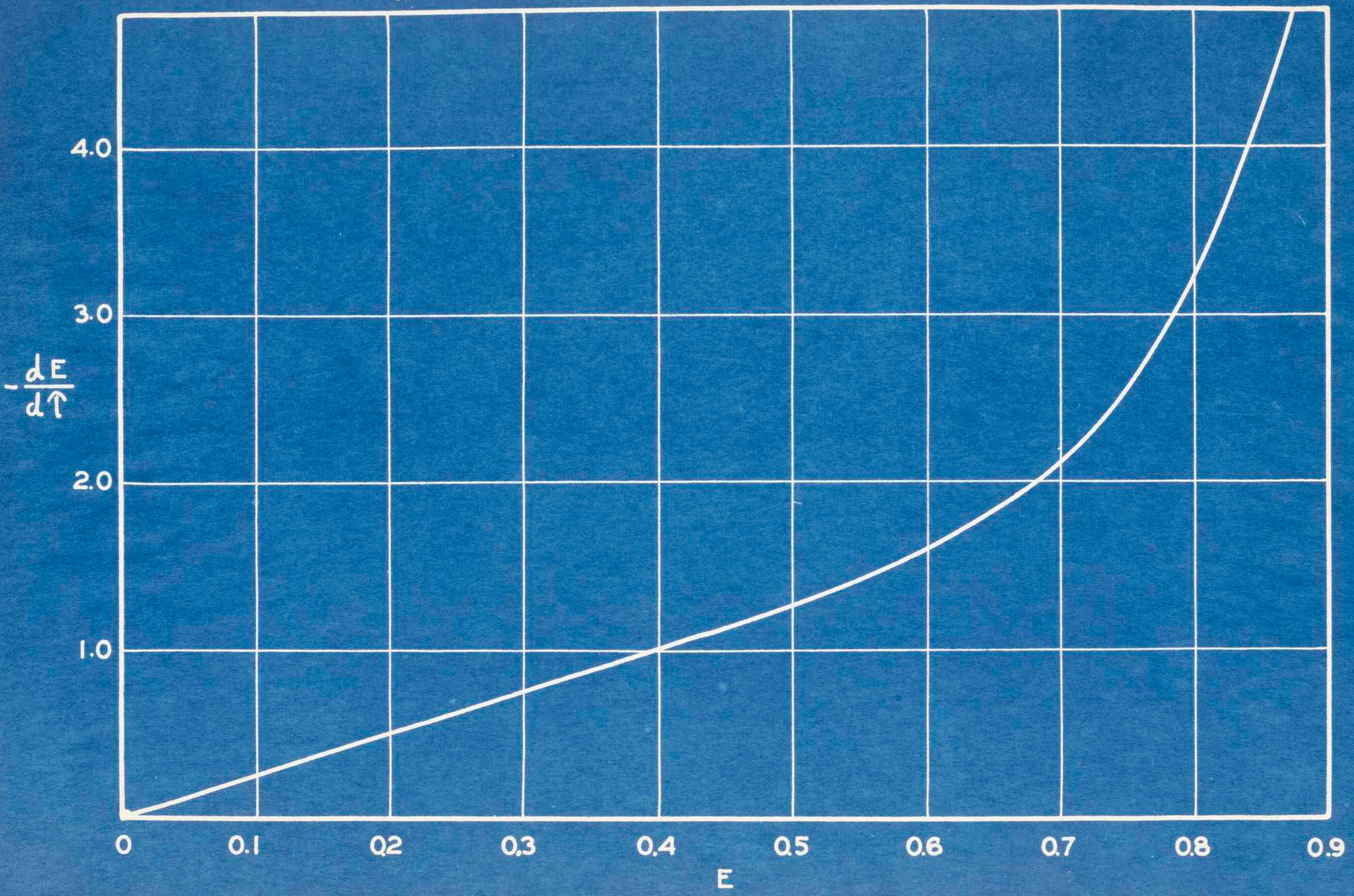
Equations (2) and (4) together give the relation between $\frac{dE}{d\tau}$ or $\frac{dE}{d\theta}$ and E, which when plotted as $\frac{dE}{d\tau}$ vs. E. (Fig. 4) gives practically a straight line up to E = 0.5, and at greater values of E curves up, convex to the E axis, going off asymptotic to the line E = 1.00.

Theoretical Equations for Internal Diffusion of Liquid Water, Surface Resistance Finite.

The moisture gradient equation (1) was derived in Appendix II using the conditions that the water concentration v was zero at x = 0 and at x = 2R, i.e., at the two surfaces. This amounts to the assumption of negligible surface resistance. It is possible to derive a corresponding equation, assuminga finite surface resistance, and a finite free water concentration on the surfaces. The conditions used in solving the fundamental differential equations are not

THEORETICAL RATE CURVE.

(SURFACE RESISTANCE NEGLIGIBLE.)



$v = 0$ at $x = 0$ and $x = 2R$

but $\frac{\partial v}{\partial \theta} = \pm hv$ at $x = 0$ and $x = 2R$

where h is a proportionality constant.

The solution is given by Carslaw[3] as

$$v = 2\sum_{n=1}^{n=\infty} e^{-kA_m^2\theta} \frac{A_n \operatorname{Cos} A_n x + h \sin A_n x}{(A_n^2 + h^2)2R + 2h}$$

$$\int_0^{2R} f(x)(A_n \operatorname{Cos} A_n x + h \sin A_n x)\, dx \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

where f (x) represents the moisture distribution across the slab at the start and A_n is the nth positive root of

$$\tan 2AR = \frac{2hA}{A^2 - h^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

The assumptions on which equation (5) is based are fewer than those used in the derivation of equation (1), and are:

1. The validity of Newton's law of diffusion.
2. The constancy of the diffusion constant.
3. That the diffusion is wholly normal to the surface plane.
4. That evaporation takes place at the surface and that the rate of change of water concentration on the surface with time is proportional to that surface concentration.

If $f(x) = 1$, i.e., the moisture concentration be assumed uniform at the start, then $v = \Delta$, and

$$\Delta = \sum_{n=o}^{n=\infty} e^{-kA_n^2\theta} \frac{A_n \cos A_n x + h \sin A_n x}{(A_n^2+h^2) R + h} \left[\sin 2A_nR - \frac{h}{A_n} (\cos 2 A_n R-1) \right] \tag{7}$$

and since $E = \frac{1}{2R} \int_0^{2R} \Delta \, dx$, E may be found from equation (7), by integrating the right hand side between the limits $x = 0$ and $x = 2R$. The result when simplified is

$$E = \frac{1}{2R} \left[Q_1 e^{-A_1^2 R^2 \tau} + Q_2 e^{-A_2^2 R^2 \tau} + Q_3 e^{-A_3^2 R^2 \tau} + \right] \quad \ldots\ldots\ldots\ldots (8)$$

where $Q_n = \frac{\left[\sin 2 A_n R - \frac{h}{A_n} (\cos 2 A_n R-1) \right]^2}{(A_n^2+h^2) R + h}$,

$$\tau = \frac{k\theta}{R^2}$$

and A_n is the nth positive root of equation (6). The use of equation (8) is restricted by the difficulty of the solution of equation (6), especially as a new solution is necessary in calculating each term of equation 8.*

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*At beginning of next page.

*Two simplifications of the calculations may be noted.

Equation (6) may be written

$$\frac{2}{\tan 2AR} = \frac{A^2}{hA} - \frac{h^2}{hA} = \frac{A}{h} - \frac{h}{A}$$

Let q = 2AR, then

$$\frac{2}{\tan q} = \frac{q}{2hR} - \frac{2hR}{q}$$

$$\cot q = \frac{q}{4hR} - \frac{hR}{q}$$

and if q is within 4° of $(n-1)\pi$, then $\cot q = \dfrac{1}{q-\pi(n-1)}$

$$\text{and } a_n = \frac{q_n}{2R} = \sqrt{\frac{h}{R} + h^2}$$

Also, since E=1, when $\tau = 0$, then from equation (8)

$$\sum_{n=0}^{n=\infty} (Q_1+Q_2+Q_3+ \ldots\ldots\ldots\ldots\ldots) = 2R$$

As h is made smaller and approaches zero, the surface resistance becomes controlling and the drying rate is specified by the assumption that $\frac{\partial v}{\partial \theta} = \pm hv$. Under such conditions, the moisture distribution through the slab would be nearly uniform and the average water content would be nearly equal to the surface water content. The assumption referred to could then be written,

$$\frac{d(T-T_E)}{d\theta} = C_1 \; (T-T_E)$$

whence $\log \frac{T-T_E}{T_0-T_E} = \log E = - C_2 \, \theta$

or $E = e^{-C_2\theta}$ ....(9)

for any given slab, where the dry density is constant,

Thus, when small values of h are substituted in equation (8) the result should approach the form of equation (9), and when large values of h are used, the result should approach the form of equation (2). In order to check the derivation of the general equation (8) various values of h were substituted, with the following results.

Equations Resulting from Substituting of Various Values of h in Equation (8) for Slab of Thickness π .

h	Equation
0.0000318	$E = e^{-0.000050\tau}$
0.000318	$E = e^{-0.00050\tau}$
0.00318	$E = e^{-0.0050\tau}$
0.0318	$E = 0.997 \, e^{-0.0467\tau} + \ldots\ldots$
0.318	$E = 0.98 \, e^{-0.425\tau} + \ldots\ldots$
3.18	$E = 0.916 \, e^{-1.72\tau} + 0.038 \, e^{-16.3\tau} + 0.027 e^{-30.2\tau}$

$$+ 0.013\,e^{-47.8\tau} + \ldots\ldots$$

31.8 $$E = 0.827e^{-2.37\tau} + 0.0885e^{-21.25\tau} + 0.0295e^{-59.1\tau}$$

$$+ 0.0134e^{-116\tau} + \ldots\ldots\ldots$$

318 $$E = 0.814e^{-2.46\tau} + 0.0904e^{-22.0\tau} + 0.0321e^{-61.3\tau}$$

$$+ 0.0165e^{-120.1\tau} + \ldots\ldots\ldots\ldots$$

Equation (2) may be written

$$E = 0.810e^{-2.47\tau} + 0.09e^{-22.2\tau} + 0.0324e^{-61.8\tau}$$

$$+ 0.0165e^{-120.9\tau} + \ldots\ldots\ldots\ldots$$

and in this form is seen to check nearly exactly the last equation in the above table. The first equations in the table for low values of h, check the form of equation (9). Thus, the general equation is seen to agree well with the special forms derived independently for the two extreme vakues of h, and the comparison serves as a check of the derivation of all three equations.

C. - The Evaporation of a Liquid from a Liquid Surface.

Case II of the general classification of drying mechanisms is that of the evaporation of the liquid from the solid surface, the assumption being made that the resistance to diffusion of the liquid to the surface is negligible. Except from complications introduced by the presence of the solid, the drying process under such conditions may be expected to be governed by the principles involved in the evaporation of a liquid from a liquid surface.

The phenomenon of the evaporation from a liquid surface of a liquid into a gas has been dealt with in many publications[4,5,2]. A relatively stagnant gas layer is recognized to be present at the liquid-gas interface, and the rate of diffusion of vapor through this film is governed by the effective gas film thickness and the driving force causing diffusion. The latter is equal to the difference between the partial vapor pressure at the liquid surface and the partial vapor pressure of the vapor in the main body of the gas. The diffusion equation applying may be written

$$\frac{dw}{d\theta} = K_s A \, (p_s - p_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)^{*}$$

where $\frac{dw}{d\theta}$ = rate of diffusion of vapor, weight per unit time.

A = effective surface area,

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*see page .

p_s = partial vapor pressure of vapor over liquid

p_a = partial vapor pressure of vapor in the main body of the gas

$(p_s - p_a) = \Delta p$ = driving force,

K_s = surface coefficient of vapor diffusion.

Although this vapor diffusion equation is simple in form, its use in connection with the drying of solids is complicated by the uncertainty of the terms. The constant K_s will depend on the direction and velocity of the air currents past the surface, as well as the temperature and other conditions; the effective surface area A in the case of a solid with a rough surface may vary in some unknown way with the water content of the solid; and p_s will depend on the liquid and on the temperature of the liquid at the solid surface.

In the adiabatic evaporation of a liquid from a liquid surface, the latent heat of evaporation must be supplied by conduction through the gas film from the main body of the gas. A high liquid temperature corresponds to high values of the vapor pressure p_s, the driving force Δp, and the rate of vaporization. As long as the liquid temperature is below that of the gas, heat will flow from the gas to the liquid, but if this heat inflow is not equal to the necessary heat of vaporization, heat will be extracted from the liquid which will consequently be cooled. The values of p_s, Δp, and the rate of vaporization are reduced, increasing the temperature difference between gas and liquid until the heat inflow from the gas is equal to the required latent heat of evaporation. A condition of dynamic equilibrium is thus reached, and the end point temperature of adiabatic evaporation of the liquid is the so-called wet-bulb temperature.

When a liquid is evaporating adiabatically under equilibrium conditions, it is at the wet bulb temperature and the rate of evaporation, which remains constant, as given by the equation (10) as

$$\frac{dw}{d\theta} = K_s A\ (p_w - p_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

where

$\frac{dw}{d\theta}$ = rate of evaporation

A = effective surface area

p_w = partial vapor pressure over the liquid at the wet-bulb temperature.

p_a = partial vapor pressure of the liquid in the main body of the gas.

If r_w represents the latent heat of vaporization of the liquid at the wet-bulb temperature, then this rate of vaporization may also be expressed as

$$\frac{dw}{d\theta} = \frac{1}{r_w}\,\frac{dQ}{d\theta} = \frac{1}{r_w}\,h_c A\ (t_a - t_w) \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

where

$\frac{dQ}{d\theta}$ = rate of heat flow, gas to liquid

h_c = surface coefficient of heat transfer, gas to liquid

t_w = wet-bulb temperature

t_a = gas temperature

From (11) and (12) above, it follows that

$$(p_w - p_a) = \frac{h_c}{K_s r_w} (t_a - t_w) \text{ ....}(13)$$

which equation assumes that the gas is maintained at a substantially constant temperature t_a, even though heat is flowing from gas to liquid. Outside influences on the gas film conditions, such as the effect of forced gas convection on the film thickness may be expected to influence h_c and K_s to the same extent. The ratio of h_c to K_s will, therefore, be constant, and since r_w is nearly constant over ordinary temperature ranges, we may write as a close approximation:

$$(p_w - p_a) = (\text{constant}) (t_a - t_w) \text{ ....}(14)$$

Since p_w is a function of t_w, this is equivalent to stating that for given values of t_a and p_a, t_w is constant, i.e., that the wet-bulb temperature is independent of gas film conditions.

The conclusion that the wet-bulb temperature is independent of gas film conditions is based on the assumption that h_c is proportional to K_s, and also on the assumption that all of the heat transferred is conducted through the gas film. In cases where the water receives heat by radiation from the surroundings, or by conduction through a solid, the latter assumption does not hold, and the equilibrium temperature of the water is higher than the true wet bulb. Thus, in measuring the wet bulb temperature by means of a wetted wick around a thermometer bulb, an appreciable fraction of the total heat flow to the wick may be by radiation from the warmer surroundings. By blowing air rapidly past the wick the total heat interchange may be greatly increased by increasing that fraction transferred by conduction through the gas film, and the heat flow by radiation, which is not changed appreciably, becomes a negligible fraction of the total. The wick then cools to the true wet-bulb temperature.

The rate of evaporation of a liquid into a gas, under adiabatic conditions, is seen from (12) to be proportional to the wet-bulb depression (t_a-t_w). The same relation follows from the vapor diffusion equation (11) and equation (14).

Expressing the rate of evaporation by (12) is equivalent to considering the problem as one of heat transfer, the temperature difference or driving force being equal to the wet-bulb depression. This is a convenient point of view when the evaporation process considered is adiabatic and the liquid temperature constant. The vapor diffusion point of view is perhaps simpler to follow when the process considered is the more complicated case of the drying of a solid under conditions where the liquid temperature no longer remains constant.

Since the rate of evaporation into a gas, of a liquid from a liquid surface is governed by the rate of diffusion of vapor and heat through a surface film of gas, variables affecting the effective thickness of the gas film are primary factors influencing the rate of evaporation. The direction and velocity of gas flowing past the surface are probably the most important factors, although the gas temperature, pressure, and the shape of the surface are other factors known to influence the effective gas film thickness. Data on the effect of air velocity on the rate of evaporation of water into air has been obtained by Carrier[6], Hinchley and Himus[7], and Coffey and Horne[8], which will be compared in a later section with data obtained by the writer.

Evaporation of a Liquid from the Surface of a Solid.

In the foregoing section the vaporization of a liquid from a liquid surface has been discussed. That process is similar to the drying of a solid where the liquid content is so high that free liquid covers the solid surface, and the same equations may be expected to apply.

In many drying operations, part of the surface area of the solid is not wetted but is impervious to the liquid being vaporized. The total surface area of the solid may be divided into two fractions, the dry and the wetted areas. Although no liquid is evaporated at the dry areas heat may be absorbed by the solid at these areas, increasing the rate of evaporation from the wet areas. The equilibrium temperature of the wetted surface under such conditions may be shown to be higher than the wet bulb temperature of the air.

Let A represent the wetted area and A' the dry area. K_5 is the surface coefficient of vapor diffusion and h_c is the surface coefficient of heat transfer at the wetted surface as before. Let H represent the overall coefficient of heat flow from air to liquid surface via the dry area A'. The rate of evaporation is given by

$$\frac{dw}{d\theta} = K_s A\ (p_s - p_a) \ldots\ldots\ldots\ldots (11a)$$

where p_s is the partial pressure of vapor over the liquid at the wetted surface, and p_a the partial pressure of vapor in the gas. The total heat flow is the latent heat r_s times the rate of evaporation, whence

$$\begin{aligned} \frac{dw}{d\theta} &= \frac{1}{r_s}\left[HA'\ (t_a - t_s) + h_c A\ (t_a - t_s) \right] \\ &= \frac{(t_a - t_s)}{r_s}\left[H\ A' + h_c A \right] \ldots\ldots\ldots\ldots (15) \end{aligned}$$

and from (11a) above,

$$\begin{aligned} (t_a - t_s) &= \frac{K_s r_s\ A\ (p_s - p_a)}{(HA' + h_c\ A)} \\ &= \frac{K_s r_s\ (p_s - p_a)}{H \dfrac{A'}{A} + h_c} \ldots\ldots\ldots\ldots (16) \end{aligned}$$

From equation (13) the wet bulb depression is

$$(t_a - t_w) = \frac{K_s r_w}{h_c}\ (p_w - p_a) \ldots\ldots\ldots\ldots (13)$$

$$\text{Therefore, } \frac{(t_a - t_s)}{(p_s - p_a)} = \frac{h_c\ (t_a - t_w)}{\left(H \dfrac{A'}{A} + h_c\right)(p_w - p_a)} \ldots\ldots\ldots\ldots (17)$$

since r_s is practically equal to r_w.

Furthermore, fromm(17)

$$\frac{(p_s-p_a)}{(t_a-t_s)} > \frac{(p_w-p_a)}{(t_a-t_w)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

Since p_s increases with t_s and p_w with t_w therefore from (18) for any given values of p_a and t_a,

$$(p_s-p_a) > (p_w-p_a) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(18)$$

$$(t_a-t_s) < (t_a-t_w) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(19)$$

and $$t_s > t_w \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(20)$$

In other words, the equilibrium surface temperature t_s, under such conditions, is higher than the wet bulb temperature.

Furthermore, although the temperature difference (t_a-t_s) is less than the wet bulb depression, the rate of evaporation, which is proportional to p_s-p_a, is increased. From the heat transfer point of view, the heat inflow at the dry area more than offsets the decreased heat flow at the wetted surface caused by the decreased temperature difference.

An interesting conclusion from the above relations is that the total rate of drying of a wet solid is not decreased in proportion to the amount of surface covered with a layer impervious to the liquid.

For example, consider a very thin sheet of porous material wetted with water, the area of each surface being A. The material is to be considered to be so wet that the surface is covered with a layer of water, and when drying may be expected to assume the wet-bulb temperature of the air. Let the dry and wet-bulb temperatures of the air be 40.0° C. and 27.0° C. respectively, in which case $p_a = 20.6$ m.m. and $p_w =$ 26.6 m.m. Then the total rate of drying, weight of water per unit time, is given by

$$\frac{dw}{d\theta} = 2\ K_sA\ (26.6-20.6) = \frac{40-27}{r_w}\ (2h_cA)$$

Now let one face of the sheet be covered with a thin membrane impervious to water or water vapor, and which offers a negligible resistance to the flow of heat, i.e., assume $H = h_c$. Then the total rate of drying, weight of water per unit time, is given by

$$\frac{dw}{d\theta} = K_sA\ (p_s-20.6) = \frac{40-t_s}{r_s}\ (2h_cA).$$

Neglecting the difference between r_s and r_w, the ratio of the rate of loss of water in the first case to that in the second case is

$$\frac{\text{Rate (both faces wet)}}{\text{Rate (one face dry)}} = \frac{2(26.6-20.6)}{p_s - 20.6} = \frac{40-27}{40-t_s}$$

Since p_s is a function of t_s, the last part of the equation may be solved by the use of steam tables, whence $t_s = 29.4°$ C. and $p_s = 30.6$ m.m.

$$\therefore \frac{\text{Rate (both faces wet)}}{\text{Rate (one face dry)}} = \frac{2\,(26.6 - 20.6)}{30.6 - 20.6} = 1.2$$

Thus, the rate of loss of water has been decreased less than 20% although the wetted face area was decreased by 50%.

Other Influences of the Presence of a Solid on the Rate of Evaporation of a Liquid.

The influence of having part of the total solid surface dry or impervious to liquid or vapor has been discussed in detail. A special case of this phenomenon is found when the solid surface is so rough as to be jagged and points of relatively dry solid jut out through the liquid surface layer into the gas. Such roughness may not only decrease the wetted surface area but influence the surface coefficient of heat transfer h_c.

Solids influence the liquid vapor pressures in several ways and so cause the rate of vaporization to be different than in the case of a pure liquid. Solids soluble in the liquid lower the vapor pressure and decrease the rate of evaporation. Solids containing capillary pores conceivably increase the vapor pressure of the liquid, and this effect probably is the explanation of "Von Schroeder's paradox."[9] Von Schroeder found that gelatine absorbed 1000% water when immersed in liquid water but less than 400% when in saturated water vapor at the same temperature. Later experimenters considered von Schroeder's data worthless, although still later Washburn[10] found that moistened clay will dry fairly completely if suspended in a closed vessel above water.

Most solids absorb or adsorb water, the amount of water held depending on the humidity and to a certain extent on the temperature of the air in contact with the solid. This "equilibrium" or hygroscopic water content is zero when the air is dry, but ranges from practically zero in the case of such materials as glass to upwards of 25% for some textiles and leathers when the air is saturated with water vapor. Thus, the partial pressure of water over the solid varies from zero for the dry solid to the vapor pressure of water for the wet solid, providing this pressure is not lowered by solution of the solid. The partial pressure data are available in the form of humidity equilibrium relations. These data are of importance in connection with the rate of drying, since the partial pressure gradient is directly affected by a decrease in the partial pressure of water over the solid.

D. - Constant Rate and Falling Rate Periods

As long as the solid being dried is so wet that the surfaces are covered with a layer of the liquid, the conditions are not greatly different from the evaporation of a liquid from a liquid surface, with no solid present. The surface will cool to an equilibrium temperature, and if heat is supplied only by conduction through the gas film through which the vapor diffuses, this will be the wet-bulb temperature. As long as conditions remain unchanged the rate of drying is constant, and this part of the drying process is called the constant-rate period.

Much experimental data shows, however, that the rate of drying of a solid does not remain constant over the complete range of liquid concentrations, i.e, from the initial to the equilibrium liquid concentration. At some intermediate liquid concentration the drying rate falls off from the constant rate of the constant rate period, approaching zero as the equilibrium liquid concentration is approached. The liquid concentration at the end of the constant rate period is called the critical liquid concentration, and is designated by T_c. That part of the drying process coming after the critical liquid concentration is termed the falling rate period. If the liquid concentration is initially lower than the critical, no constant rate period will be exhibited, and the falling rate period will constitute the whole of the drying process. Some of the possible reasons for the rate falling off from the constant rate have been mentioned - these and others will be discussed in detail in a later section.

Evaporation of Liquid Mixtures.

Special processes, especially in the chemical industries, involve the drying of solids wetted with mixtures of two or more liquids, usually commercial solvents. In cases where the structure of the solid allows the rapid diffusion of the liquids through it, and evaporation takes place at the solid surface, the rate of vaporization will fall continually due to the increasing proportion of the less volatile liquid in the liquid mixture on the solid surface. Such a process is not dissimilar to batch distillation and it is probable that relations worked out for the latter case might be applied to such a complicated drying process.

EFFECT OF PRESSURE OF INERT, VACUUM DRYING

The work of K.C.Chang[28] has brought out the fact that the rate of vaporization and diffusion through a surface gas film is a function not only of p_a and p_s, but of the partial pressure of the inert gas present. When the partial pressure of the diffusing vapor is small compared to the pressure of the inert gas, Chang's fundamental differential equation may be integrated to give essentially the form of equation (10). However, for the case of vacuum drying, or when the solid temperature approaches the boiling point, equation (10) does not hold and the equations developed by Chang should be used in applying data obtained at one pressure to the case of drying at another pressure.

E - Vaporization of the Liquid in the Interior of the Solid.

Cases III and IV of the general classification of drying mechanisms involved the vaporization of the liquid at some point in the interior of the solid, followed by diffusion of vapor through the porous solid to the solid surface with subsequent diffusion of the vapor through the surface gas film into the main body of the gas.

It some ways this process is similar to the evaporation of water from a pan filled level with marbles. As long as the marbles are completely covered, evaporation will proceed at a constant rate. When the level has receded so that dry surface of the marbles protrude above the surface, the overall rate of loss of water will decrease. Similarly, a porous material so wet that the surface is completely covered with liquid will dry at a constant rate. If the liquid level recedes into the pores of the solid, and evaporation occurs in the interior of the pores, the drying rate will fall off not only due to the decreased area for surface evaporation, but also due to the added resistance to vapor diffusion offered by the pores.

An important characteristic of this process is the decrease in the overall coefficient of heat transfer from the air to the point where the evaporation is taking place. The heat necessary must flow, not only through the surface gas film, but through the surface layer of solid through which the vapor diffuses. The decrease of the overall coefficient of heat transfer is an important criterion of the occurrence of this mechanism of drying. Furthermore, the start of the decrease in H should coincide with the critical liquid concentration.

The overall resistance to heat flow during the constant rate period is equal to the surface gas film resistance. As the critical moisture is reached and passed, and the heat must penetrate greater and greater distances into the solid, the surface resistance to heat flow becomes a smaller and smaller fraction of the overall thermal resistance. Factors affecting the surface resistance have a corresponding decreasing effect on the overall resistance. For example, the gas velocity past the solid surface has a marked effect on the surface coefficient h_c. However, in cases where the evaporation and consequent heat consumption is an appreciable distance in from the surface of the solid, the surface resistance $1/h_c$ may be a small fraction of the total resistance $1/H$. Since it is only this surface resistance which is affected by the gas velocity, the overall resistance and consequently the rate of drying under such conditions may be expected to be only slightly influenced by the gas velocity. This is of importance in practical drying problems, since it is obvious that where this mechanism of internal evaporation occurs, it is of little use to increase the gas velocity in order to speed up the rate of drying, during the falling rate period. When it is found that the rate of drying of a particular solid during the falling rate period is practically independent of the gas velocity past the surface, the surface gas film resistance to heat transfer or vapor diffusion may be concluded to be negligible. This is possible if the evaporation is taking place in the interior of the solid or if the evaporation takes place at the surface and the internal diffusion of water is very slow and controlling. However, if the solid is so obviously porous as to make the latter mechanism improbable, the finding that the rate of drying is independent of the gas velocity is a good indication.that evaporation is taking place in the interior of the solid.

In the case of the evaporation of water from the interior of the pile of marbles described above, all of the evaporation takes place from a plane and at the same distance from the top of the pile. In the case of the porous solid the pores may vary greatly in size, and evaporation may take place in a large pore at a considerable distance from the surface simultaneously with the evaporation in a small pore at a point relatively near the surface. The evaporation, therefore, is not from a plane parallel to the surface, but from a zone of width depending on the structure of the solid.

PART II

METHOD OF PROCEDURE

A - Construction of Tunnel Drier

Most of the drying experiments made were carried out in a tunnel drier of wood and beaver board construction, through which heated air was recirculated by means of a Sturtevant Monogram blower. The drier, shown in Fig. 5, consisted of a rectangular tunnel 1.23 m. long having an interior cross-section 46x46 cm. The ends were fitted with rectangular galvanized iron funnels tapered to fit 9 cm. galvanized iron pipes through which the air was recirculated. In this return line and directly over the drier was a 5.09 cm. standard thin-plate orifice by which the amount of air recirculated could be measured. However, this orifice was seldom used as its purpose was to determine the air velocity in the drier, and it was found by use of an anemometer that the air velocity varied considerably at different points across the cross section of the drier. The blower was placed in the air return line just before the galvanized iron funnel through which the air entered the drier. In the air return flue and between the orifice meter and the blower was an electric heater, attached parallel to the length of the flue. At the end of the drier where the air left was another electric heater consisting of a zig-zag spacing of michrome wire stretched on

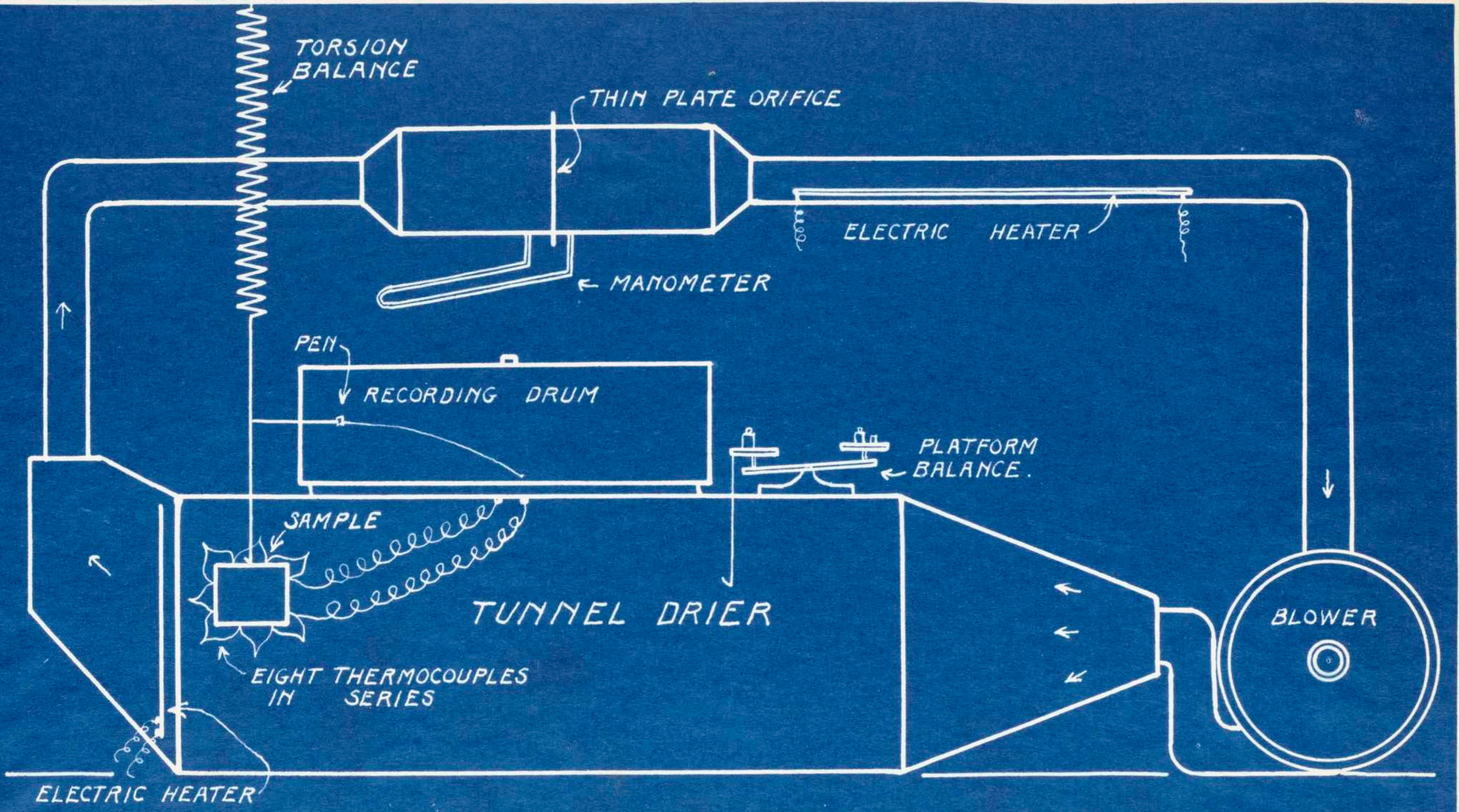


DIAGRAM OF TUNNEL DRIER.

a wood frame and placed at right angles to the direction of air flow at the point where the air entered the exit galvanized iron funnel. When both electric heaters were used it was possible to heat the air in the drier 15-20° C. above that of the air in the room. The system was by no means air tight, in fact there were numerous small openings through which air entered and left, and as the volume of air in the system was considerable, the vapor removed from the small samples dried had a negligible effect on the humidity of the air in the system. No means was provided in this drier to maintain temperature or humidity constant, although in most cases these were measured frequently throughout the period of the experiment. The air temperature and humidity, therefore, paralleled those of the air in the room although due to being heated, the air in the drier had a low relative humidity.

The weights of the sample being dried were measured either by a laboratory platform balance or by a recording torsion balance, in neither case being removed from the drier. An ordinary platform balance reading to 0.1 gm. was fastened on top and outside of the drier. A slot having several branches was cut in the paperboard roof of the drier, making it possible to guide the wire hook on which the sample was suspended, along the slot to a point under the balance, where the weighing was performed. The sample was then returned to its original position, it being possible to dry several samples simultaneously using this method. The drying was not interfered with while the sample was being weighed, since the drier was not opened, and the sample was not removed. Records were kept of the weights and time of weighings.

For several reasons it was found preferable to have a continuous record of the weight of the sample for the duration of the drying, and to obtain this a recording torsion balance was constructed. The spring was of steel piano wire wound on a lathe to about a 5 cm. coil. This coil was hung vertically and could be raised or lowered by a windlass and a cord over a pulley attached to the ceiling directly over the drier. From the lower end of the helical spring was hung a vertical straight iron wire passing through a screw eye guide and a small hole in the top of the drier. The sample being dried was suspended at the lower end of this wire. The weight record was made by a pen attached to this vertical iron wire at a point above and outside the drier. The paper on which the record was made was attached to a slowly rotating vertical drum, the support of which rested on the top of the drier. This drum was constructed of galvanized iron, and was 68 cm. in diameter with vertical sides 19-20 cm. high. On the under side of the upper enclosed face was fastened a circular iron track resting on three casters approximately equally spaced around the perimeter of the track. The horizontal top of the drum rested not only on the casters but on a wheel attached to the vertical steel drive shaft which in turn was supported on a ball thrust bearing. Most of the weight of the drum was born by this shaft and thrust bearing, the track and casters serving mainly to keep the perimeter of the drum horizontal. By the use of a series of reducing gears a small synchronous motor of the type used in electric clocks was made to drive the drum at a uniform speed. The speed of the drum was one revolution in 41.7 hours, or approximately 5 cm. per hour at the perimeter. Strong wire clips held the paper in position on the vertical face at the perimeter of the drum.

The spring was of such a length that the available height of the paper on the drum could record a change in weight of about 50-60 grams.

Before each experiment the balance was calibrated over the weight range expected. Weights approximating that of the sample were hung on the balance, and marks made on the drum every 10 gms. over a range of 50 gms. By releasing and turning the drum, a series of lines were drawn by a pencil held stationary at the level of each mark. The paper then had on it lines representing weights at 10 gm. intervals. The total weight was usually obtained at the end of the experiment by means of the laboratory platform balance, and the record used to determine change in weight. Since the horizontal lines representing weights differing by 10 gms. were always very nearly 3.2 cm. apart, each gram was represented by a vertical distance on the chart of 3.2 m.m., and the accuracy of the record was probably to within considerably better than 0.5 gm. The continuous record offered an especially convenient means of measuring the rate of drying, since the tangents to the recorded curves could be measured with relatively high accuracy.

The sample was hung so that the drying faces were parallel to the direction of air flow, and remained so except for some side to side turning of large light samples. The helical spring was twisted slightly to hold the pen in contact with the paper on the drum and this prevented turning of the wire on which the sample was hung. Whenever the recording balance was used the sample was hung in the same position in the drier, except for movement upwards as drying proceeded. The direction and velocity of the air in these runs was, therefore, always the same. The air velocity at this point was too low to measure accurately, but was 0.5-1.0 m. per second.

The air temperatures, dry and wet bulb, were measured by either glass thermometers or thermocouples. When thermocouples were used a single copper-Ideal couple was used to measure the dry bulb temperature, and a pile of eight couples in series used to meadure the wet bulb depression. For the latter purpose alternate 10 cm. lengths of 22 gauge copper and Ideal wire were twisted and soldered at the ends with fine spaghetti rubber tubing as insulation between joints. The wires were bound together, lying parallel to each other, with eight junctions, at each end of the bundle. A cloth wick was fastened around one set of junctions, and fed by water in a small bottle kept full by a siphon from a small constant level tank outside the drier.

The junctions under the wick were the cold junctions; the others exposed to the air in the drier were the hot junction. The bundle was calibrated by immersing the cold junctions in water at various temperatures, while the hot junctions were exposed to the air of the room, the temperature of both water and air being measured by glass thermometers reading to 0.1° C.

The dry and wet bulb temperatures of the air when measured by thermocouples were always recorded by a Brown recording pyrometer kindly loaned by the Hood Rubber Co. This instrument was capable of recording the temperatures of six separate thermocouples, and in this work usually recorded the temperatures at three points: the dry and wet bulb air temperatures and the temperature of the surface of the solid. A thermopile was used to measure the latter temperature, alternate junctions of 22 gauge wire being inserted in the sample near the surface, and alternate junctions allowed to protrude into the air, so that the measurement was actually of the temperature difference between air and solid. This pile was calibrated similarly to that used for the measurement of the wet bulb depression, and the leads were of lightly coiled fine wire so as not to influence the recorded weight of the sample as it rose as drying proceeded. When glass thermometers were used for the wet and dry bulb temperatures of the air, a Leeds and Northrup potentiometer indicator was used in connection with this thermopile measuring the temperature of the sample.

With the helical spring used throughout, the deflection corresponding to the width of paper on the drum was caused by a change in weight of 50-60 gms. In cases where the sample contained more than that weight of free liquid, it was necessary to readjust the position of the spring at some time during the run. The height of the spring was adjustable by means of the windlass on which was wound the cord from which the spring was suspended. This also adjusted the vertical position of the pen on the record. At the start of the run the windlass was adjusted so the pen was near the bottom of the paper and left there during the first part of the run. As the drying proceeded the pen rose and when at the top of the paper was replaced at the bottom by readjustment of the windlass. This procedure was repeated as often as necessary during the run.

B.- Preparation of Samples

Whiting

The whiting used was fine calcium carbonate prepared for use as a pigment in rubber compounding. This was mixed with water or other liquid in a mortar, forming a paste firm enough to hold its shape. Poplar wood frames were made square and of the thickness desired of the sample. The wood was shellaced and rubbed on the inside with hot paraffin to prevent the absorption of liquid. At intervals around the two sides and top of the wood frame small holes were bored through which were inserted the cold junctions of the eight-junction pile used to measure the temperature of the sample. These junctions protruded 2-3 cm. into the interior of the wood frame and the hot junctions 6-7 cm. out into the surrounding air. When the whiting paste was well kneaded it was pressed into the frame and both open faces leveled off. Care was taken to have four couples near each face and all couples as nearly as possible 2-4 m.m. from the surface. This forming in the frame was done quickly and the sample then hung in the drier to start the experiment.

When dry the dry weight and tare were obtained by weighing on the platform balance. Later, samples were formed in a frame lined with tin foil without thermocouples, and the frame removed before the start of the run, leaving a whiting block with edges covered with tin foil.

Pulp

The pulp used was viscose pulp lap obtained from the Eastern Manufacturing Co. Some samples dried were cut from the sheets as received. In other cases the pulp was digested and pressed into blocks. The sheets werevtorn into small pieces and digested in steam and hot water, forming a fairly fine and homogeneous suspension of the fibres. This material was screened and pressed by hand into thick sheets. In the "pressed pulp" samples these were pressed mechanically between heavy brass plates, using a pressure of about 24 kg. per sq.cm. The "hand pressed" samples were pressed by hand rather than mechanically. No wood frames were used with these pulp samples. Small holes were drilled around the edges of the thick samples, and the cold junctions of the thermopile inserted 2-3 cm., the hot junctions protruding into the air. The edges were covered with paraffin or collodion to prevent loss of water and secure the thermocouples. In the pulp samples the thermocouples were inserted at the center line of the slabs. The sample was soaked under water an hour or more, the excess surface water shaken off, and the sample hung in the drier.

Clay

The clay used was ordinary brick clay as used in making cheap building brick, and obtained in the form of green bricks from a Cambridge brick yard. The well-kneaded clay was in general formed in wood frames with thermocouples inserted, being handled in the same manner as the whiting paste. In later runs the thermocouples were omitted and the wood frames, lined with tin foil, were removed as soon as the sample was shaped. The tin foil stuck to the edges of the clay block, preventing evaporation from these surfaces and at the same time offering a constant resistance to heat flow from the air into the clay through these edges.

Wood

Poplar or "white" wood was dried in slabs, the grain being parallel to the faces so that drying occurred at right angles to the direction of the grain. The edges of the slabs were covered with M.J.B. (a nitrocellulose) cement, and hung in the drier by screw eyes inserted in the samples. In order to wet the wood, the samples were soaked under water at room temperature for various periods ranging from a week to four months. It was not attempted to obtain the temperatures of these wood samples during drying.

Soap

Several cakes of "Babbitt's Best Borax" laundry soap were cut into small pieces and the whole well mixed and put through an ordinary kitchen meat grinder. The mass was then sprinkled with water, kneaded, and again put through the meat grinder. After further kneading it was firmly pressed into wood frames without thermocouples, and dried in the frames.

Starch

"Argo" laundry starch was mixed with water to form a thick paste, which was pressed into wood frames in a manner similar to the whiting water paste.

Nitro-Cellulose

The nitro-cellulose used was obtained from Picatinny Arsenal by Prof. C.S.Robinson. It was of wax-like consistency and when chilled was pressed into brass rings cut from brass tubing. The solvent contained was said to be one third ether and two thirds alcohol.

C.- Moisture Gradient Determinations

Moisture gradients were determined at various stages in the drying process for soap, whiting and pressed pulp.

The same soap block , 2.54 cm. thick was used for gradient measurements at different times during the drying process. A square chunk about 3.3 x 3.3 cm. was cut from the face of the soap slab being dried, and the edges of the square hole so formed immediately lined with tin foil to prevent drying from these surfaces. The chunk cut was placed in a square welded steel frame into which it just fitted. Square pieces of iron 3.3 cm. x 3.3 xm. x 1.9 m.m. were placed in this steel frame under the soap chunk one at a time, thus raising the upper face of the soap by increments of approximately 1.9 m.m. above the upper face of the steel frame. Each time the soap was raised in this way the soap protruding above the upper face of the steel frame was sliced off with a sharp knife. In this way the whole chunk was sliced parallel to the drying faces into thin slices approximately equal in thicknesses. As each one was sliced it was weighed quickly on a weighed watch glass and placed in the heated drier. The soap chunks were sliced into 13 slices, the first and 13th being the face slices. After coming to constant weight the slices on the watch glasses were again weighed, and the original water content of each slice calculated.

The moisture gradients in whiting were determined in a similar manner except the chunks cut for slicing were each taken from a separate whiting block in a wood frame. Moreover, these frames were 3.18 cm. thick so that instead of cutting 13 slices from face to face of each block, only nine slices were cut, from the surface in to a point a little beyond the center line of the slab.

In the case of the pressed pulp the chunks to be sliced were prepared before the start of the drying, due to the difficulty of cutting such samples from a large slab during drying. The small blocks, all cut from the same slab of pressed pulp, were coated on the four edges and one face with M.J.B. cement. They were then soaked under water and all put in the drier at the same time. After different periods of time, they were removed and sliced in the steel frame parallel to the drying face as in the case of the soap or whiting.

D.- Experiments on the Effect of Air Velocity

A series of experiments was carried out to determine the effect of varying air velocity past the surface of wet pulp (Runs V-1 to V-19). These were carried out in a horizontal 11 cm. i.d. galvanized iron pipe through which air was forced by a blower driven by an electric motor. A rheostat in the power line to the motor afforded a means of varying the blower speed and the air velocity. A small block of pulp with the edges covered with M.J.B. cement was placed upright in the flue 10-15 cm. from the exit end. The pulp block was first soaked under water, the excess water on the surface removed by shaking, and the sample dried 10-15 minutes before the weight readings were started. This was done to eliminate the possibility of loss of water by dripping during the run. Every fifteen minutes the sample was removed and weighed quickly on a laboratory balance reading to 0.01 gm. Air velocity was measured by an anemometer placed directly at the end of the flue, and in a position corresponding to that occupied by the sample. The wet and dry bulb temperatures of the air were measured by thermometers placed in the air blast at the exit end of the flue. The run was not continued until the sample was dry, but only until the water content had fallen somewhat below 100%, dry basis. No measurements were made of the temperature of the sample.

E.- Equilibrium Moisture Relations

Considerable data was obtained on equilibrium moisture relations of several materials using the method described by Wilson and Fuwa.[11] Air from the laboratory compressed air line was bubbled through two bottles containing sulphuric acid solution, through a flask containing glass wool, and finally through a U-tube containing the sample. In passing through the two acid bottles the air humidity was adjusted to a value depending on the acid strength. The second bottle was packed with bits of broken glass, so that the air rising was broken up into a number of small bubbles, affording a large area of contact between acid and air. The flask containing glass wool was simply to remove any acid which might have been entrained in the air. The air conditioned in this way was passed over the sample in the U-tube until a constant weight was attained. This required from three days to two weeks, depending on the type and exposed area of the sample. The dry weight of the sample was obtained using dry air conditioned with concentrated acid. The humidity of the air used was found from the acid strength by reference to published humidity equilibrium data of sulphuric acid.[12] At the time of the final weighing of the sample, after a constant weight ~~rate~~ had been reached, the acid in the second acid bottle was titrated with standard sodium hydroxide solution. In order to speed up the determinations, five trains as described above were used, and the samples switched from one to the other, five different acid strengths being used. Equilibrium was approached from the wet side in some cases, and in others from the dry side, although it was difficult to do both for the same strength acid, as the acid strength changed slowly.

PART III

DISCUSSION OF RESULTS

Definite examples of the three general drying mechanisms described in the introduction will be discussed in detail. These are: internal diffusion controlling (Case I): surface evaporation controlling (Case II): and internal evaporation controlling (Case III or IV). They will be discussed in that order, the first being illustrated by data obtained on the drying of soap (Runs 6 - 10). The second case is illustrated by data obtained on the drying during the constant rate period of water from several solids, and of several liquids from whiting. The third case will be illustrated by data obtained on the drying of pulp during the falling rate period.

The drying of specific solids such as clay, wood, pulp, and whiting will be discussed in detail in later sections.

A - INTERNAL DIFFUSION CONTROLLING - SOAP

Soap is a well known example of that class of solids through which water diffuses so slowly that the rate of drying is in general limited by the rate of internal diffusion. The data of runs 6 - 10 was obtained over a period of five months on the drying of several thicknesses of soap slabs at 23 - 30°C. Five thicknesses were used, 0.63, 1.27, 1.90, 2.54, and 3.17 cm. respectively, although the 2.54 cm. slab was used to obtain moisture gradient data. The initial moisture content was 20.2% on the dry basis as determined by analysis of a sample of the batch of well-mixed wet soap from which all the slabs were formed. A certain amount of shrinkage took place, with consequent retreat of the slab edges from the wood frames. The total edge area amounted to from 8.9 to 44.6% of the area of the two faces, but as the bottom and at least one of the two sides were always in contact with the wood frame, the fresh area for drying exposed by shrinkage was at the most 4.5 to 22.3% of the face area. Moreover, since the space between the slab edge face and the wood frame was never more than about 3 mm., the difficulty of drying from these edge surfaces was large compared to that from the face areas past which air was flowing. The conditions therefore approximated the drying of infinite slabs.

The drying of solids under such conditions was discussed in the introduction and the following relation derived:

$$E = \frac{8}{\pi^2}\left[e^{-\left(\frac{\pi}{2}\right)^2\tau} + \frac{1}{9}\,e^{-9\left(\frac{\pi}{2}\right)^2\tau} + \frac{1}{25}\,e^{-25\left(\frac{\pi}{2}\right)^2\tau} + \dots\right] \qquad (2)$$

where

$E = \frac{T - T_E}{T_O - T_E}$ = ratio of free water to initial free water

$\tau = \frac{K\,\theta}{R^2}$

K = liquid diffusion constant

R = half slab thickness

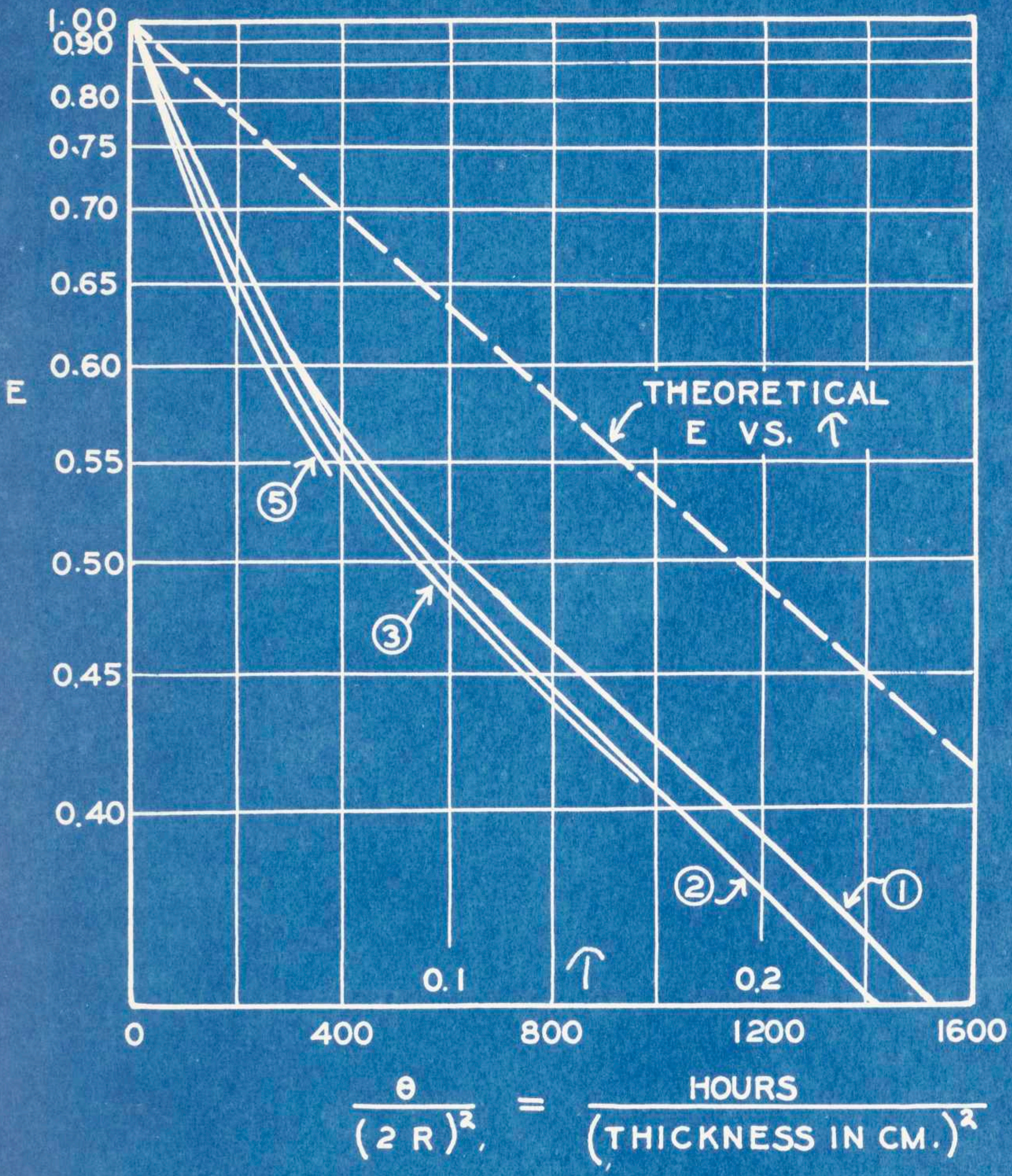
θ = time from start of drying

This relation between E and τ is shown plotted on semi-log paper in Fig. 2. In order to compare experimental data with this equation, various values of K may be assumed and the data plotted as E vs. τ on Fig. 2, the best value of K being that which gives the best comparison of the data with the theoretical curve. This method is laborious, however, and was abandoned in favor of the use of a special plotting paper.

A special plotting paper was constructed, using a uniform abscissae scale, but so changing the ordinate scale as to force the theoretical relation (2) to be a straight line. Then using this special paper, since the abscissae scale is uniform, data following the theoretical relation (2) will fall on a straight line when plotted on this paper as E vs. Υ, as E vs. $\frac{\theta}{R^2}$ or as E vs. θ. By comparison of the location of such a straight line with that of the theoretical line, the value of K may be solved for, directly. The data of several runs for slabs of the same material but of different thicknesses plotted as E vs. θ should fall on straight lines the slopes of which would vary inversely as the square of the slab thickness.

Fig. 6 shows the data of runs 6, 7, 8, and 10 plotted as E vs. $\theta/(2R)^2$. Lines are shown as there were so many readings as to make to plot confusing if it were attempted to show the points. The plotting paper used is the special scale paper described above, on which the theoretical relation (2) is represented by a straight line. The lines for the various slab thicknesses coincide fairly well, in spite of the 25-fold variation in the term R^2. The thicker slabs appear to dry relatively faster, when compared on this basis. This phenomenon is no doubt due to the relatively greater edge surface, exposed by shrinkage away from the wood frames, at which a certain amount of drying takes place. As pointed out above, the face area of all the slabs was the same, so that the relation of edge surface to face area was proportional to the thickness. Although the theoretical relation is represented by a straight line on this plot, the lines representing the data on soap are seen to curve in each

DRYING OF BORAX SOAP SLABS.



THICKNESS 1. 0.63 CM. 2. 1.27 CM.
3. 1.90 CM. 5. 3.17 CM.

case, at values of E of 0.50 - 0.55. This curvature may be explained as being due to a decrease in the diffusion constant K as the drying proceeds and the moisture concentration falls off. The decrease in K is no doubt intimately connected in this case with the shrinkage of the soap. It shows up in the plot of the data as a decrease in the slope of the drying curve and a consequent curvature.

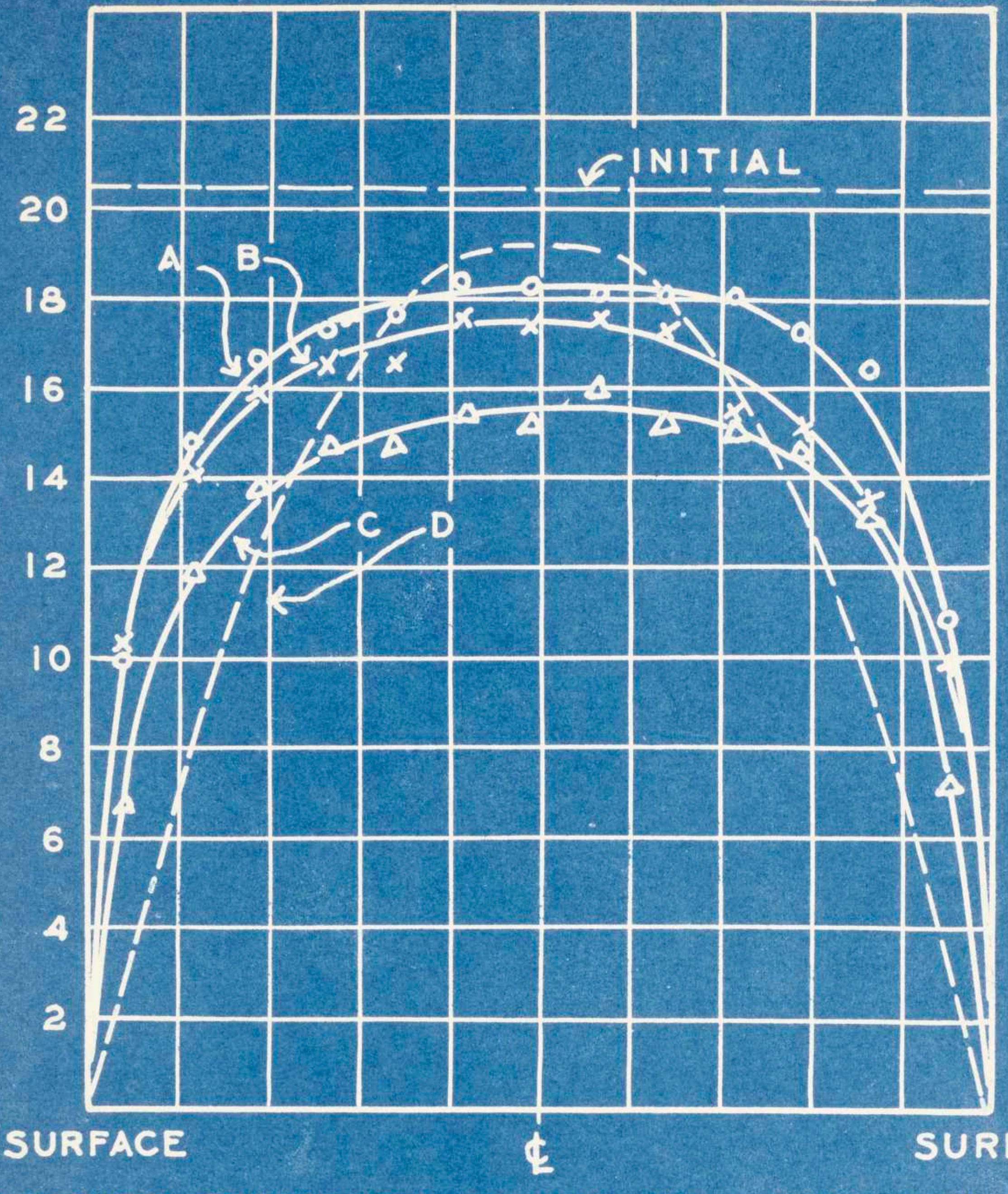
An approximate value of K for the soap may be obtained by comparing Fig. 6 with the theoretical relation on Fig. 2. For example, in the case of runs 6 and 7, a value of $E = 0.60$ is reached at $\theta/(2R)^2 = 310$. Fig. 2 shows the corresponding value of τ to be 0.126

$$\therefore \tau = 0.126 = K\theta/R^2 = 310 \times 3600 \times K \times 4$$

and $K = 2.82 \times 10^{-8}$, which is an approximate value of K between $E = 1.00$ and $E = 0.60$, i.e., between average water concentrations of 20 and 12%, dry basis. The value of K is less than this in the later stages of drying, but its relation to the moisture concentration of the soap is not easily determined from the data obtained.

The decrease in diffusion constant K with moisture concentration is also indicated by the moisture gradient data obtained in Run 9. Fig. 7 shows the moisture gradients, with percent free water on the dry basis plotted versus the location in the slab. The points are placed at abscissae representing the center lines of the slices analyzed. The

RUN 9.



MOISTURE GRADIENTS IN 2.54 CM. SOAP SLAB:—

A.- 166 HOURS. B.- 383 HOURS. C.- 1152 HOURS.

D. - THEORETICAL CURVE FOR AVERAGE MOISTURE CONTENT 13.1% (CORRESPONDING TO CURVE C) BASED ON INITIAL OF 20.5%.

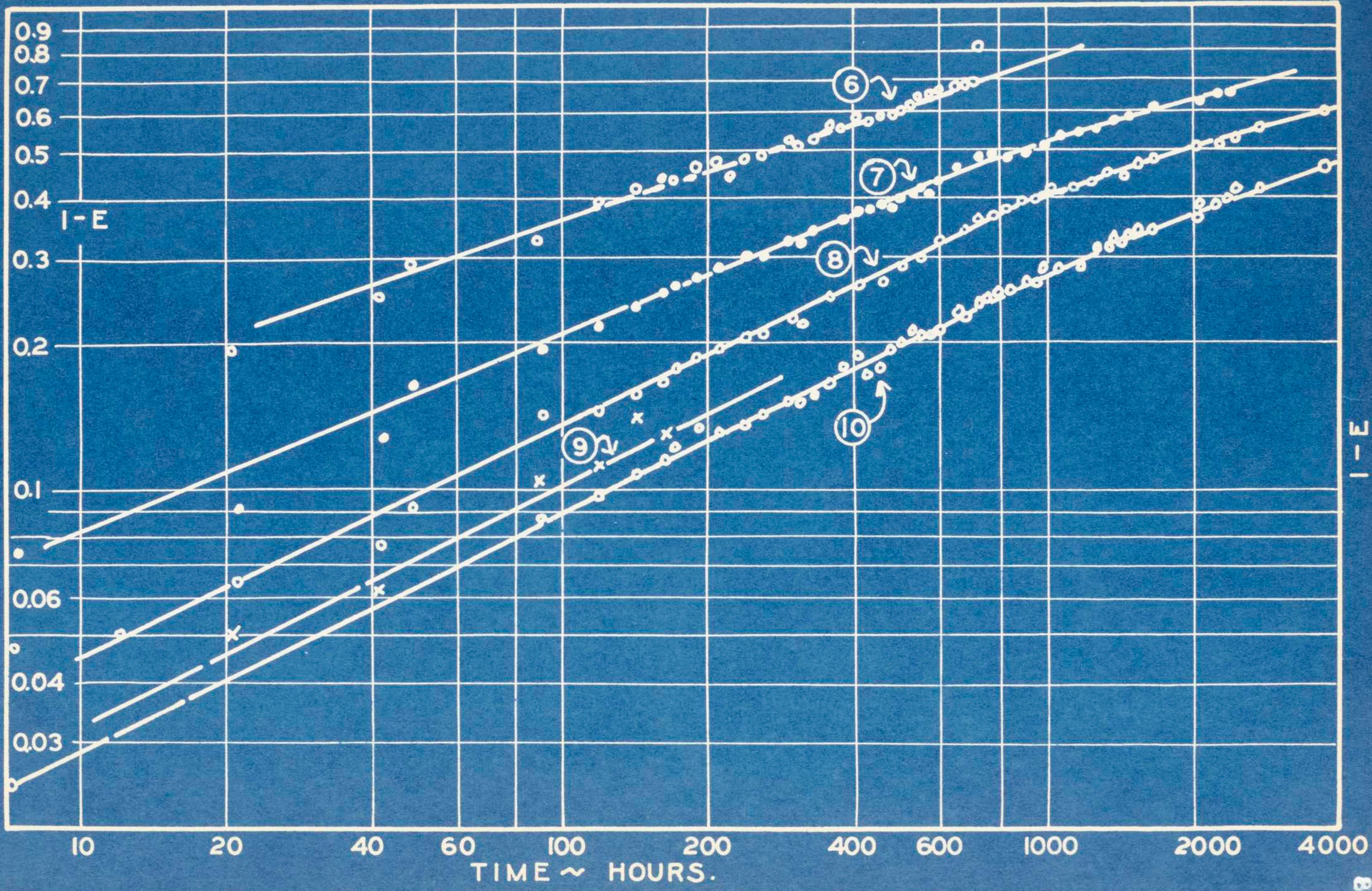
initial moisture gradient is represented by a horizontal line at 20.2% free water.

Date was obtained on the moisture gradients in the same slab after 166, 383, and 1152 hours, and are represented by the three solid curves on Fig. 7. By graphical integration of the area under the third curve the average moisture concentration at that time was found to be 13.1%; E is therefore $\frac{13.1}{20.2}$ or 0.65. The theoretical moisture gradient curve, (from Fig. 1) corresponding to a value of E of 0.65 is shown by the dashed line on Fig. 7. The actual gradient curve is therefore seen to be much flatter than the theoretical curve for the same free moisture in the slab. This may be explained as being due to the lower values of the diffusion constant K at the lower moisture concentrations, i.e. near the faces. Where K is low a relatively steeper gradient curve is necessary to cause the water to diffuse than in the center where moisture concentration and consequently K is greater.

Discrepancies in the soap drying data as compared with the theoretical relations are therefore found to appear in three ways: in the failure of the curves of Fig. 6 to coincide; in their failure to be linear; and in the comparison of the moisture gradient data. The first is explained by the exposure of the slab edges to drying as the soap thrinks, the thicker slabs exposing a relatively larger edge area. The last two are explained by the decrease of the internal diffusion constant K with moisture concentration.

As pointed out in the Introduction, values of 1-E, calculated from equation (2) when plotted vs. τ on log paper give a curve linear over a wide range, but asymptotic to 1-E = 1. (see Fig. 3). Fig. 8 shows the data of Runs 6-10 on soap, plotted as 1-E vs. θ, on log paper. By plotting in this way, the data are seen to fall in nearly straight lines, and in general to parallel the theoretical curve. The decrease in K with moisture content shows up in the fact that the slopes of the data curves decrease more rapidly than does that of the theoretical curve, indicating a relatively lower drying rate in the later stages of drying. By dividing the abscissae by R^2, the curves could be brought very close together, although at high values of 1-E they would be found to fall in order of the slab thicknesses, due to the exposure of the slab edges as described above.

DRYING OF SOAP   1-E VS. θ ON LOG PLOT.



B - SURFACE EVAPORATION CONTROLLING

Constant Rate Period

The second drying mechanism to be considered is described briefly as "surface evaporation controlling". The liquid evaporates at the surface and the resistance to diffusion of vapor through the surface gas film is large compared with the resistance to diffusion of liquid through the solid to the surface.

The adiabatic evaporation of a liquid from a liquid or from a wet solid surface has been discussed in the Introduction. The fundamental equation applying was seen to be the gas film diffusion equation.

$$\frac{dW}{d\theta} = K_s A\ (p_s - p_a) \qquad (10)$$

where

$\frac{dW}{d\theta}$ = rate of drying, weight evaporated per unit time.

A = effective surface area

p_s = partial vapor pressure of vapor over liquid

p_a = partial vapor pressure of vapor in the main body of the gas.

K_s = surface coefficient of vapor diffusion.

Effect of Forced Air Convection

In many drying operations all or nearly all of the drying is accomplished during the constant rate period, and the mechanism is that of surface evaporation controlling.

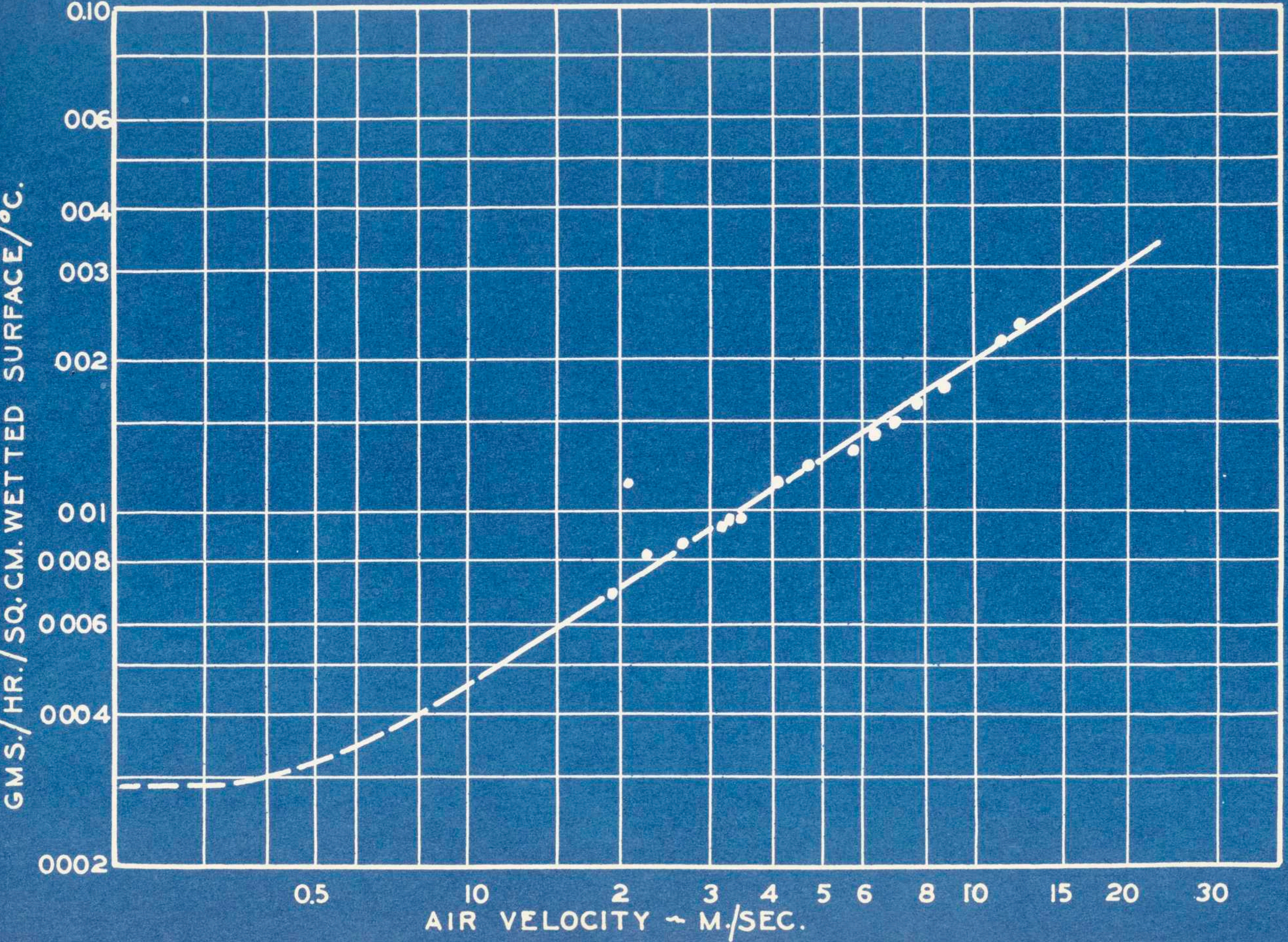
Factors affecting the rate of drying under these conditions are therefore of great importance. High air temperature will cause p_s to be large; dry air corresponds to low values of p_s; and thin sheets expose large drying surfaces per unit weight of material. However, for a given shape of the material being dried adiabatically under definite conditions of air temperature and humidity, the rate of drying can be influenced only by factors which influence the coefficient K_s. The most important variables affecting K_s are the direction and magnitude of the currents of air or other gas used.

In runs V-1 to V-19 inclusive, very wet blocks of pressed pulp (5.0 x 5.2 x 1.52) (cm.) containing over 100% water, were dried in a small flue through which air was forced by a blower. Frequent weighings were made and the rate of drying at the instant when the pulp contained 100% water was calculated. Since the edges of the block were covered with a cement, and the block was placed longitudinally in the flue, the actual drying took place from faces placed parallel to the direction of air flow. The air velocity was changed from run to run, and measured in each case by an anemometer in the flue.

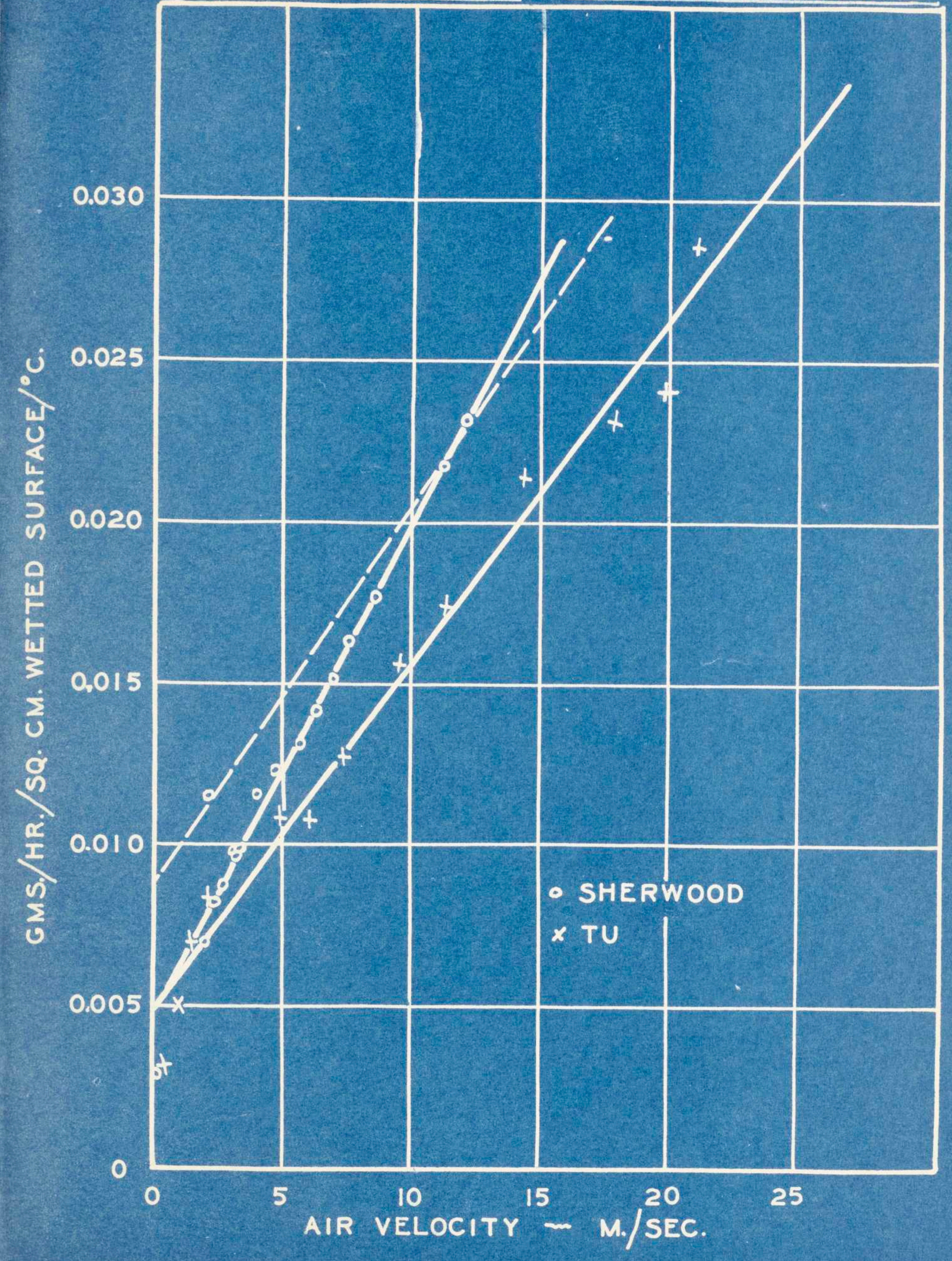
The actual temperatures of the sample were not measured, but assuming for the moment that this very wet pulp actually reached the wet bulb temperature, the rate of evaporation as gms./(hr.)(sq.cm.)/(°C.) may be calculated by dividing the rate as gms./(hr.)(sq.cm.) by the observed wet bulb depression. This has been done and is shown plotted vs. air velocity in Fig. 9. In this plot logarithmic paper is used and the slope of the line is roughly 0.6, indicating the rate of evaporation to be proportional to the 0.6 power of the air velocity. This is approximately the same as the exponent found by Chappell and McAdams[14] for the variation with air velocity of the coefficient of heat transfer from air to the outside of pipes. An analogy might be expected, since the resistance to diffusion is in each case an air film whose thickness depends on the air velocity past the surface. The curve approaches an asymptote at the lower end corresponding to the value of the rate of vaporization under conditions of natural air convection.

The same data together with that of Tu[15] are shown replotted on ordinary coordinate paper in Fig. 10. Tu's data was obtained in a similar manner, but using a thinner pulp block (9.0 x 9.9 x 0.82 cm.) The actual temperature of the pulp was measured by several thermocouples in series inserted in the sample. The actual temperature difference so found, rather than the wet bulb depression, was used in calculating the rate of evaporation per °C. Since the temperature of the sample was always slightly higher than the wet bulb temperature, the actual

DRYING OF PULP ~ CONSTANT RATE PERIOD.



DRYING OF PULP — CONSTANT RATE PERIOD.



temperature difference is less than the wet bulb depression, and the rate of evaporation per °C. calculated using the actual Δt might be expected to be relatively greater than the same rates calculated using the wet bulb depressions.

The temperature of the pulp may be shown to approach the wet bulb temperature as the air velocity is increased. This follows from equation (16).

$$(t_a - t_s) = \frac{K_s r_s \, A \, (p_s - p_a)}{(HA' + h_c A)} \qquad (16)$$

where $t_a - t_s$ is the actual temperature difference, h_c is the surface coefficient of heat transfer from air to wetted surface, and H is the overall coefficient of heat flow from air to wetted surface, via the dry surface; i.e. from air to the dry surfaces, and through the solid to the wet surface where evaporation takes place. Since the resistance of the solid is such a large fraction of the total resistance to heat flow in the second case, H may not be expected to vary appreciably with air velocity. Furthermore, even at low air velocities, H will be small compared to h_c, and since for the experiments with pulp blocks described A' was less than A, h_c A will be large compared with HA' in the denominator in Equation (16). At high air velocities, HA' will be negligible, and the equation may be written.

$$(t_a - t_s) = \frac{K_s r_s}{h_c} \; (p_s - p_a) \qquad (16a)$$

But the wet bulb depression is seen from (13) to be

$$(t_a - t_w) = \frac{K_s r_w}{h_c} (p_w - p_a) \qquad (13)$$

whence, under the above conditions, $t_s = t_w$
Thus as the air velocity is increased, the surface temperature approaches the wet bulb temperature, and the temperature difference approaches the wet bulb depression.

In a similar manner it may be shown from (16) that for any given values of h_c and H, the surface temperature approaches the wet bulb temperature as the dry surface A' is made negligible compared with the wetted surface A. The ratio of the temperature difference to the wet bulb depression is a function of the ratio of dry to wetted surface, as will be discussed below in connection with the experiments in the tunnel drier. These experiments indicate that for the low air velocity used in this drier, a ratio of A'/A of 0.6, as in the case of the block used in runs V-3 to V-19, corresponds to a temperature difference Δt of about 65-70% of the wet bulb depression. With the high air velocities of some of the V-series of runs, the temperature difference Δt might be expected to approach closely the wet bulb depression. The above assumption, that the wet pulp actually reached the wet bulb temperature, which was used in calculating the points for Fig. 10, is valid for the high air velocities, i.e. at the right hand side of the plot. At the left hand side the error caused by this assumption is seen to cause the calculated values to be some 35-40% lower than they should; the true curve should therefore be similar to that shown dashed, of a slope nearly the same as the line through the points representing Tu's data.

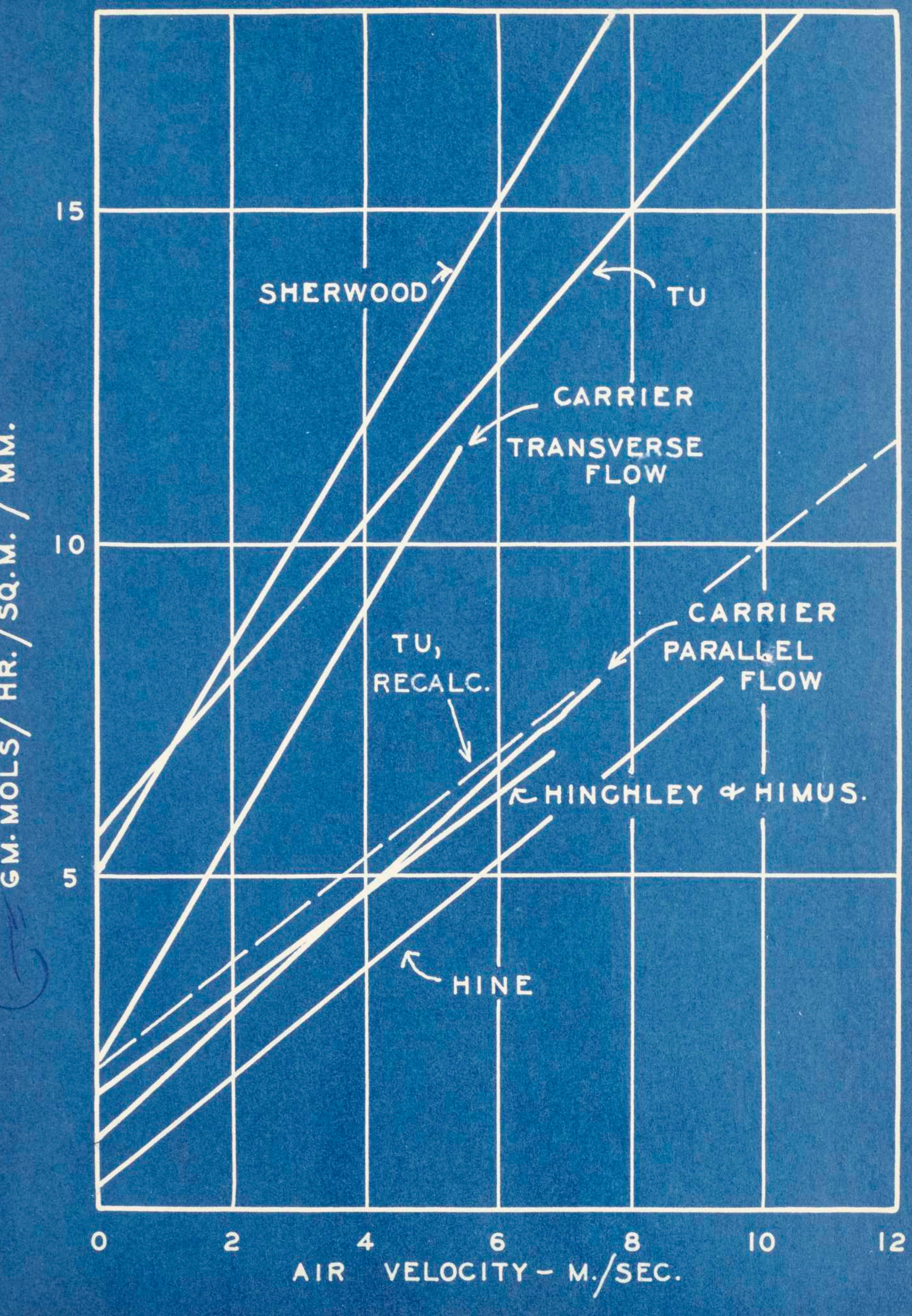
Both curves on Fig. 10 are higher than would be expected for the limiting case where the whole surface is wetted, i.e. $A'/A = 0$. From the heat transfer point of view the added dry area (the rates shown are per unit <u>wetted</u> area) increases the heat inflow (and hence evaporation) more than enough to offset the reduction of heat flow due to the decrease in temperature difference below the wet bulb depression. Or, since the added dry surface is seen to raise the surface temperature above the wet bulb temperature, p_s and consequently Δp are increased. For the author's data on Fig. 10 the ratio of A'/A was 0.6; for the data of Tu shown this ratio was 0.16; for a wholly wet surface the corresponding curve should be somewhat lower than either of those shown.

COMPARISON OF VARIOUS DATA ON EVAPORATION FROM LIQUID SURFACES

Data on the effect of air velocity on the rate of evaporation from free liquid surfaces is of importance in drying during the constant rate period. In this part of the drying process the surface is wet with liquid, and except for complications due to the presence of the solid, as previously discussed, the process is essentially that of the evaporation of a liquid from a liquid surface. Since the rate of evaporation varies greatly with the air velocity, a knowledge of the quantitative relation is of value in the calculation of an economic balance to determine the optimum air velocity to be used. Considerable data on this subject is available in the literature, and some of the most important has been collected and represented by curves on Fig. 11. The rate of evaporation is expressed on this plot as gm. mols per hour per sq. meter per m.m. partial pressure difference, and the air velocity in meters per second.

W.H.Carrier[6] concluded from his own data, together with that of Coffey and Horne[8] that the rate of evaporation of water was a linear function of the air velocity and directly proportional to the partial pressure difference, or "driving force".

EVAPORATION OF LIQUIDS.



Carrier gives his conclusions in the form of equations, which when rearranged, are

$$G = 1.045 + 0.92\ u,$$ for parallel flow of air, and $G = 2.21 + 1.90\ u$ for transverse flow of air where G is the rate as gm. mols/(hr.)(sq.cm.)(m.m.) and u is the air velocity in m./sec. These equations are represented on Fig. II by lines drawn over the range covered by the data.

Perhaps the most extensive and valuable data on the evaporation of water was obtained by Hinchley and Himus[7]. These investigators evaporated water from shallow pans placed flush with the floor of a tunnel drier through which air was forced at various velocities. Maintaining the air velocity constant, they varied the water temperature, and hence the partial pressure difference $p_s - p_a$, or Δp. As did Carrier, these authors found the rate of evaporation to be directly proportional to the partial pressure difference Δp, and to be a linear function of the air velocity. They express their results in the form of an equation, which when recalculated, may be written

$$G = 1.72 + 0.75\ u$$

The line representing this equation is shown on Fig. II.

T.B.Hine[13] has published data on the rate of vaporization of liquids other than water, namely, nitrobenzene, toluene, m-xylene, and chlorbenzene. These experiments were carried out on a large scale in a large ventilating flue at Edgewood Arsenal, evaporation taking place from a round copper pan 59.06 cm. in diameter placed flush with the floor of the flue. The data obtained show that for the liquids used the weight evaporated per unit time at any given wind velocity was proportional to the product of the molecular weight and the vapor pressure. Since the air used contained no vapors of the liquids, Δp is equal to the vapor pressure of the liquid. Thus, the gm. mols evaporated per unit time per unit Δp was constant at any wind velocity, and was found to be a linear function of the wind velocity. The results were summarized in the form, of an equation which may be rewritten as

$$G = 0.365 + 0.815 u$$

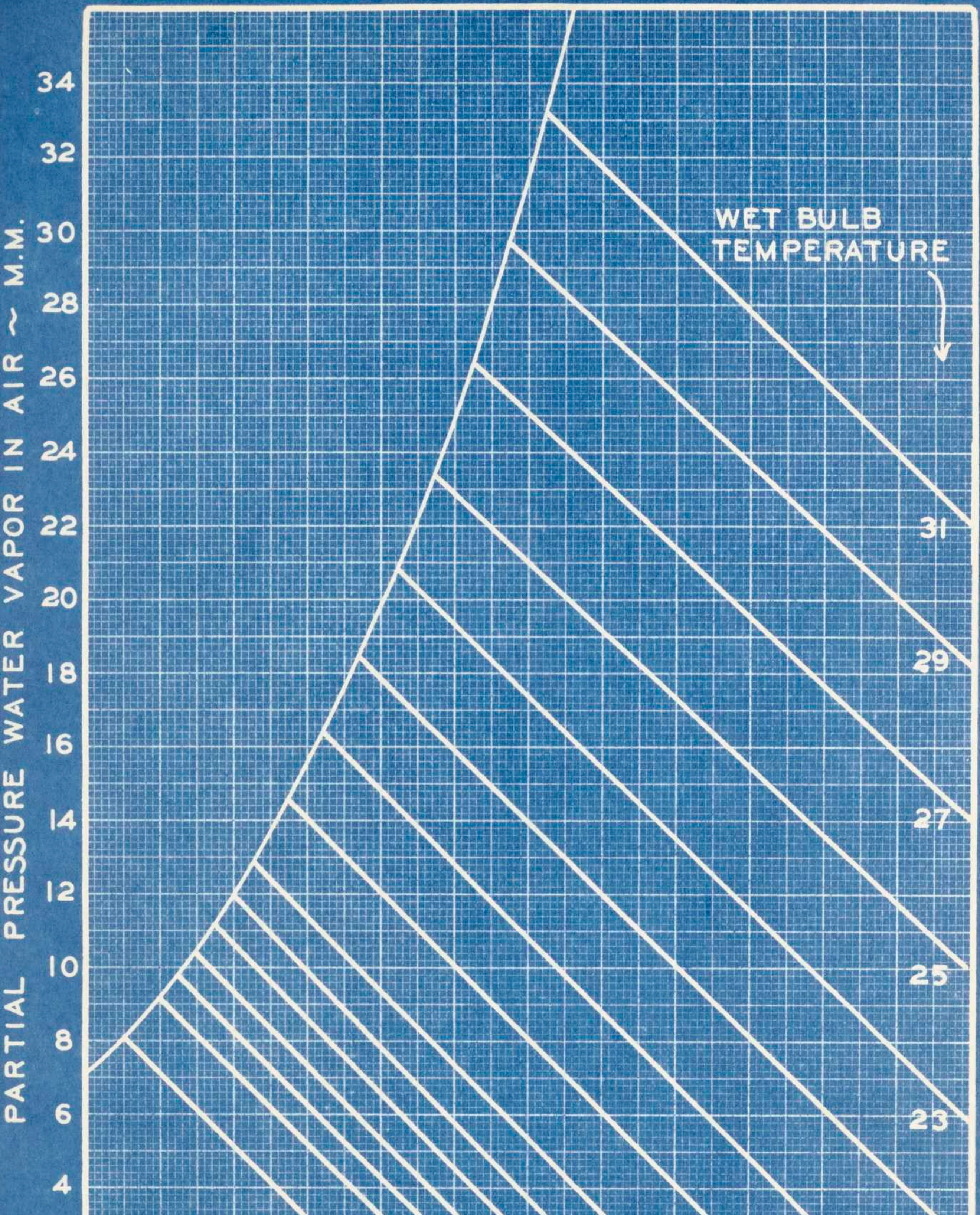
and is also represented on Fig. II. The average deviation of the results from this equation, for 46 runs, was stated to be 10.72 per cent, neglecting signs. From the plot by Hine, showing both the experimental points and the above equation, it would appear evident that the first and second constants on the right hand side of the equation are too low and too high respectively.

The data of Tu and of the author, as shown in Fig. 10 have been replotted in Fig. 11, for comparison with the data from the literature discussed. In order that this data might be put on the same basis, i.e., the rate expressed as gm. mols per hr. per sq.m. per m.m. Δp, the assumption was made that one m.m. Δp was equivalent to 2.0° C. Δt, which is very nearly true[6] when the surface is at the wet bulb temperature. If, however, due to the presence of dry surfaces in close proximity to the wet, as in the case of the wet pulp blocks, the sample temperature is raised above the wet bulb temperature, the Δt is decreased and the Δp increased, and the ratio is rapidly altered.

Since in Tu's experiments the actual surface temperatures were obtained by means of thermocouples, it is possible to calculate the actual Δp, and hence to replot Tu's data on the same basis as that of Carrier, Hine, Hinchley and Himus on Fig. 11. Tu's data is recorded in such a way that it is possible to recalculate only about half of his runs, but the location of the resulting points is indicated by the dotted line shown, marked "Tu, recalculated". As predicted above, this correction brings this data down in line with that of Carrier, Hinchley and Himus and Hine.

In passing, attention may be called to Fig. 12, from which is easily obtained the partial pressure of water vapor in air, given the wet and dry bulb thermometer readings. This plot is found convenient in calculation of Δp, as in the recalculation of Tu's data, above.

It is to be noted that the lower curves of Fig. 11, i.e., those of Carrier, Hine, and Hinchley and Himus, represent the relation between the air velocity and the minimum drying rate per unit wet area, under conditions of drying at constant rate. This minimum rate is obtained when there is no dry surface near through which heat may flow to the evaporation zone. These curves are of value in predicting this minimum drying rate. Caution must be observed, however, in using these curves for the prediction of drying rates of liquids other than water, for, as will be explained below, there is doubt as to the value of Hine's method of correlation.


PARTIAL PRESSURE WATER VAPOR IN AIR ~ M.M.
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
6
10
20
30
40
50
AIR TEMPERATURE ~ °C.
WET BULB TEMPERATURE
31
29
27
25
23
21
8
10
12
14
15
17
19

EVAPORATION OF WATER FROM WHITING, CLAY, AND PULP DURING CONSTANT RATE PERIOD

As pointed out above, the constant rate periods in the various drying experiments are examples of drying with surface evaporation controlling, and fall under Case II of the original classification of drying mechanisms. Most of the experiments carried out with whiting, clay, and pulp showed evidences of a constant-rate period, and the data on the constant-rate period for these runs may be separated for analysis. This has been done for a number of runs using water, and the average drying rates etc. summarized in Table 1, below. The conditions varied somewhat during this part of the experiment for any one run, but in most cases did not deviate greatly from the average values recorded.

TABLE I

Run	MATERIAL	Thickness Cm.	t °C.	D.B. -W.B.	Ratio dry to wetted Surface	Gms./hr. /sq.cm.	Gms./hr. sq. cm. /°C. t	Gms./hr. sq. cm. /°C.(D.B.-W.B.)	Gms./hr. sq. cm. /m.m. p	Heat Transfer Coefficient, c. g. s. H.
33	WHITING	0.63	12.3	13.3	0.33	0.0318	0.00259	0.00240	0.00414	0.000397
35	"	0.63	10.4	11.3	0.33	0.0264	0.00254	0.00233	0.00399	0.000388
31	"	1.59	9.2	10.4	0.69	0.0279	0.00303	0.00268	0.00446	0.000461
32	"	2.54	11.6	12.5	1.33	0.0419	0.00361	0.00335	0.00456	0.000569
16*	"	3.17	8.5	10.5	1.84	0.0574	0.00675	0.00546	0.00615	0.00099
21	"	3.17	9.0	11.1	1.64	0.0392	0.00435	0.00353	0.00467	0.000715
30	"	3.17	12.5	15.0	1.64	0.0516	0.00413	0.00344	0.00527	0.000649
38*	"	3.17	7.7	8.5	1.67	0.0459	0.00596	0.00540	0.0093	0.000933
39	"	3.17	13.0	16.4	1.67	0.0529	0.00406	0.00322	0.0042	0.000603
34	"	3.81	9.6	12.1	1.78	0.0361	0.00376	0.00298	0.00342	0.000619

TABLE I (CONT'D)

61	PULP	0.69	14.9	18.7	0.093	0.0395	0.00265	0.00211	0.00313	0.000394
66	"	0.69	15.7	19.5	0.093	0.0437	0.00279	0.00224	0.00313	0.000418
37	"	0.76	8.3	8.9	0.118	0.0264	0.00318	0.00296	0.00584	0.000607
36	"	1.12	12.3	13.7	0.149	0.0388	0.00315	0.00283	0.00411	0.000441
70	"	1.70	15.1	19.6	0.396	0.0572	0.00379	0.00292	0.00377	0.000575
41	"	1.80	10.5	13.4	0.322	0.0405	0.00386	0.00302	0.00412	0.000556
60	CLAY	0.63	16.1	19.4	0.33	0.0395	0.00245	0.00204	0.00326	0.000373
59	"	1.59	12.9	15.6	0.69	0.0348	0.00270	0.00223	0.00329	0.000407
58	"	3.17	13.5	18.1	1.64	0.0490	0.00363	0.00271	0.00349	0.000548

Considering first the runs with whiting it is seen that the rate of drying as gms. water per hour per sq. cm. varies roughly two fold. Runs 16 and 38 are seen to be out of line with the other eight, and this is explained by the fact that in these two cases the samples did not occupy the regular position in the drier on the hook of the recording balance. In these two cases the samples were placed on the floor or hung from the roof of the drier, locations where the air velocity past the surface differed from that obtaining in the region of the recording balance. This is indicated not only by the abnormal rates of vaporization but also by the high values of the coefficient of heat transfer H. The other eight runs with whiting are more uniform, and in general the rate of drying is dependent on the humidity conditions of the air. Attempts have been made to allow for the varying humidity by calculating the rates as

gms./(hr.)(sq.cm.)(°C. Δt.),

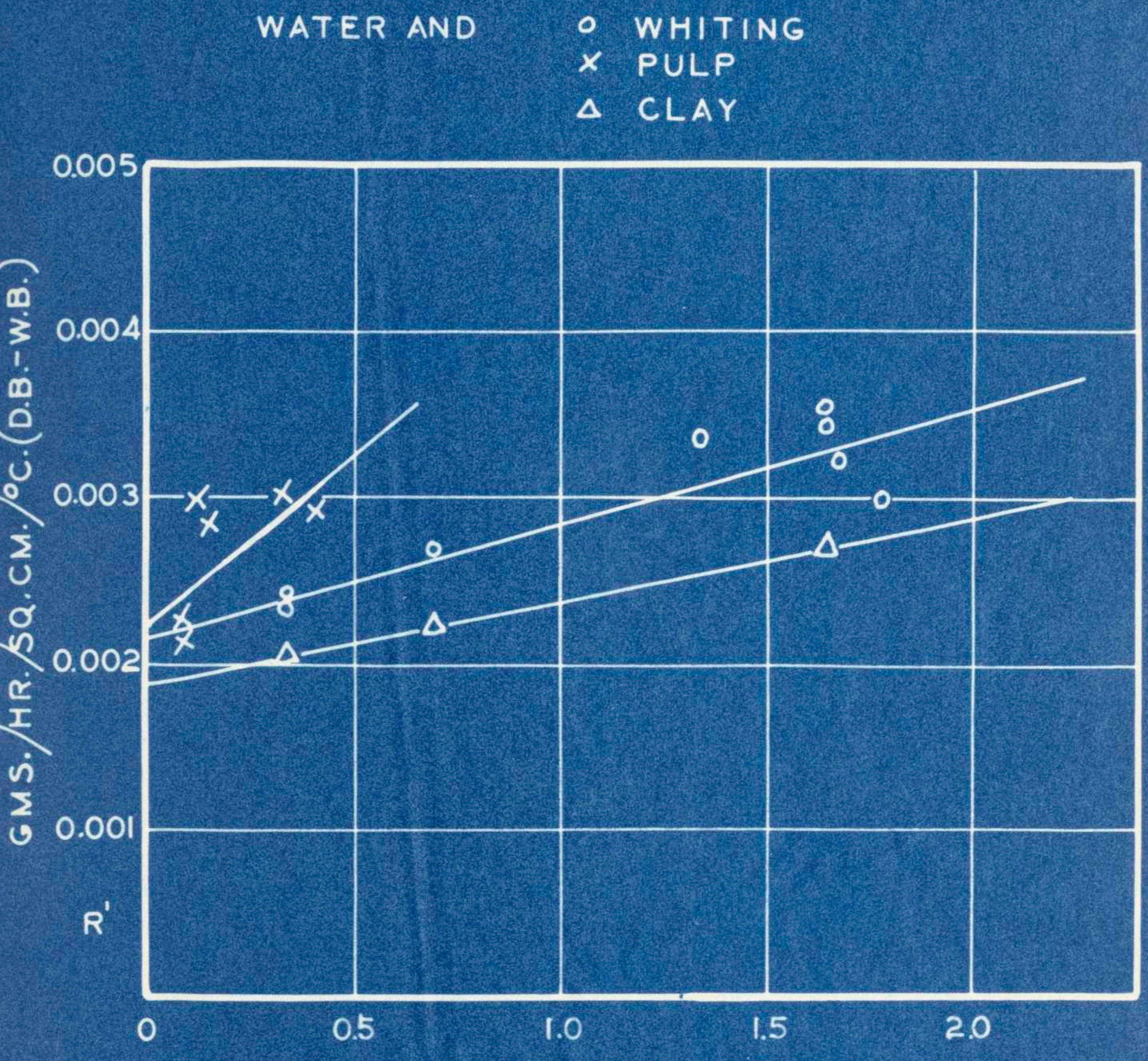
as gms./(hr.)(sq.cm.)(°C. Wet-bulb depression),

and as gms./(hr.)(sq.cm.)(m.m. actual Δp.)

The latter was calculated using the actual difference between the vapor pressure of water at the temperature of the sample and the partial pressure of water vapor in the air, m.m. The per cent deviation from the average, neglecting signs, for the eight runs considered was 17%, 13% and 7%, respectively, for the above three terms. The data are thus seen to be best correlated by expressing the rate as gms./(hr.)(sq.cm.)(m.m.Δ p.), the average value of which for whiting is 0.00434.

Since the surface temperature of the sample, and consequently the vapor pressure of water on the surface changes with the relative amount of dry surface in proximity to the wet surface, the calculation of the rates as gms./(hr.)(sq.cm.)(m.m.Δp.) allows for variations in the ratio of dry to wetted surface. Correlation on the basis of gms./(hr.)(sq.cm.)(°C. wet-bulb depression) does not do this, and it would be expected that the latter would vary with the ratio A'/A. Fig. 13 shows the data of Table 1 so plotted as to show this relation. An approximately linear relation is found for the clay and for the whiting, both of which were dried in wood frames. The greater shrinkage of the clay away from the wood frame possibly increased the overall resistance to heat flow to the clay, via the dry surface, more than in the case of the whiting, and may explain the lower relative position on the plot of the curve for clay. The edges of the pulp slabs were covered with either paraffin or

CONSTANT RATE PERIOD.

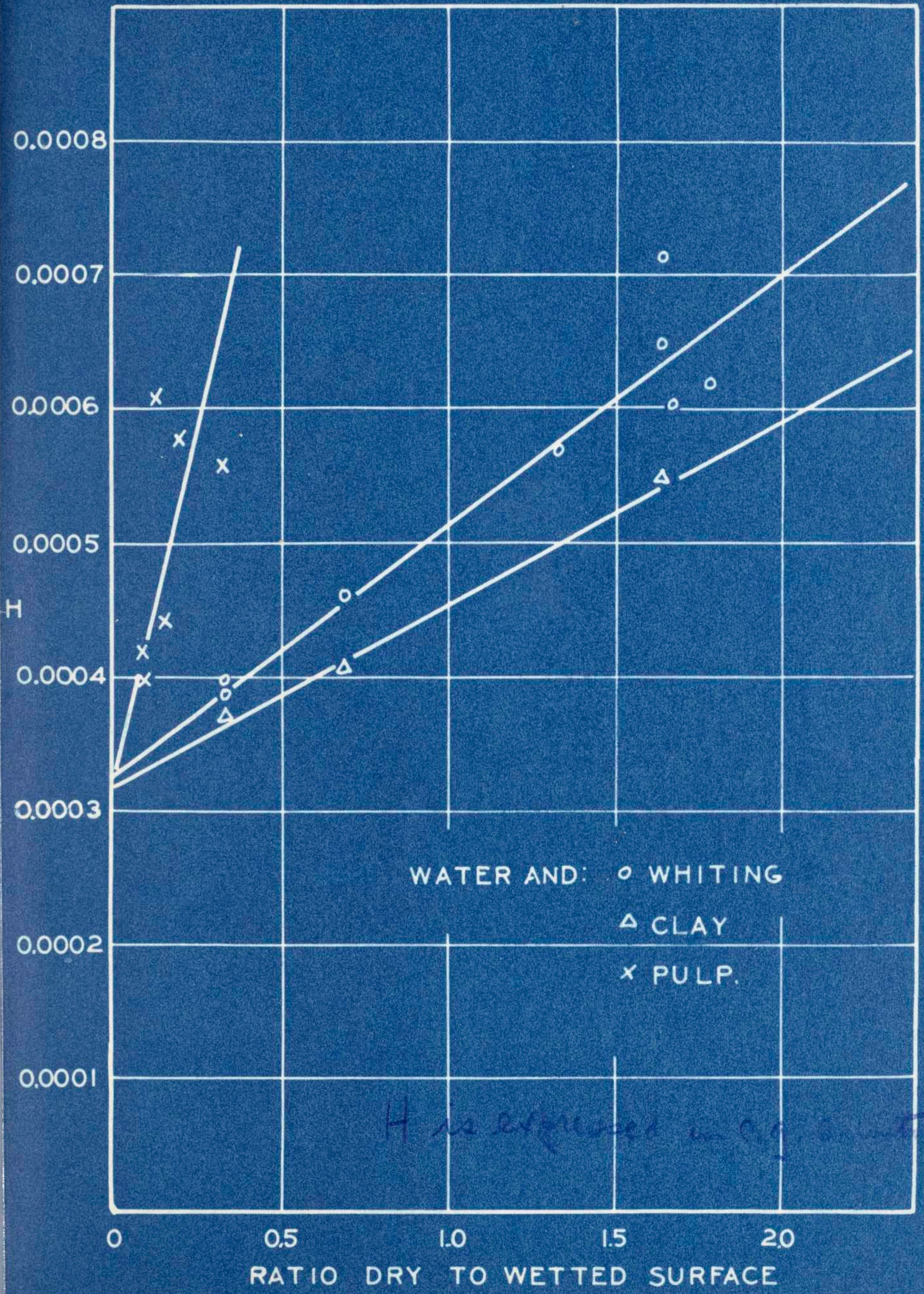


M.J.B. cement, of varying thickness, so that as might be expected, a definite relation is not indicated for the pulp. However, it is significant that the intercepts of the three curves at the ordinate scale, i.e., at the point corresponding to a wholly wet surface, are nearly identical, indicating that the rate of drying under similar drying conditions is the same for all three materials, during the constant rate period. Moreover, the value of the intercept, 0.002 gms./(hr.)(sq.cm.)(°C. wet-bulb depression) or 1.11 gm. mols./(hr.)(sq.cm.)(°C.), corresponds to about 2.2 gm. mols./(hr.)(sq.cm.)(m.m. Δp.), which checks well with the value read from Fig. 11 for evaporation from a free liquid surface using an air velocity of 1.0 m./sec., which was approximately the air velocity used in the tunnel drier. This substantiates the suggestion made above, that the four lower curves of Fig. 11 might be used to predict rates of drying of wet materials during the constant rate period. The same thing is indicated by the fact that the average value of the gms./(hr.)(sq.cm.)(m.m. actual Δp.) for the 17 runs of Table 1 (excluding runs 16 and 38) is 0.00417, or 2.32 gm. mols./(hr.)(sq.m.)(m.m.).

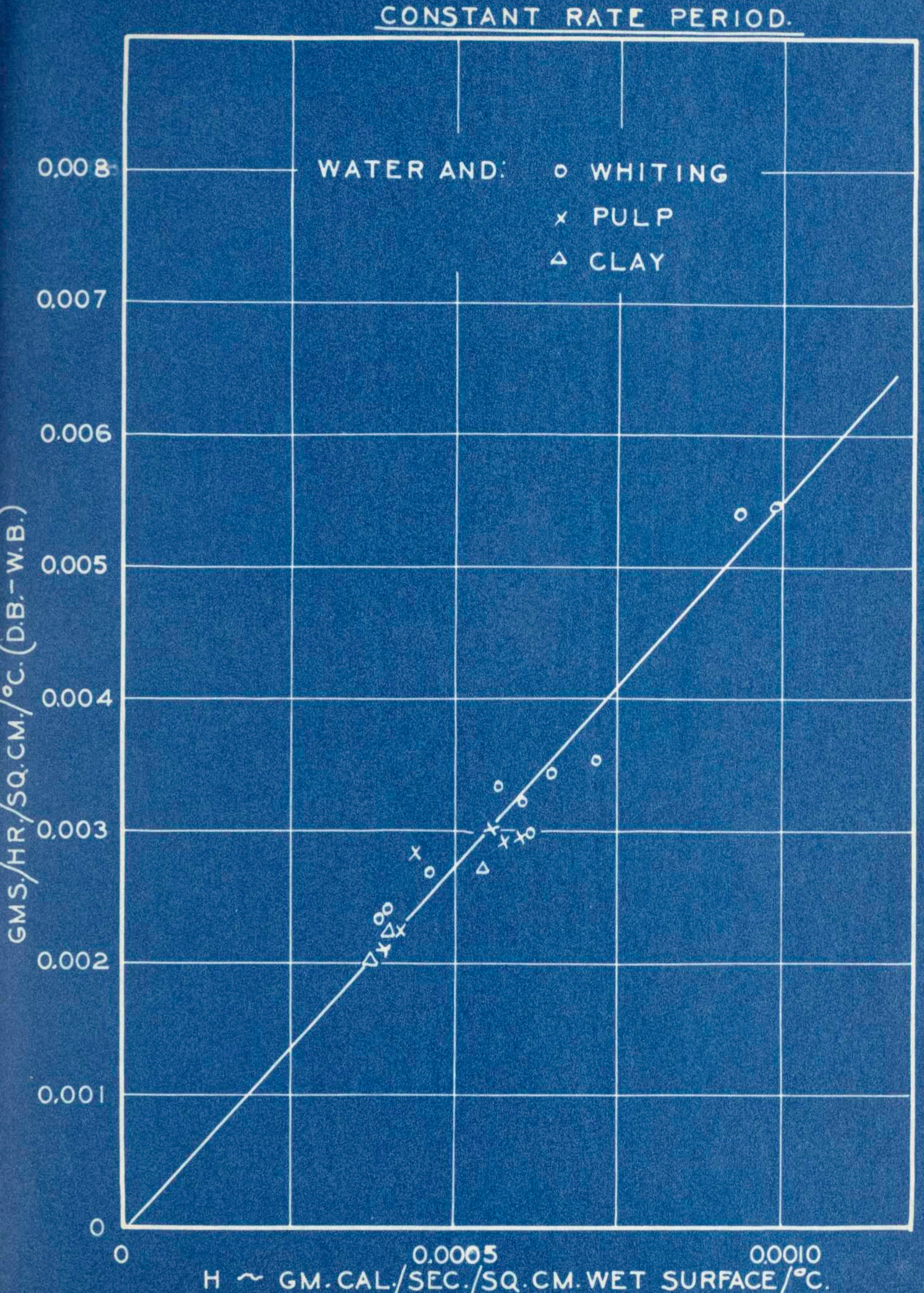
The overall coefficients of heat transfer reported in Table 1 are calculated on the basis of the wetted area only, and it might therefore be expected that these coefficients would vary with the ratio of dry to wetted surface. That such is the case is shown by Fig. 14, which indicates that H varies with the ratio A'/A in a similar manner to the rate of vaporization per °C. wet bulb depression. (Fig. 13). The plots are similar, the varying thickness of the edge coating on the pulp slabs again causing the points for pulp to fall erratically. The intercept of 0.000325 for a wholly wet surface corresponds to a value of H in English units of 2.4, and it is interesting to note that Chappell and McAdams[14] give this value of H for about a 3 cm. pipe when air is flowing transversely with a velocity of 1.0 m./sec.

The similarity of Figs. 13 and 14 suggest that the rate of vaporization varies directly with H, and this is seen to be the case from Fig. 15. All of the runs of Table 1, including 16 and 38 are shown plotted as gms./hr./sq.cm./°C. (D.B.-W.B.) vs. H, and a straight line passing through the origin is found to represent the data well. This shows that in these runs the rate of vaporization was influenced by the same factors as was the overall coefficient of heat flow.

CONSTANT RATE PERIOD.



H is expressed in c.g. units


CONSTANT RATE PERIOD.
WATER AND:
o WHITING
x PULP
△ CLAY
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
GMS./HR./SQ.CM./°C. (D.B.-W.B.)
0
0.0005
0.0010
H ~ GM. CAL./SEC./SQ. CM. WET SURFACE/°C.

EVAPORATION OF VARIOUS LIQUIDS FROM WHITING DURING CONSTANT RATE PERIOD

A number of runs were made using 3.17 cm. whiting blocks but mixing the whiting with other liquids than water. The data on the constant rate period for these runs and for those runs shown in Table 1 for water in 3.17 cm. blocks are summarized in Table II below.

TABLE II

Run	Liquid	Δt	D.B. -W.B.	Gms./hr. /sq.cm.	Gms./hr. /sq.cm. /°C. Δt	Gms./hr. sq.cm./ m.m. Δp	Heat Transfer Coeffi- cient h c.g.s.
17	Toluene*						
19	Amyl Acetate*						
20	" "						
22	Carbon Tetrachloride *						
23	Acetone	16.1		0.349	0.00217	0.00217	0.000789
24	Xylene[b]	4.1	8.0	0.109	0.00266	0.0042	0.000735
25	Acetone	12.7	30.0	0.250	0.00197	0.00126	0.000666
27	Benzol*						
28	Ethyl Acetate*						
29	Alcohol	13.7	17.7	0.132	0.00096	0.00209	0.000599
16	Water[a]	8.5	10.5	0.0574	0.00675	0.00615	0.00099
21	Water	9.0	11.1	0.0392	0.00435	0.00467	0.000715
30	Water	12.5	15.0	0.0516	0.00413	0.00527	0.000649
38	Water	7.7	8.5	0.0459	0.00596	0.0093	0.000933
39	Water	13.0	16.4	0.0529	0.00406	0.0042	0.000603

*no constant rate period.

[a] not in recording balance position in drier.

[b] surface cracked badly.

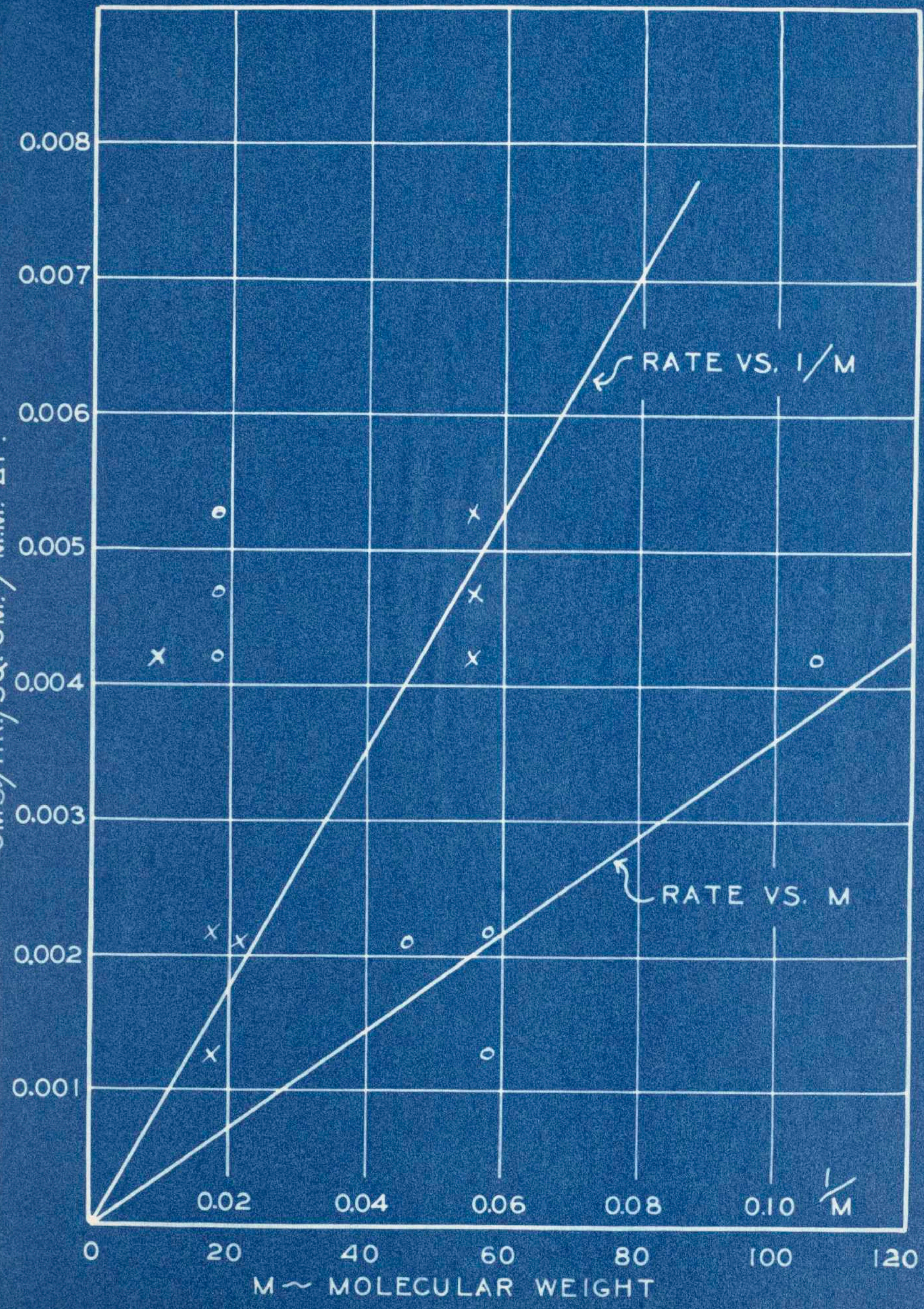
The data obtained on the constant rate period for these liquids are meager due to the fact that five of the nine liquids showed no constant rate period when evaporated from whiting under the conditions of these experiments. Moreover, in the case of run 24, using xylene, the surface of the whiting was seen to crack badly from the first, so that the observed rate of drying is undoubtedly abnormally high.

The rates as gms./(hr.)(sq.cm.)(m.m. actual p) are shown plotted in Fig. 16 vs. the molecular weight of the liquid M, and vs. 1/M. The circles represents the data plotted vs. M, and the crosses plotted vs. 1/M, for Runs 23,24,25,29,21,30, and 39. Neglecting the three points for water, the circles fall roughly on a straight line passing through the origin. However, when the data are plotted vs. 1/M, as indicated by the crosses, only one point is found to deviate widely from a straight line through the origin, and that is the one for run 24, where the rate was known to be abnormally great*. This data therefore indicates the rate to be inversely proportional rather than directly proportional to the molecular

---

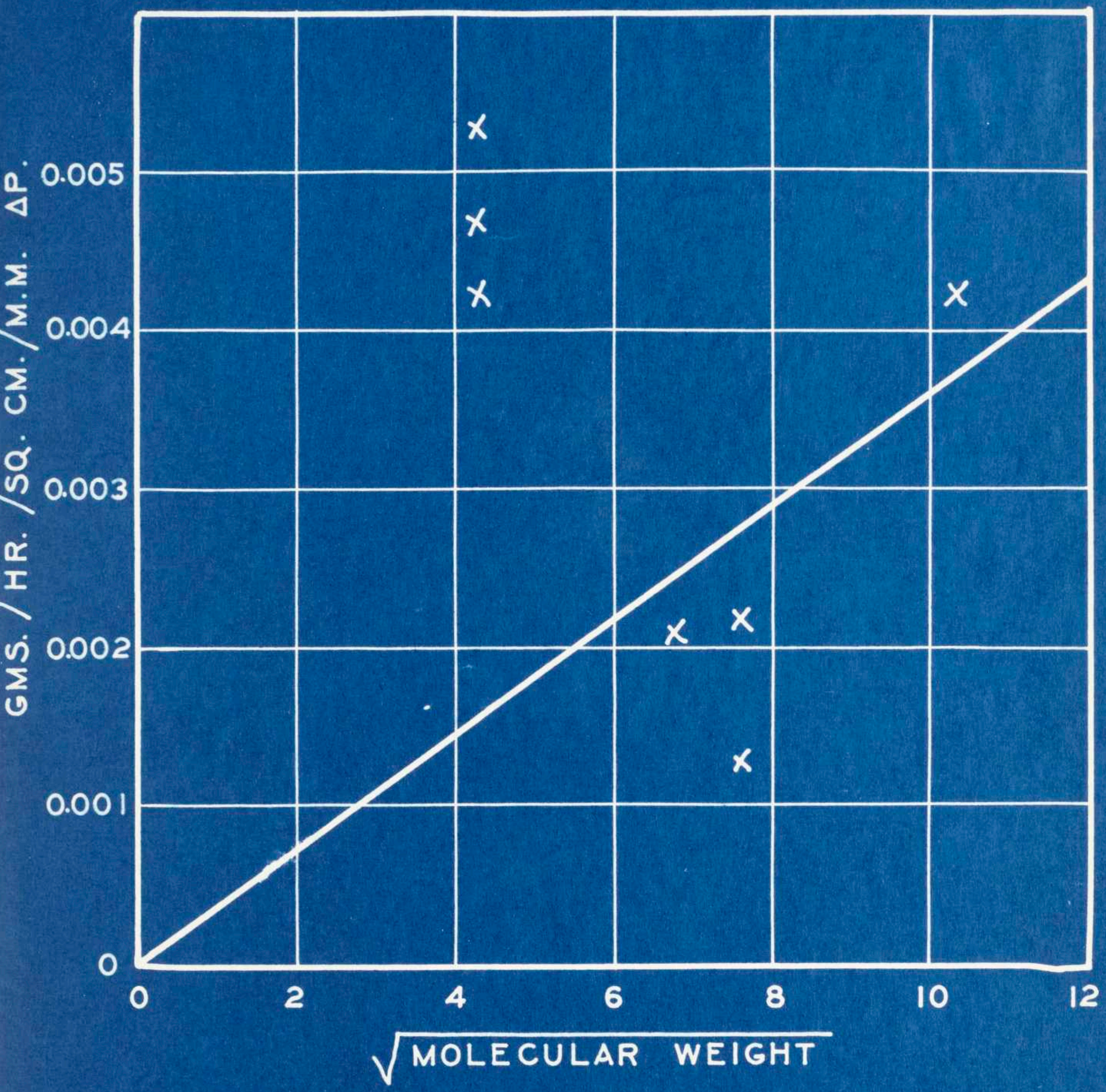
*Fig.17 shows a plot of the same data vs. $\sqrt{M}$ as suggested by the work of K.C.Chang[28], who concluded that the film resistance should be proportional to the square root of the product of the molecular weights of diffusing vapor and inlet gas, (in this case air). The resulting plot does not show as good a relation as when the data is plotted vs. 1/M.

3.17 CM. WHITING BLOCKS.



3.17 CM. WHITING BLOCKS

CONSTANT RATE RERIOD.



weight. Hine[13] as discussed above, found the reverse, since his data for four liquids show the gm. mols. hr./sq.m./m.m. Δp. to be constant at any air velocity. Lewis and Whitman[5] state that in cases of gas diffusion, the diffusivity decreases with increase in molecular weight, but that the change in diffusivity is small compared with that in molecular weight; in other words that the rate K_g is proportional to some power of M between 0 and -1. Due to the unsatisfactory state of the data on the evaporation of liquids other than water, it is suggested that Fig. 11 be used for water only.

EFFECT OF RADIATION FROM SURROUNDINGS ON RATE OF DRYING DURING CONSTANT RATE PERIOD

It is well known that a wet-bulb thermometer will not read accurately if the radiation from the surroundings is an appreciable fraction of the total heat inflow necessary to maintain evaporation of the water on the wick. In order to minimize this radiation error it is usually recommended that a high air velocity past the wick be used, as by so doing the heat inflow by convection is greatly increased without much change in radiation, so that the radiation is made a proportionately smaller fraction of the total heat transfer.

In a like manner, wet solids drying in a current of air approach the wet bulb temperature as the radiation to the solid is made a smaller and smaller fraction of the total heat flow.

The effect of radiation from the surroundings on the sample temperature and rate of drying may be calculated with fair accuracy as will be shown below. Let R" represent the evaporation coefficient as gms./hr./sq.cm./unit absolute humidity difference, r_s the latent heat of vaporization at the liquid surface, p_e the black body coefficient of the surface, and h_c the surface coefficient of heat flow by convection. The rate of evaporation is given by

$$\frac{dW}{d\theta} = R''A\ (H_s - H_a) \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

also

$$\frac{dW}{d\theta} = \frac{dQ}{d\theta} \times \frac{1}{r_s}$$

and assuming the surroundings to be at the air temperature

$$\frac{dW}{d\theta} = \frac{1}{r_s}\left[h_c\ A\ (t_a - t_s) + Ap_A \left\{\left(\frac{t_a}{100}\right)^4 + \left(\frac{t_s}{100}\right)^4\right\}\right]$$

in which t_s and t_a are in ° C.absolute (°K.)

Combining the above

$$\frac{r_s R''}{h_c}(H_s - H_a) = (t_a - t_s) + \frac{p_e\ c}{h_c}\left[\left(\frac{t_a}{100}\right)^4 - \left(\frac{t_s}{100}\right)^4\right] \ldots\ldots\ldots (18)$$

Now Lewis[4] has shown that for conditions of evaporation at the wet bulb temperature,

$$\frac{h_c}{R''} = S = \text{the specific heat of the wet air} \ldots\ldots (19)$$

Since h_c and R'' are primarily dependent on the gas film thickness, and, within limits, not on the surface temperature, it might be expected that the relation (19) would hold for evaporation at a temperature somewhat above the wet bulb. Applying it, therefore, to the case in question,

$$\frac{r_s}{S}(H_s-H_a) = (t_a-t_s) + \frac{p_e\, c}{h_c}\left[\left(\frac{t_a}{100}\right)^4 - \left(\frac{t_e}{100}\right)^4\right] \ldots\ldots (20)$$

To illustrate the use of this equation by an example, let the effect be calculated of radiation from surroundings to t_e to a very wet sheet of material drying under the following conditions:-

t_a = 40° C., or 313° C. abs.

t_w = 27° C. or 300° C. abs.

H_a = 0.0170, S = 0.246, r_s = 587 (approx.)

p_e = 0.9

h_c = 0.000612, or 4.5 in English units

then, substituting in (20)

$$\frac{587}{0.246}(H_s - 0.017) = (313-300) + \frac{0.(x0.000137}{0.000612}\left[\left(\frac{313}{100}\right)^4 - \left(\frac{t_s}{100}\right)^4\right]$$

and by reference to a humidity chart this equation may be solved by trial and error, giving t_s = 27.6° C. (approx.) corresponding to a correction of less than 5% on the temperature difference and also on the rate of drying. Since in the experiments described, 40° C. was approximately the highest temperature level attained, it is believed that the correction for evaporation by radiation did not exceed 4-5%, and was in most cases less. In the loft drying of paper, or in similar cases, sheets near the walls might be affected by radiation, and those in the center surrounded by wet sheets be not so affected. Although the difference in the rates of drying might be small, the correction applies to the drying accomplished, so that when nearly dry the water contents of the sheets in the two locations in the drier might vary quite appreciably.

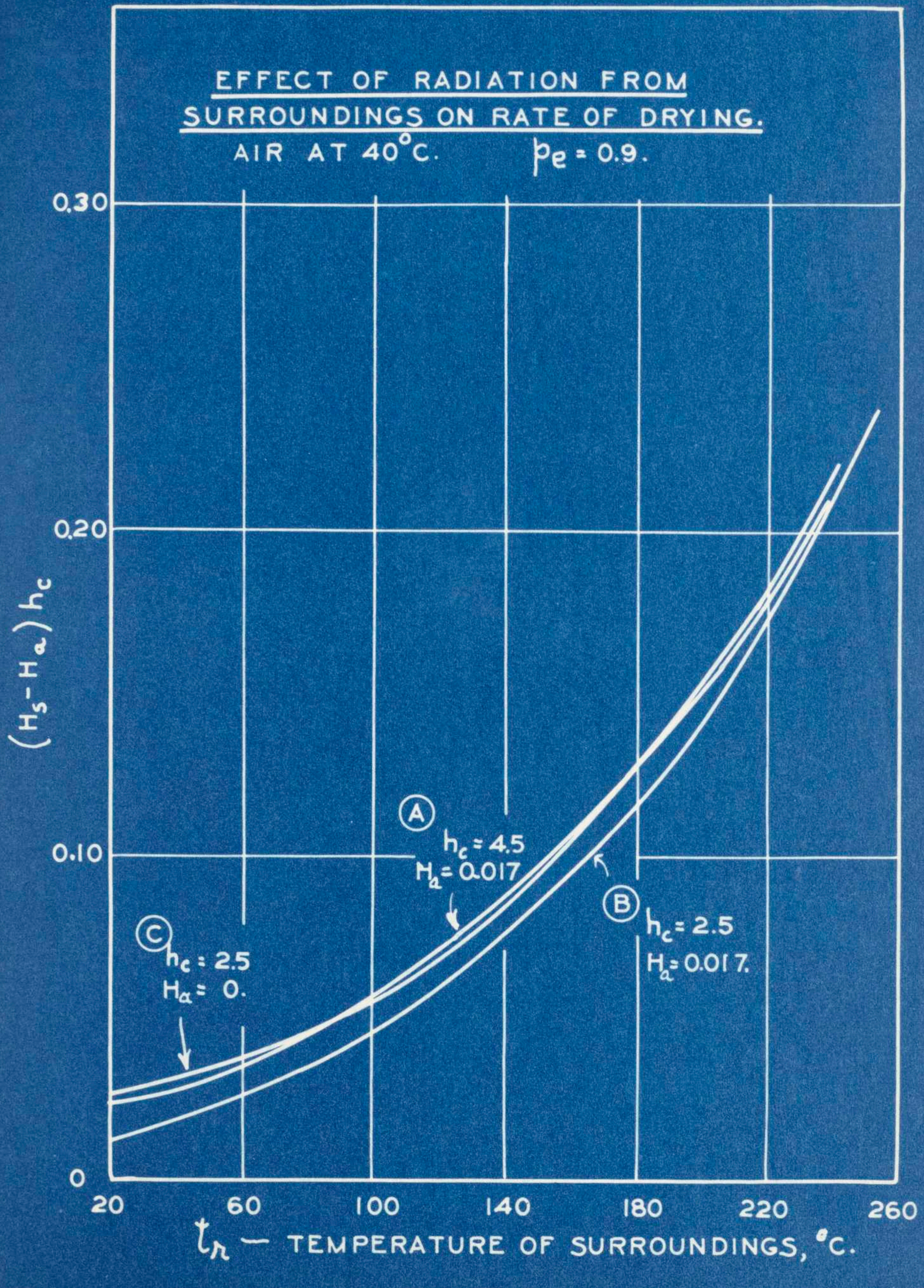
The general equation, for surroundings at t_r, is

$$\frac{r_s}{S}(H_s-H_a) = (t_a-t_s) + \frac{p_e c}{h_c}\left(\frac{t_r}{100}\right)^4 - \left(\frac{t_s}{100}\right)^4 \quad \ldots.(21)$$

Solving this equation for different values of t_r and a given value of p_e, and of t_a, it is possible to find the corresponding values of t_s and H_s. Since the rate of drying is proportional to the difference H_s-H_a, it is possible to calculate the drying rates for different conditions of radiation.

As a basis, call the drying rate unity when $t_r = t_a = 40°$ C., i.e., when the surroundings are at the air temperature. When the surroundings are at 190° C. with a surface temperature t_s of 40° C., i.e., just equal to the air temperature, the rate is found to be 4.92. Likewise when the surroundings are at 292° C., the rate is 11.7 and the surface at 51.1° C. These calculations refer to the example stated above and the results would be different with other assumed values of h_c, p_e, Ha, t_a, etc. They are suggestive, however, of the possible value of radiant heat in speeding up certain drying operations.

Fig. 18 shows the relative drying rate, which from equations (17) and (19) is seen to be proportional to $(H_s - Ha) \times hc$, plotted vs. the temperature of the surroundings. It will be obvious that when radiation is eliminated, i.e., $t_r = t_s$, the rate of drying depends on h_c only. The difference between curves A and B, at $t_r = 27°$ C., is maintained nearly constant over the whole range of t_s, so that at high values of the latter, a change in h_c makes only a small percentage change in the drying rate.



EFFECT OF RADIATION FROM SURROUNDINGS ON RATE OF DRYING.

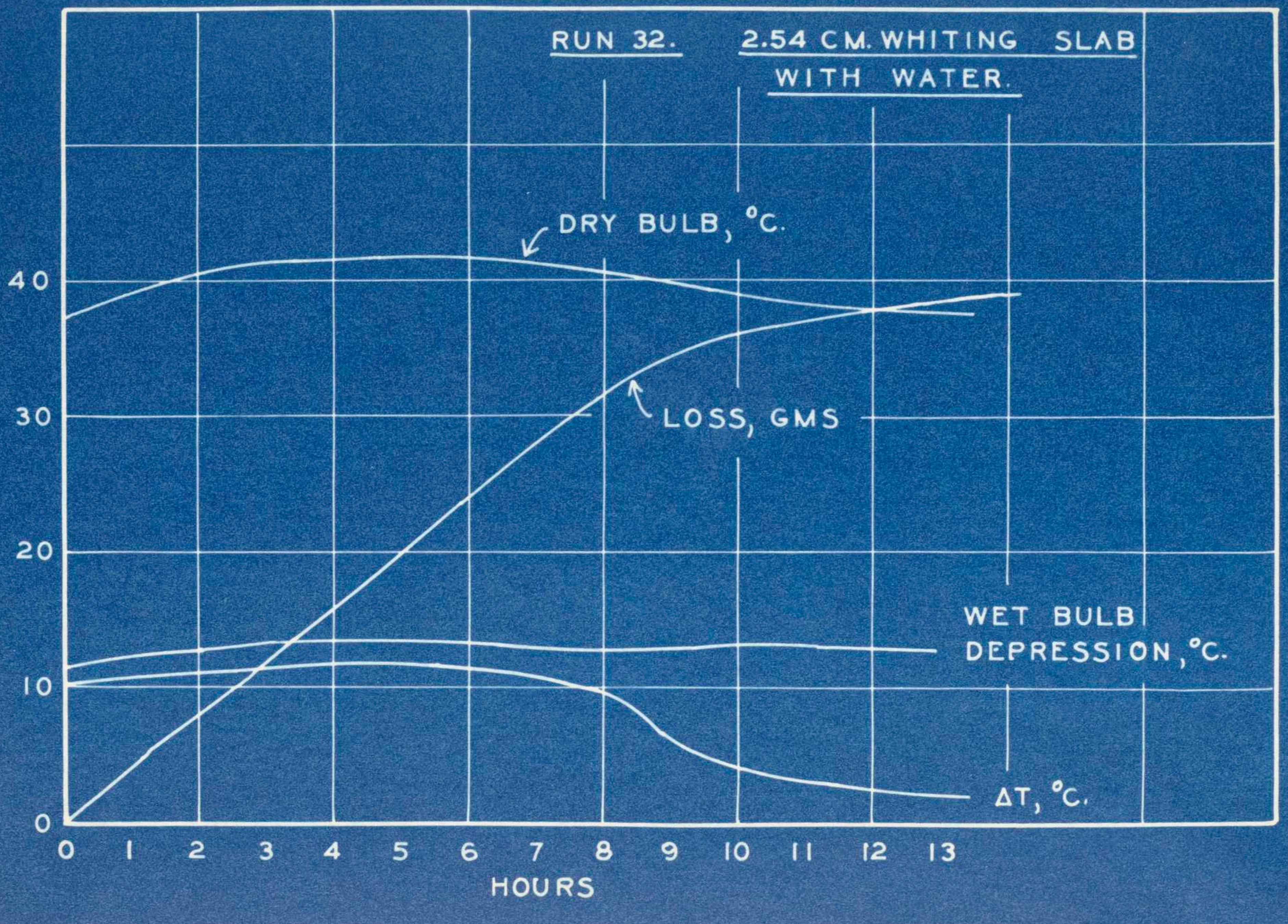
AIR AT 40°C. $p_e = 0.9$.

Curve C is for the dry air but with the same value of h_c as in case B. Curves B and C are seen to approach each other at high values of t_r, indicating that at high values of t_s, the air humidity is an unimportant variable.

C - THE DRYING OF WHITING DURING THE FALLING RATE PERIOD

As pointed out in the Introduction, the constant rate period in any drying operation is always followed by a falling rate period, during which the rate of drying continually decreases. The point at which the rate starts to fall off from constancy is called the critical point, and the moisture content of the material at the critical point is called the critical moisture content, usually expressed on the dry basis. This critical moisture content varies with different materials, being 5.7% in the runs with whiting, and, as will be shown later, being as much as 50-80% for pulp. Thus, the moisture limits in a commercial drying operation may both fall in the constant rate period range, both in the falling rate period range, or lie on either side of the critical moisture content.

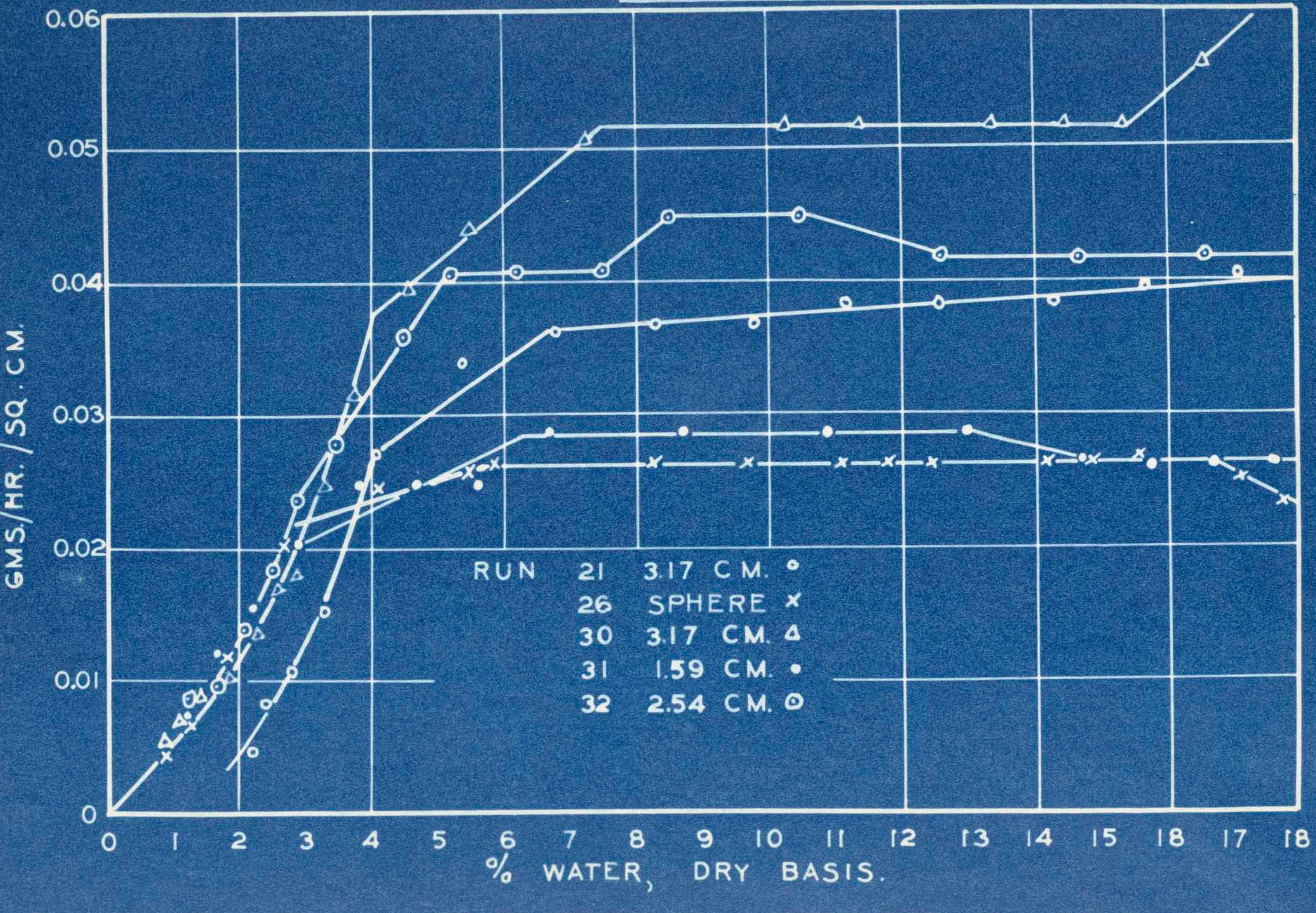
Figure 19 shows graphically the type of data obtained on the drying of whiting slabs. This particular data is that of Run 32 using a 2.54 cm. whiting sample, mixed with water. The figure shows the loss in weight, air temperature, wet bulb depression, and temperature difference Δt, as recorded by the recording balance and pyrometer. The linear portion of the loss in weight curve represents the constant rate period, which is seen to end at

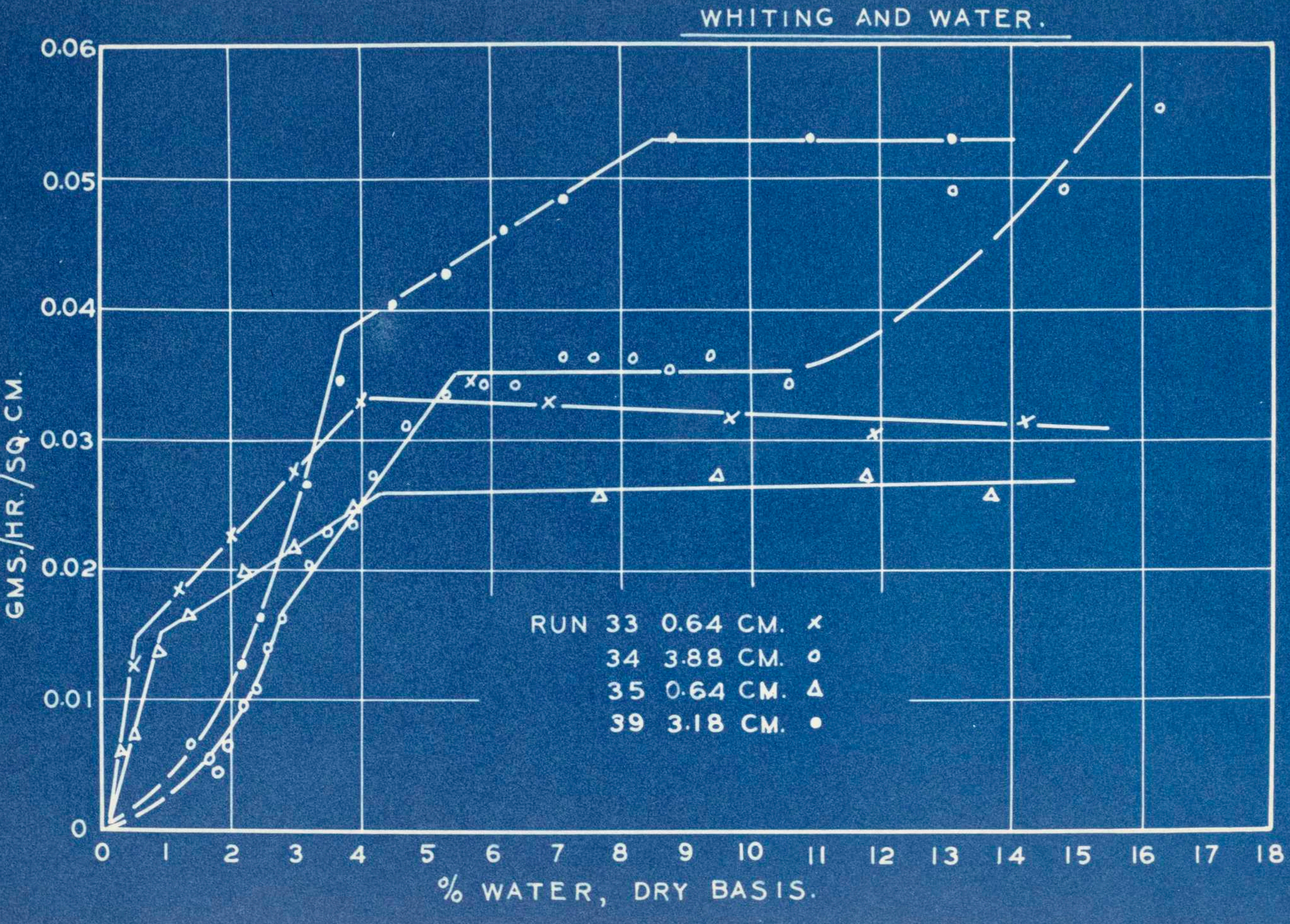

RUN 32.
2.54 CM. WHITING SLAB WITH WATER.
DRY BULB, °C.
LOSS, GMS
WET BULB DEPRESSION, °C.
ΔT, °C.
0
10
20
30
40
0
1
2
3
4
5
6
7
8
9
10
11
12
13
HOURS

about 7.6 hours. During this period the Δt parallels the wet bulb depression, indicating an almost constant difference in temperature between the sample and the air. At practically the same point that the loss in weight curve indicates the end of the constant rate period, the value of Δt starts to fall away from the wet bulb depression, showing the temperature of the sample to rise and approach the air temperature. This constancy of sample temperature during the constant rate period, followed by warming of the sample up to the air temperature during the falling rate period was found to be a general phenomenon and occurred in all cases studied. It appears that the Δt should be looked upon as decreasing <u>because</u> the rate of vaporization decreases, rather than vice versa.

The division of the drying operation into constant rate and falling rate periods is shown clearly in Figures 20 and 21, where the results of several runs with whiting are shown plotted as gms. /(hr.)(sq.cm.) vs. the water content of the sample. The hooks in the curves at the extreme right-hand ends are doubtless due to adjustment of the sample temperature at the start of the drying to the temperature prevailing during the constant rate period. The rates prevailing during the constant rate period vary with the conditions and with the slab thickness, as discussed in the previous section. The critical

WHITING AND WATER.



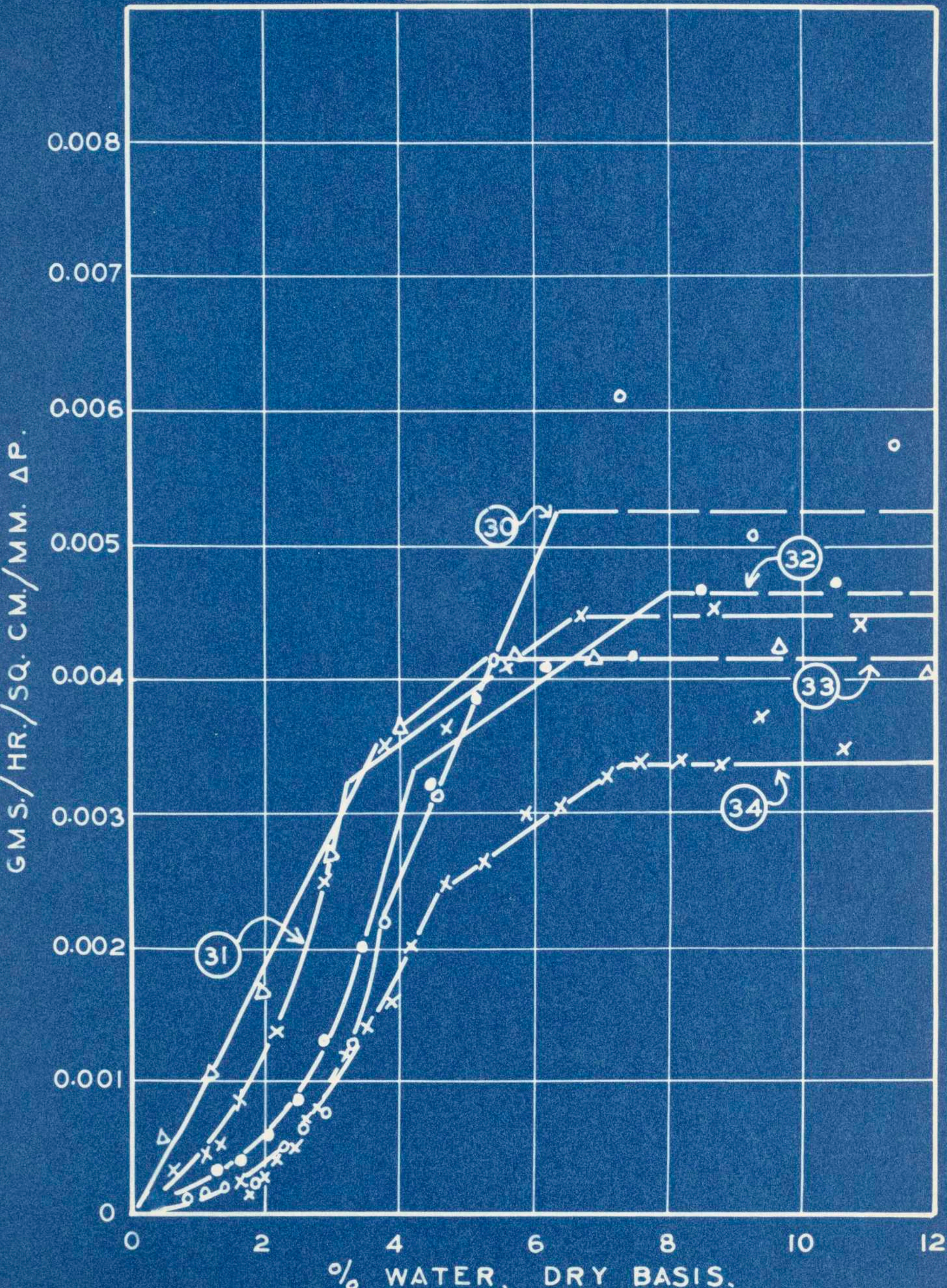

WHITING AND WATER.
0.06
0.05
0.04
0.03
0.02
0.01
0
GMS./HR./SQ.CM.
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
% WATER, DRY BASIS.
RUN 33 0.64 CM. ×
34 3.88 CM. ○
35 0.64 CM. △
39 3.18 CM. ●

moisture contents vary from 4 to 8%, and show some indication of varying with the slab thickness. During the constant rate period the higher rates correspond to the thicker slabs, but during the last part of the falling rate period the reverse is true. The curves must therefore cross, and in the region of 3% water the rate appears nearly independent of the slab thickness. If the rate curves are inspected closely, it will be seen that the falling rate period may be divided into two zones. This is shown especially clearly in the case of Runs 32 and 34. As the water content decreases, the critical point is reached at about 5%; then follows a linear portion of the rate curve, down to about 3%, and finally a curved portion, from there to dryness. For convenience, the region of the sloping linear portion of the rate curve will be called Zone A; that of the lower curved portion of the rate curve Zone B.

During the whole of the falling rate period, since the temperature of the solid rises, the vapor pressure of water on the surface must increase, and the driving force Δp must increase. Furthermore, the rate of vaporization continually falls off during the same period, so that it is evident that the coefficient K_s, the rate of vaporization per unit area per unit Δp, must decrease more rapidly than the rate of drying. Fig. 22 shows this coefficient, plotted against the average water content, for several of the whiting runs previously shown. The division of the falling rate period into two zones is again evident, the limits of each zone being unchanged.

E.A.Fisher[16-21] has also found that for a number of materials the rate curve was of the shape described above. In some cases he found the curve for zone A to be linear and to pass through the origin: in others linear but having an appreciable intercept when extended to cut the rate axis. Fig. 23 shows an example of Fisher's data on wool fabric: the three curves are for one, two, and three thicknesses respectively. Since the rate of change of moisture concentration, rather than the actual loss in weight per unit time, is plotted as ordinates, the curves are at different levels and the rates during the constant rate period do not coincide. However, they are found to be inversely proportional to the thickness of the material indicating that if the rates were plotted as actual weight per unit time the three curves would coincide. The vapor pressure curve for water over wool is shown on the same plot in relative units.

WHITING AND WATER.



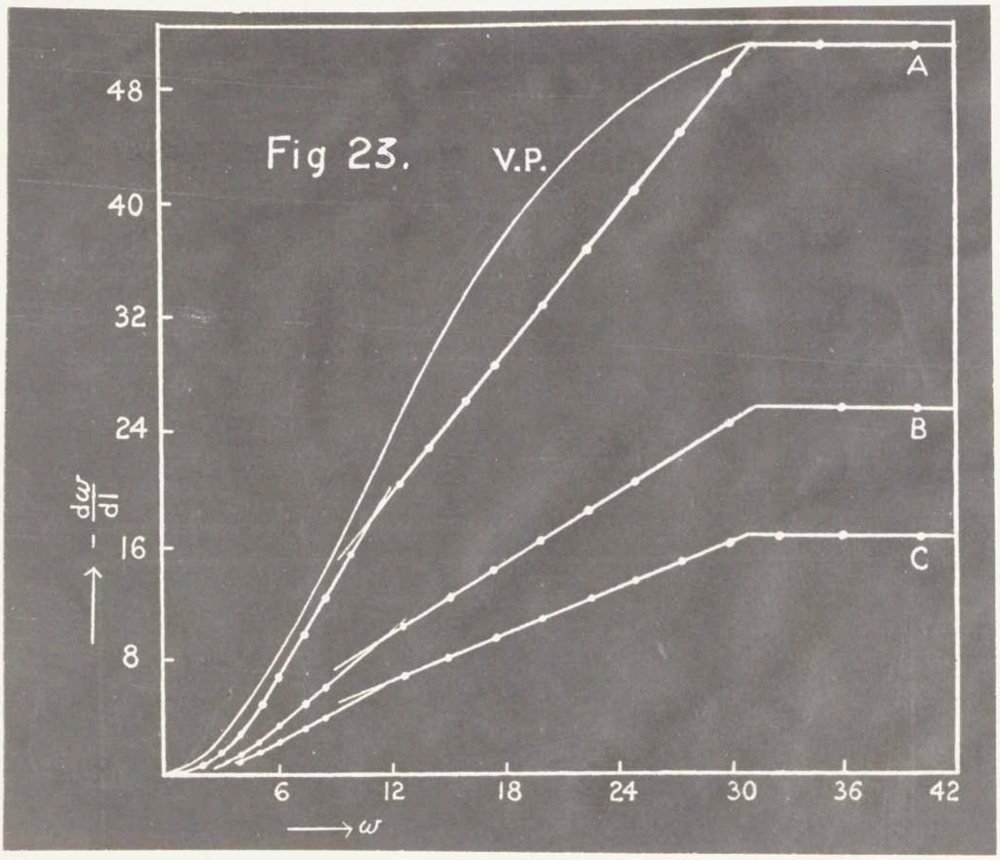


Fig 23.
V.P.
A
B
C
48
40
32
24
16
8
$-\frac{d\omega}{dl}$ ⟶
6
12
18
24
30
36
42
⟶ ω

CAUSES OF DECREASING RATE OF DRYING

Having established the existence of two zones in the falling rate period during the drying of whiting, it is of interest to inquire the cause of the discontinuities observed between the zones, and indeed of the initial decrease in drying rate at the critical point, i.e., why there should be a falling rate period.

One possibility is that the rate of drying decreases because the vapor pressure curve for water over the solid decreases at low moisture contents of the solid, so that the driving force p and the rate of vaporization must decrease. The rate of drying curve would not have to parallel exactly the equilibrium curve, but if thus were the true reason for the decrease in drying rate, we should expect the critical point to fall in the region of moisture content where the vapor pressure curve approaches its maximum value. This is found to be the case for the data of Fisher's on wool shown in Fig. 23. As the moisture content decreases the vapor pressure begins to fall off at 30-33%; the critical moisture lies in the same range. However, the equilibrium of vapor-pressure curve for whiting approaches a maximum at probably less than 1% water, whereas the critical moisture as shown above varied from 4-8% water. Likewise in the case of pulp the maximum on the vapor pressure curve is reached at 15-25% water whereas the critical moisture was 50-80%. Nor did the two values check any better for the wood or clay tested. In the case of Fisher's wool the coincidence of the two points does not prove that the vapor pressure controls the drying rate; it is merely necessary to have such a check if this explanation were correct. In Fig. 23 the vapor pressure curve shown is for a single temperature, and is drawn in relative units; since it flattens off to coincide with the rate curve A during the constant rate period, it corresponds to the vapor pressure curve of the wool at the temperature of the solid during the constant rate period. If the explanation suggested were correct, the rate curve should parallel the vapor pressure curve as long as the temperature of the wool remained constant and equal to the temperature prevailing during the constant rate period. However, as the wool temperature rises continually throughout the falling rate period, the rate curve should everywhere be above the vapor pressure curve drawn. This is seen not to be the case, and the vapor pressure may be eliminated as a possible controlling factor, in this region of the drying curve.

Four other possible mechanisms suggest themselves, any one of which would explain the decrease in drying rate during the falling rate period. These are:

(a) A decrease in the evaporating surface as the larger capillaries become empty, or as the water wedges become smaller, as suggested by Fisher[17], i.e., the wetted surface is a function of the water content, as suggested by Lewis.[1]

(b) Change of mechanism to Case I, as described in the Introduction (resistance to internal diffusion of liquid controlling, with evaporation at surface).

(c) Change to Case III: evaporation in the interior of the solid, resistance to internal diffusion of liquid controlling.

(d) Change to Case IV: evaporation in the interior of the solid, resistance to vapor removal controlling.

The first and second mechanisms presuppose continued evaporation at the solid surface, as distinct from the third and fourth cases. Under conditions of Case II the overall resistance to heat transfer from air to solid should not be affected, and the coefficient H should remain the same as during the constant rate period. The overall temperature difference should be directly proportional to the rate of vaporization. The constancy of H may, therefore, be regarded as a criterion of evaporation from the surface.

The heat transfer coefficient H is also constant when the mechanism is that of Case I, internal diffusion controlling but evaporation at the surface. However, the first and second possibilities are distinguishable by noting the effect of slab thickness during the falling rate period. If the rate falls due to decrease in the wetted area, the rate will remain independent of the slab thickness. On the other hand, if the rate falls due to a change of the drying mechanism to Case I, the rate should be inversely proportional to the slab thickness. Moreover in the latter case the rate curve should be convex to the moisture concentration axis, and very steep at the start of the falling rate period. (See Fig. 4).

Drying by the mechanism of evaporation from the interior of the solid may be distinguished by the decrease in the overall coefficient H from the value found during the constant rate period. Since the vaporization and hence the heat consumption is at points within the interior of the solid, the heat must flow not only through the surface air film as during the constant rate period, but through a surface layer of relatively dry solid.

The third possibility, that of internal evaporation with internal liquid diffusion controlling, should involve a variation in rate with slab thickness similar to Case I; that is, the rate should vary approximately inversely with the slab thickness. In examples of case (d), evaporation in the interior of the slab with resistance to vapor diffusion controlling, that rate is doubtless also an inverse function of slab thickness at any given percent water, so that there is no apparent means of distinguishing (c) and (d).

Thus the criteria of the occurrence of the four mechanisms suggested as explaining the falling rate period are:

(a) Decrease in wetted surface area: no decrease in H: rate independent of slab thickness.

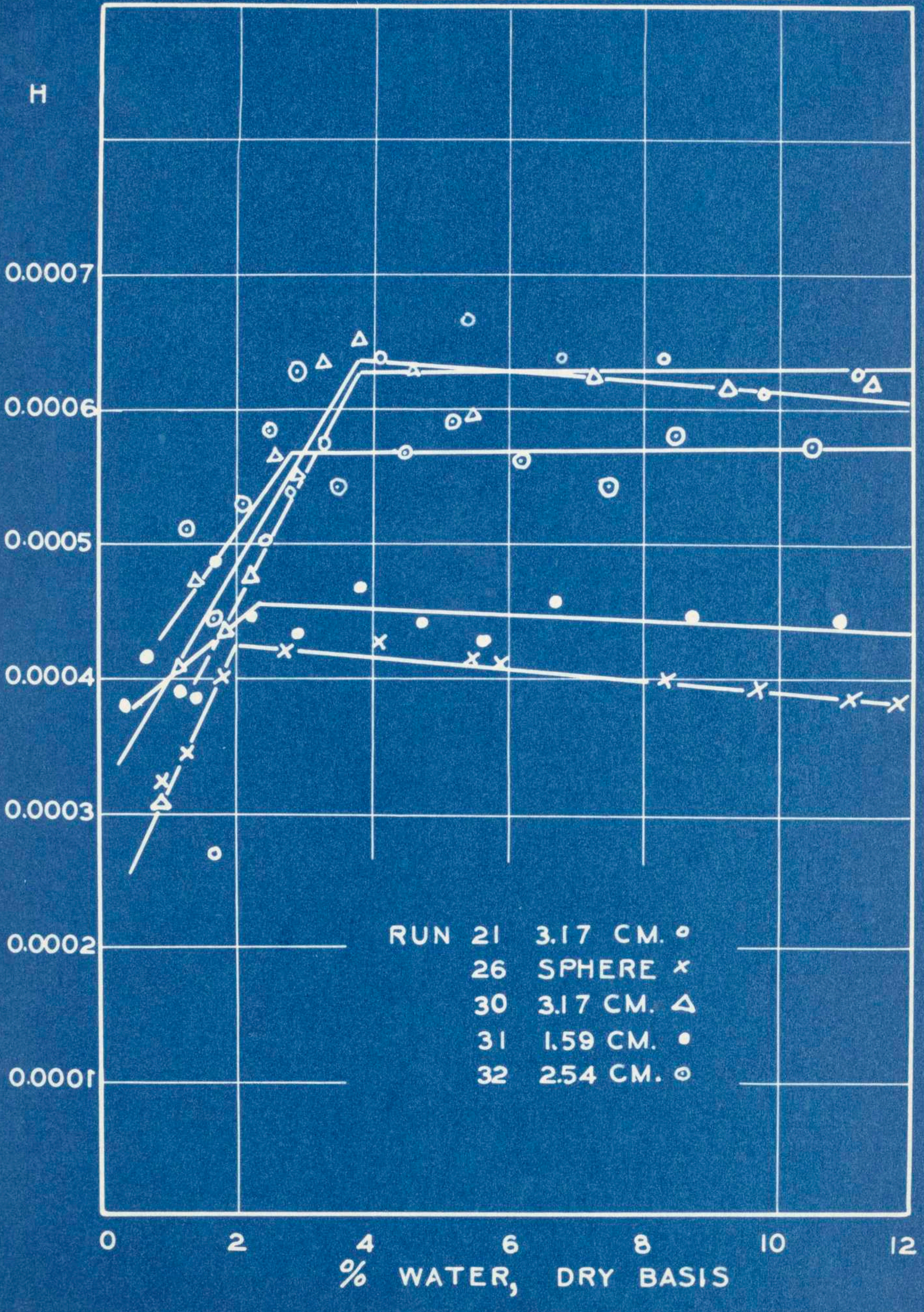
(b) Case I, internal diffusion controlling, evaporation at solid surface: no decrease in H; rate varies inversely with slab thickness.

(c) or (d) Evaporation in interior of the solid: decrease of H.

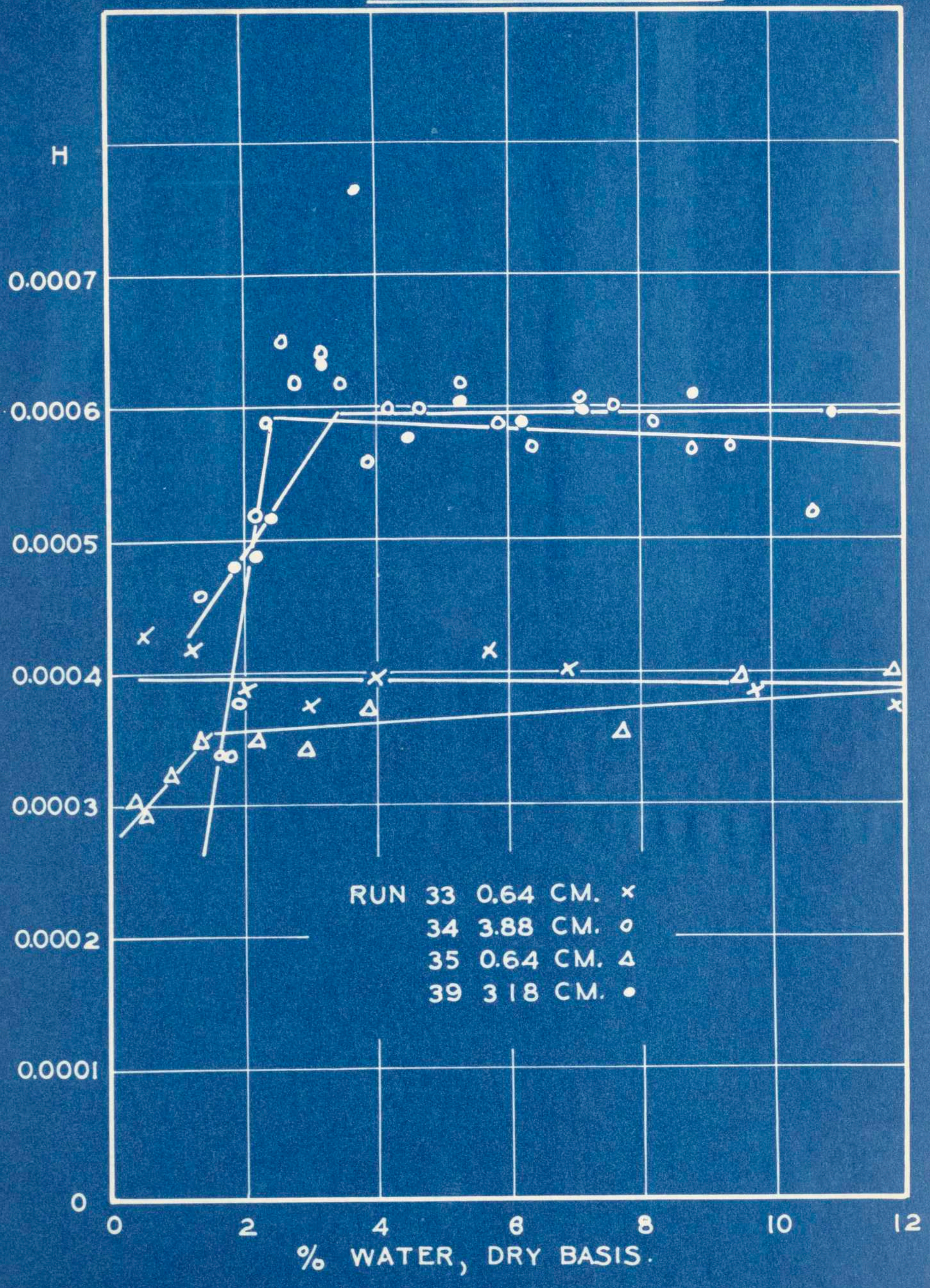
As has been shown, the whiting data indicated that the falling rate period might be divided in zone A and zone A, and it is of interest to apply the above tests to determine the drying mechanism during these periods.

Figs. 24 and 25 show the calculated values of the overall coefficient of heat transfer, H, plotted vs. the water content for the same whiting runs as in Figs. 20 and 21. As discussed in a previous section, the value of H during the constant rate period is found to be a function of the thickness

WHITING AND WATER.



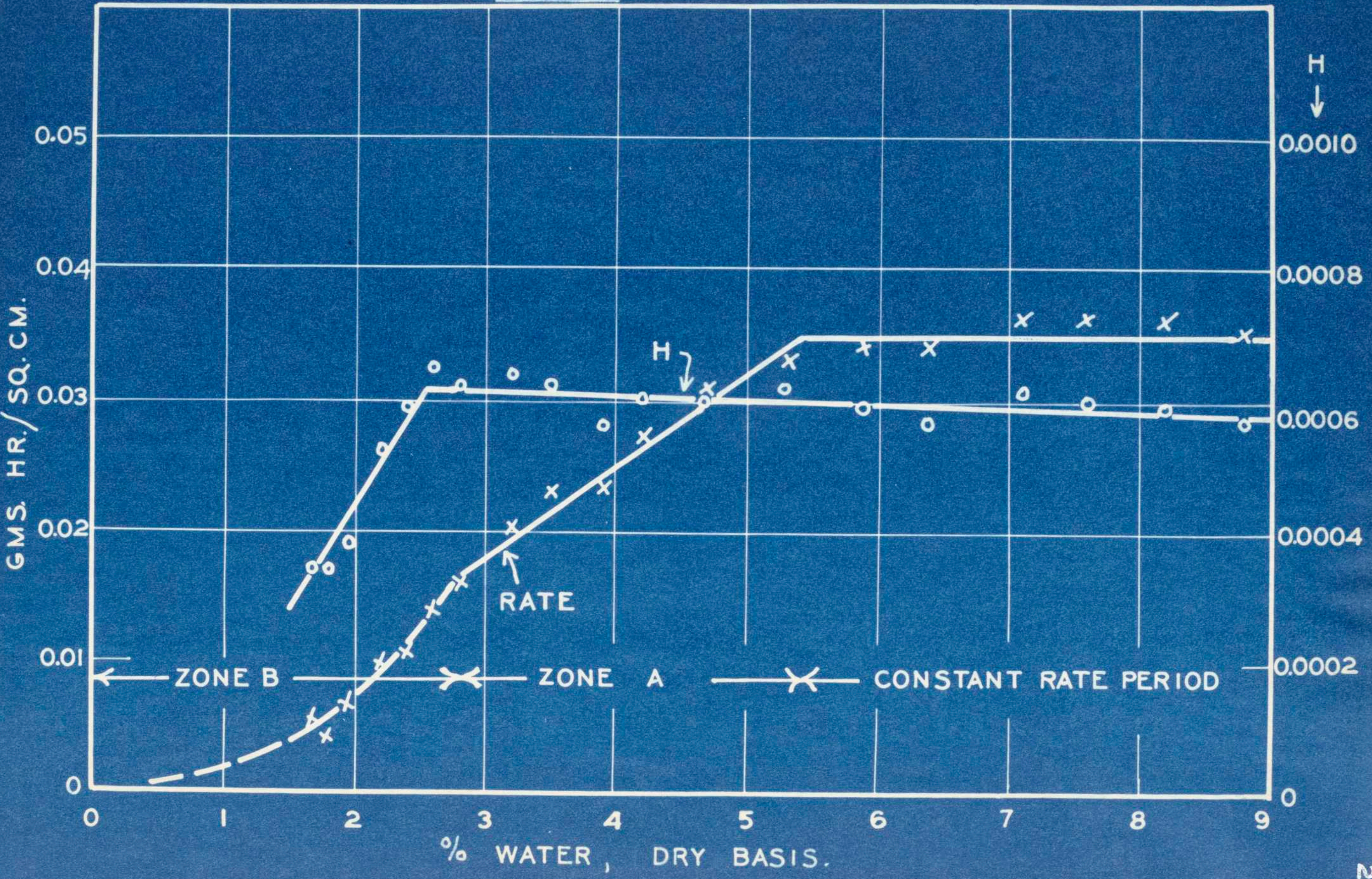
WATER AND WHITING.



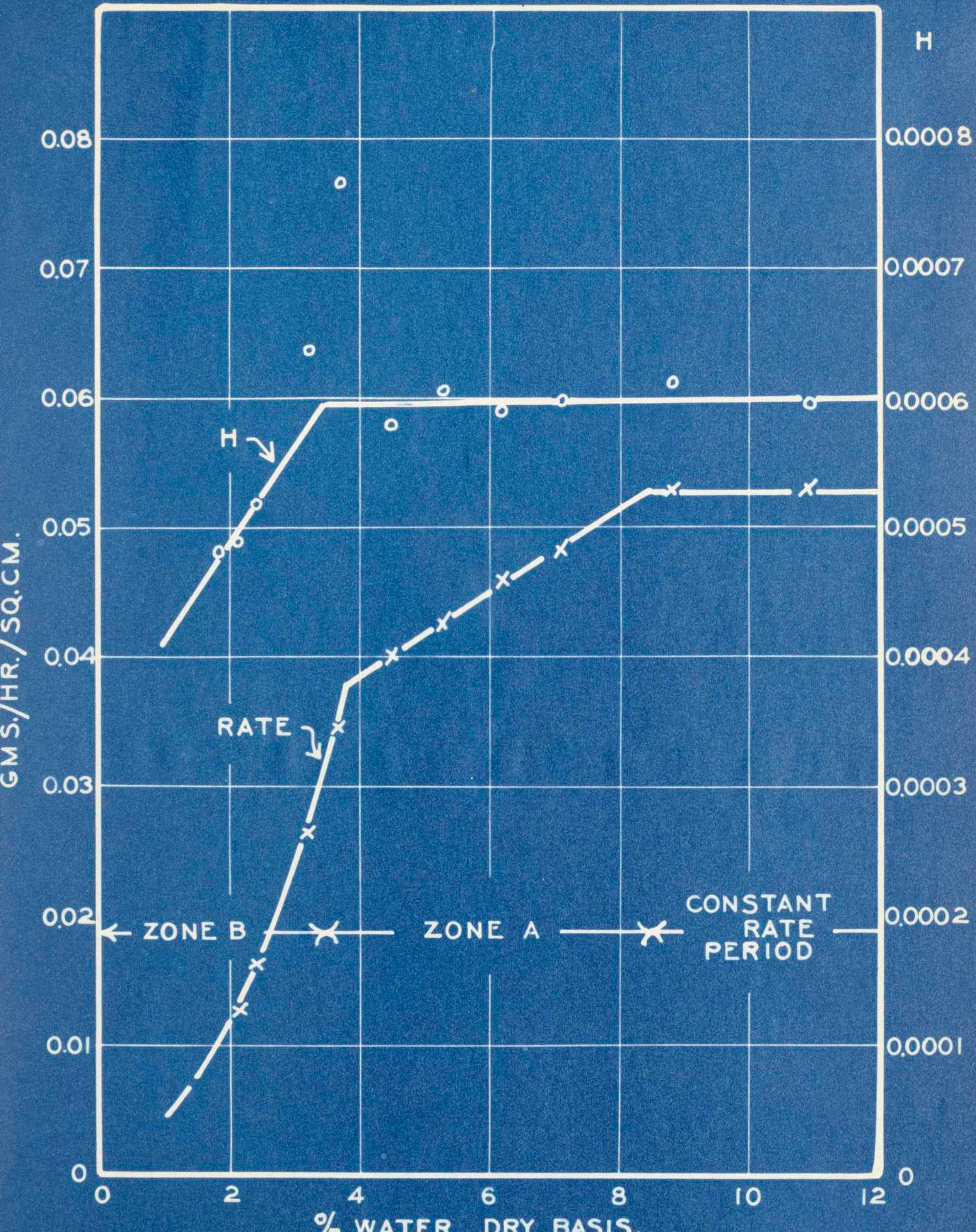
of the sample. It should be especially noted that the breaks in the H curves do not come at the critical moistures for the runs shown. The value of H continues constant as the critical moisture is reached and passed and remains constant over the first portion of the falling rate period. In every case the break in the H curve occurred almost simultaneously with the discontinuity in the rate curve, i.e., H remains constant in zone A. This is brought out more clearly by Figures 26 and 27,which show both the rate and H vs. moisture content on the same plot, for runs 34 and 39 respectively.

From the data shown it is evident that for whiting the overall coefficient of heat transfer H is constant over zone A of the falling rate period. Furthermore, the rate curves in zone A do not show the initial steep slope, the curvature, nor the relation to the slab thickness that would be expected if internal liquid diffusion were controlling. It is therefore to be concluded that in zone A the mechanism of drying is the first possibility above: evaporation from the solid surface, decrease of wetted surface with moisture content.

RUN 34. WHITING AND WATER 3.82 CM.



RUN 39. WHITING AND WATER 3.17 CM.



In zone B the value of H decreases with water content, indicating the evaporation to be taking place at points beneath the solid surface. In this zone it is also noticeable that the rate varies approximately with the slab thickness. The mechanism of drying in zone B is, therefore, that of (c) or (d) in the above classification. After the beginning of zone B, the evaporation (on the whole) no longer takes place at the solid surface, but from points beneath the surface, and during zone B either the rate of internal diffusion or the rate of vapor diffusion through the relatively dry surface layer is the controlling factor.

It seems evident that the reason for the change of mechanism at the end of zone A is due to a decrease in the rate of arrival of moisture to the surface to a point where it is slower than the rate of vaporization from the surface, allowing for the decreased "wetted area" at this point. Since the rate of vaporization from the surface becomes greater than the rate of supply of water from the interior of the solid, water is removed rapidly from the solid near the surface. A relatively dry surface layer of increasing thickness is formed and evaporation commences at points beneath the surface. If the solid should be dried to too great a distance from the surface, the resistance to vapor diffusion of the "dry" zone would be so great that the rate of removal of vapor would be slower than the rate of arrival of water from the interior, and water would tend to accumulate and reduce the thickness of the "dry" zone. An equilibrium is, therefore, established between the thickness of this layer and the rate of internal diffusion of water. The quantitative relations to fit the case will be derived in a later section on the drying of pulp.

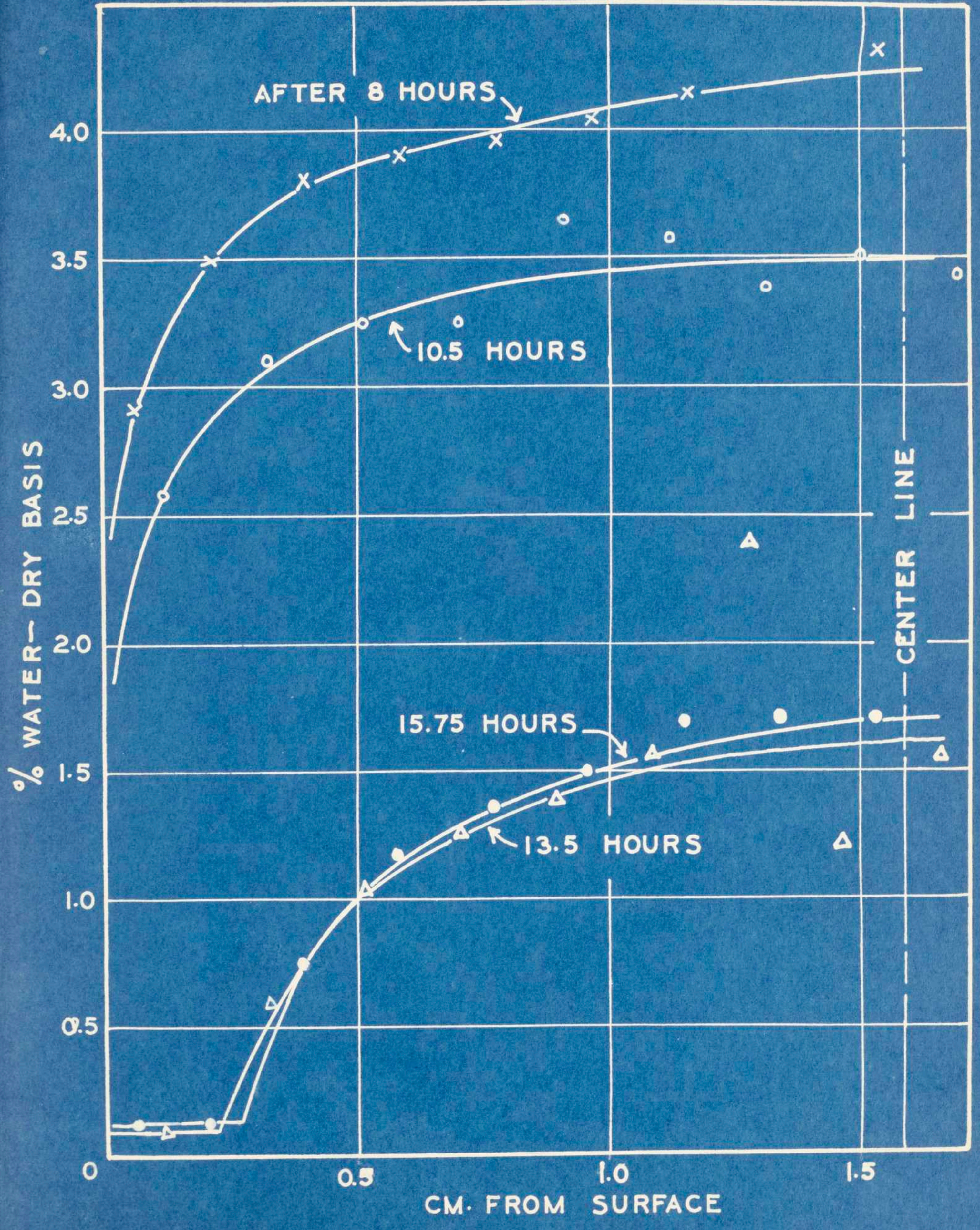
This mechanism of drying with a retreating zone of evaporation may be likened to the combustion of a gas-air mixture in a tapered pipe, the mixture flowing from small to large end. Here the flame front will take up a position at the point in the tube where the lineal velocity of the gas feed is equal to the rate of flame propagation. If the rate of gas flow is reduced, the flame front retreats toward the small end of the tube.

MOISTURE GRADIENTS IN WHITING

Two runs (38 and 39) were made to obtain moisture gradient data during the drying of whiting slabs. The slabs tested were each 3.17 cm. thick, and the moisture gradients were determined by cutting slices parallel to the drying face, and analyzing the slices for moisture. A separate sample was used for each gradient determined so that the results are not for the same sample, but for identical samples dried simultaneously. Due to their slightly different positions in the drier, the samples dried at slightly different rates, for example in run 38 samples 38c and 38d were sliced after 13.5 and 15.75 hours respectively and yet the gradient curves obtained almost coincided.

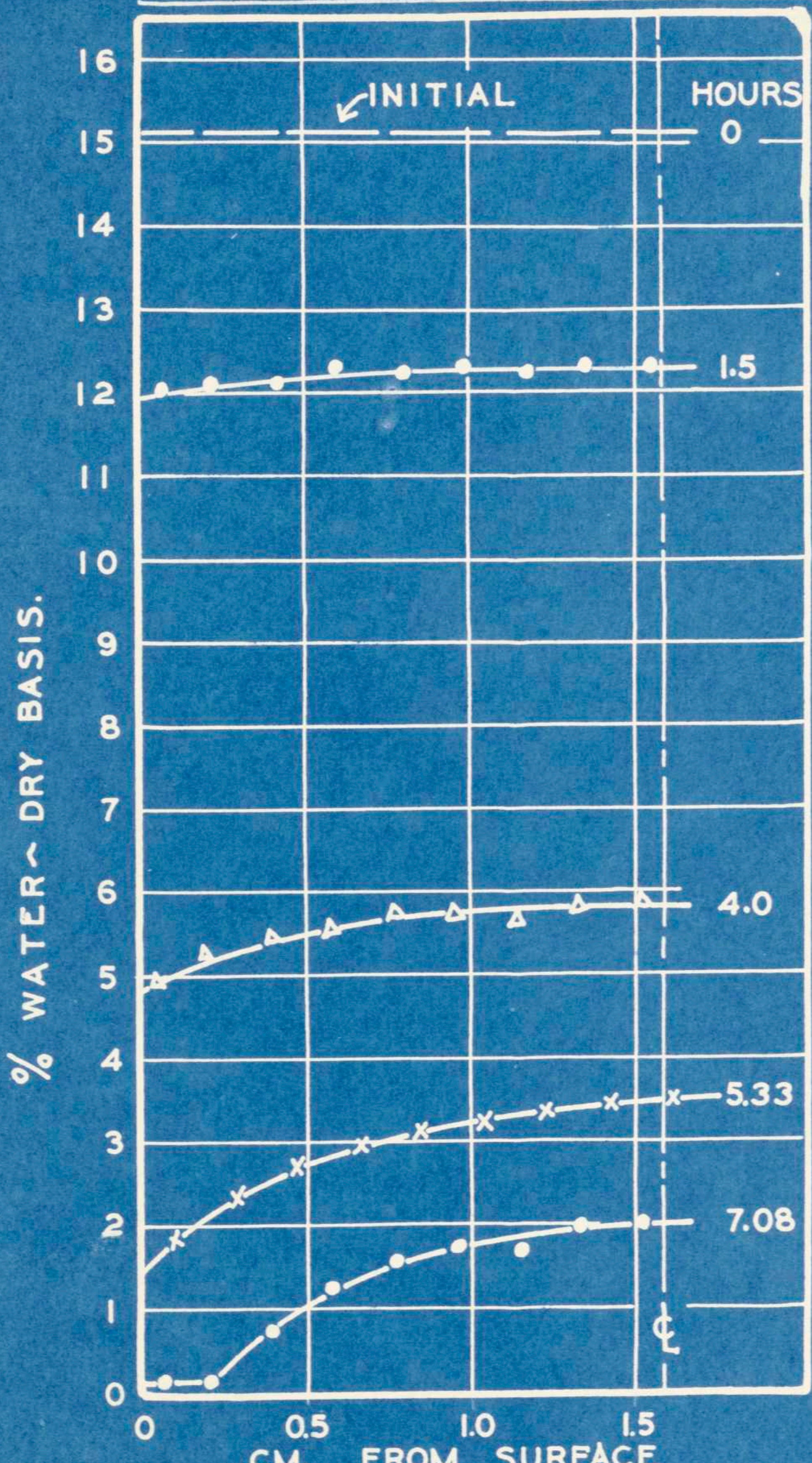
The results of these two runs are shown in Figs. 28 and 29 in which the moisture concentration is plotted vs. the position in the slab. The points represent the average moisture concentrations of the slices plotted at abscissae representing the center lines of the slices. Fig. 29 shows the moisture distribution to be almost uniform during the constant rate period. Sample 39 dried at the same time but not sliced, showed a critical moisture of about 8.5% and Zone A to end at about 4% water (see Fig. 21). The second gradient curve was, therefore, obtained during zone A, and the third and fourth in Zone B. In this second gradient curve, corresponding to an average water content of about 5.5% (Fig. 29), the slope is not greatly different than for the first gradient curve, but the lower curves show appreciably greater slope. This is to be expected if internal diffusion is controlling in Zone B. It should

MOISTURE GRADIENTS IN WHITING ~ RUN 38.



RUN 39.

MOISTURE GRADIENTS IN WHITING.



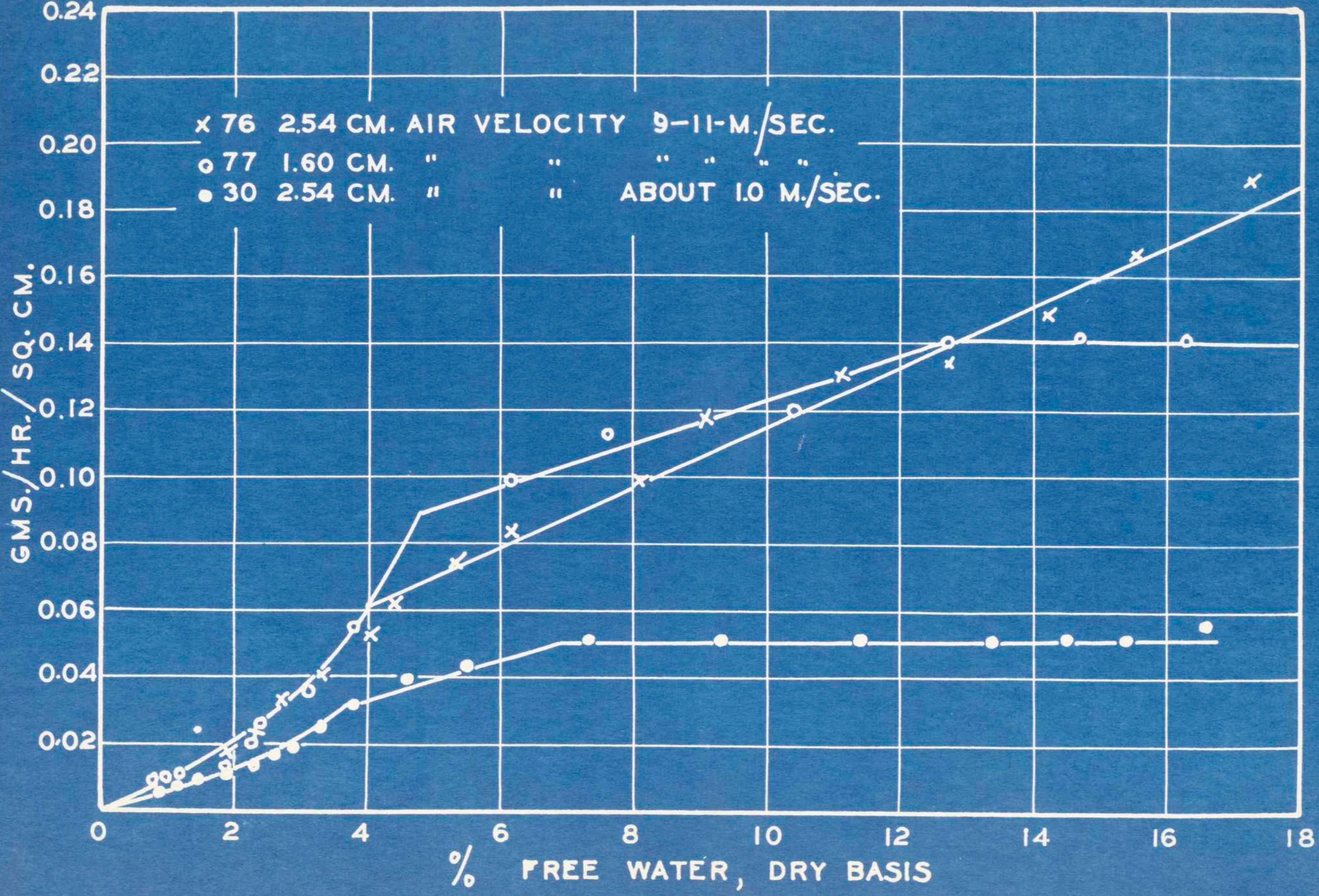
be noted that at low water concentrations in both Runs 38 and 39 the first two slices near the surface show equal very small moisture contents, indicating the formation of a relatively dry layer through which vapor diffuses. An analysis of the moisture concentration gradient during the constant rate period will be made in detail in a later section on the drying of clay.

EFFECT OF AIR VELOCITY ON THE RATE OF DRYING OF WHITING

Two runs were made drying whiting at high air velocities at room temperature. The wet whiting was formed in wood frames lined with tin foil, and the frames removed, leaving the tin foil as a protection against evaporation from the edges. The blocks, 2.54 cm. and 1.60 cm. respectively, were stood on their edges on a balance platform at the end of a duct through which air was forced by a blower. The air flow was parallel to the slab faces, and the velocity, as measured by an anemometer placed in the position occupied by the sample, was between 9 and 11 m. per sec.

The results of these runs are shown graphically in Figure 30 where the rate as gms./hr./sq.cm. is shown plotted vs. the water content.

EFFECT OF AIR VELOCITY ON DRYING WHITING BLOCKS.



The data of Run 30, obtained in the tunnel drier using warm air at low velocity is shown on the same plot for purposes of comparison. The data of Run 77 compares well with that of Run 30. The curve in Zone B is higher and compares with that for Run 30 approximately in inverse proportion to the slab thicknesses, as might be expected. In a later section it is shown that the moisture gradient during the constant rate period is a parabola, and that the difference between the center line and surface concentrations is directly proportional to the drying rate in this range; thus for a given surface concentration the center-line concentration and hence the average water content is greater for the higher air velocity and drying rate. Since it is no doubt the surface concentration which determines the critical water content, the critical water content may be expected to increase with air velocity. Comparison of the curves for Runs 30 and 77 shows this to be the case. The data of Run 76 is harder to explain: no constant rate period is indicated, and the curve for Zone B practically coincides with that of Run 77 for the same range, even though the slab thicknesses are different.

SEMI-LOG PLOTS OF DATA ON THE FALLING RATE PERIOD

The mechanism of drying during the falling rate period has been seen to be complicated, and in the case of whiting this period was divisible into two zones, involving two different drying mechanisms. However, for practical analysis of drying data, and for computations involved in the design and operation of commercial drying equipment, it is of importance to have a simple equation which, even if it is only an approximation, is readily manipulated. Such an equation may be derived by making the assumption that the rate of drying is a linear function of the water content of the material. Although this is seen from Figs. 20 and 21 to be only a rough approximation, the integrated equation will be shown to fit the data surprisingly well.

Two new symbols will be defined: E' is the free water content divided by the free water content at the critical point, and is equal to $\frac{T-T_E}{T_c-T_E}$: θ' is the time after the start of the falling rate period

$$\therefore \frac{dE'}{d\theta} = \frac{1}{T_c - T_E} \left(\frac{dT}{d\theta}\right)$$

$$\frac{dE'}{d\theta'} = \frac{1}{(T_c-T_E)\ A\ \rho\ R} \left(-\frac{dW}{d\theta}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (22)$$

Now if the assumption be made that the rate of evaporation be a linear function of T, then since the rate is zero at $T = T_E$ and equal to the constant rate

$$\left(\frac{dw}{d\theta}\right)_{C.R.} \quad \text{at } T = T_c,$$

$$\left(\frac{dW}{d\theta}\right) = \left(\frac{dW}{d\theta}\right)_{C.R.} \times \frac{T-T_E}{T_c-T_E} \quad \ldots\ldots\ldots\ldots\ldots(23)$$

whence
$$\frac{dE'}{d\theta'} = \frac{E'}{(T_c - T_E)\rho R} \left(\frac{dW}{A d\theta}\right)_{C.R.} \quad \ldots\ldots\ldots\ldots\ldots(24)$$

and
$$\ln E' = \frac{\theta'}{(T_c-T_E)\rho R} \left(\frac{dW}{A d\theta}\right)_{C.R.} \quad \ldots\ldots\ldots\ldots\ldots(25)$$

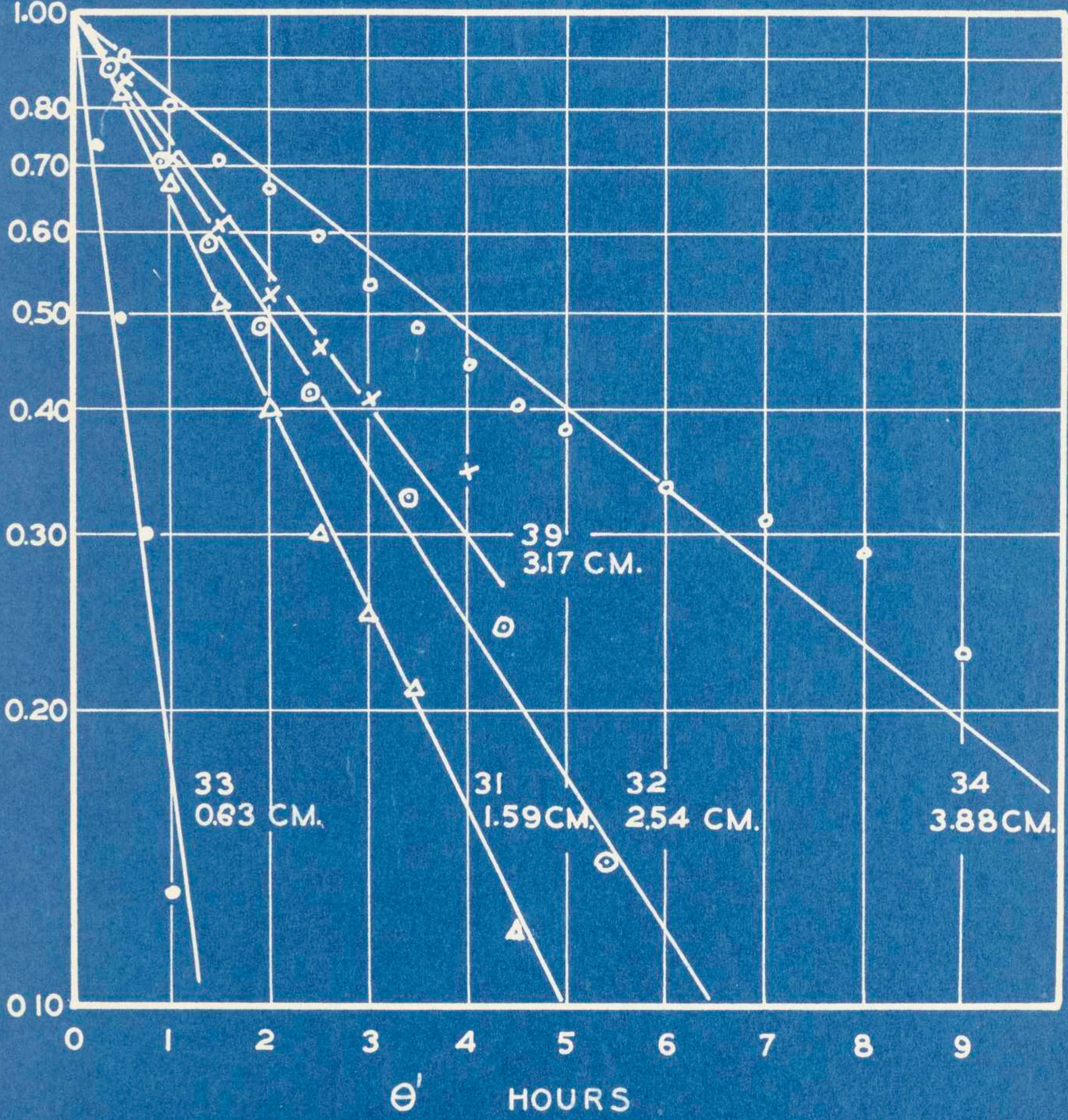
The last equation indicates that as long as (23) holds, a plot of E' vs. θ' on semi logarithmic paper will give a straight line. It should be noted that this will be so no matter what value of T_c is used in calculating E', and it is, therefore, not important to know T_c exactly to obtain this linear relation on semi log paper. In fact T_o may be substituted for T_c and the curve will still be linear over the range where (23) applies. By substituting To for Tc, E' becomes E, so that a plot of E vs. θ on semi log paper will be a straight line over the region where (23) applies. Such a plot would be curved concave downward over the range of the constant rate period.

To illustrate this method of analyzing drying data, the results of Runs 31, 32, 33, 34 and 39 on whiting are shown plotted in Fig. 31. As may be seen from this figure, the resulting curves are approximately straight although the rate curves (see Figs. 20 and 21) are by no means linear over the same range. Equation (25) indicates that the slopes of the curves of Fig. 31 should be inversely proportional to the slab thickness, providing the ratio of the evaporation rate during the constant rate period to $T_c - T_E$ is independent of the slab thickness. Since the slopes of the curves should vary inversely with slab thickness, the time (θ') to reach a given value of E' should vary directly with the thickness. Fig. 32 shows the time to reach a value of E' of 0.20 (i.e., θ' at $E' = 0.20$) plotted vs. the slab thickness, for the runs shown in Fig. 31. The result is nearly a straight line, in spite of the fact that the constant rates varied nearly two fold due to edge effects. Thus an expression of the form

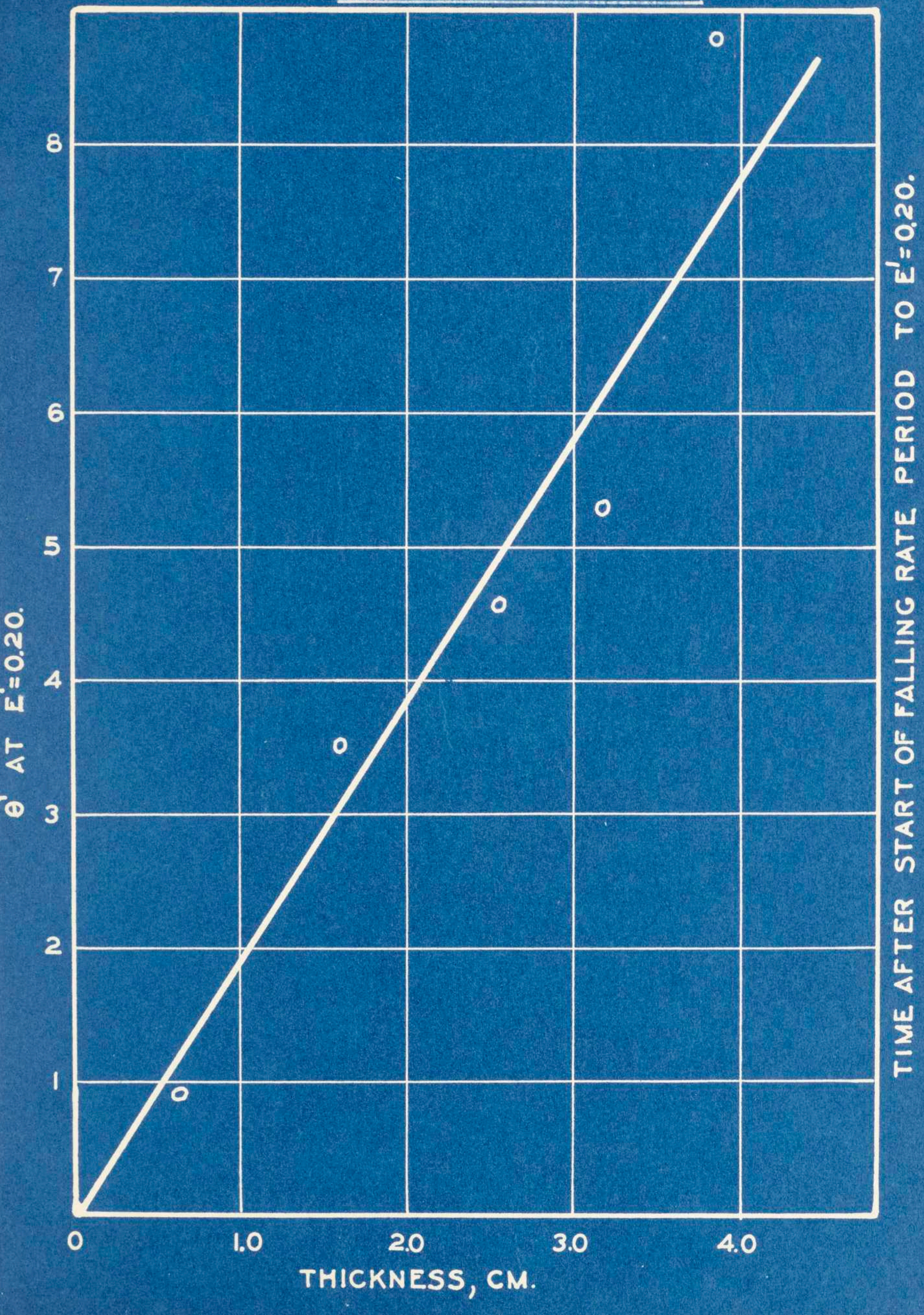
$$\log E' = -\frac{C\theta'}{R} \quad \ldots\ldots\ldots\ldots(26)$$

is seen to approximate the data on whiting for the falling rate period. The actual value of C

WHITING AND WATER.



WHITING AND WATER.



for the conditions prevailing in the experiments described is about 0.36.

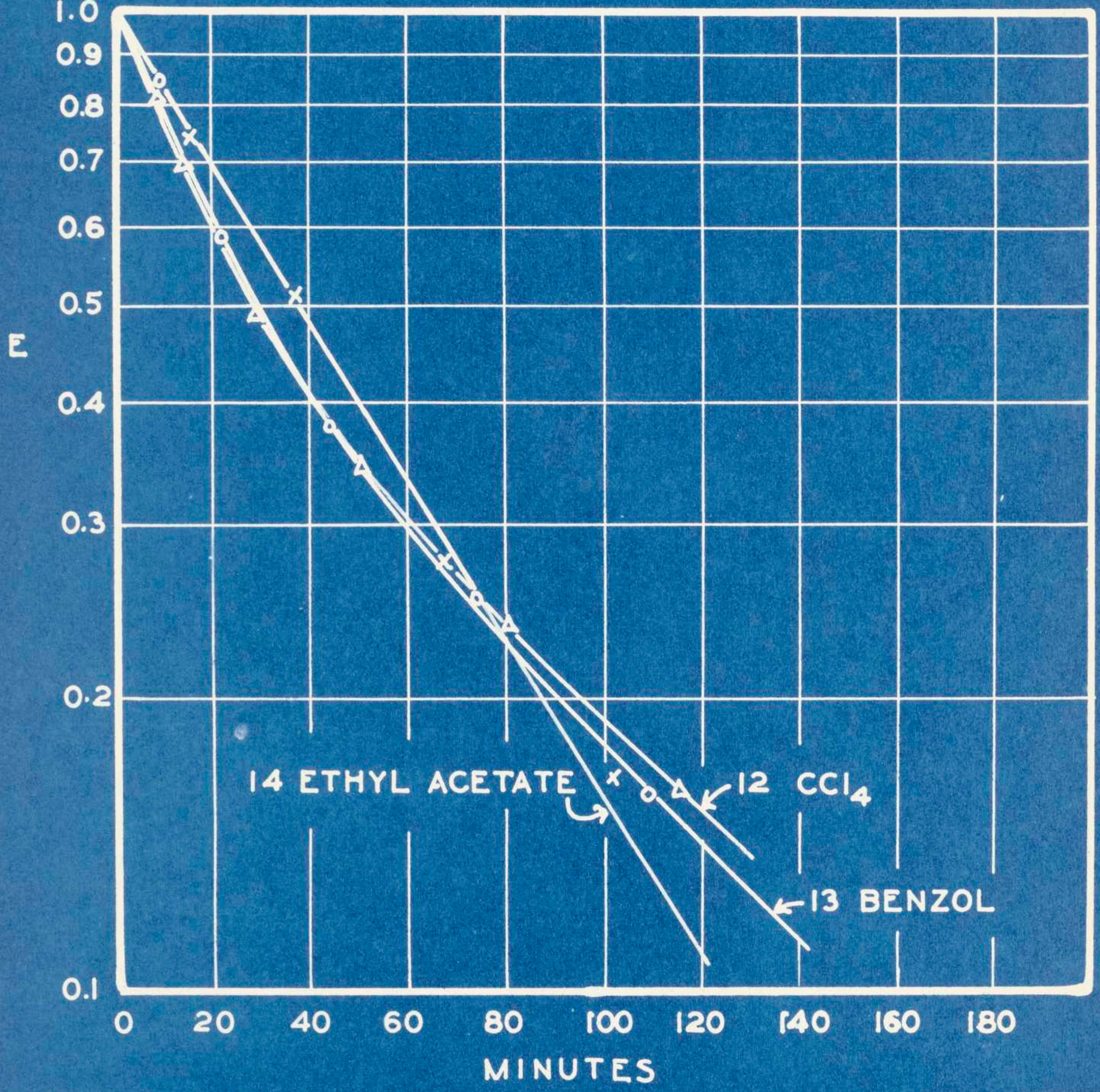
In a later section the data on pulp for the falling rate period will be shown to be susceptible to a similar analysis. The general method of plotting E' vs. θ' is recommended as a valuable aid in the analysis of drying data of various kinds, where an approximate method of prediction is required.

WHITING AND VARIOUS LIQUIDS-FALLING RATE PERIOD

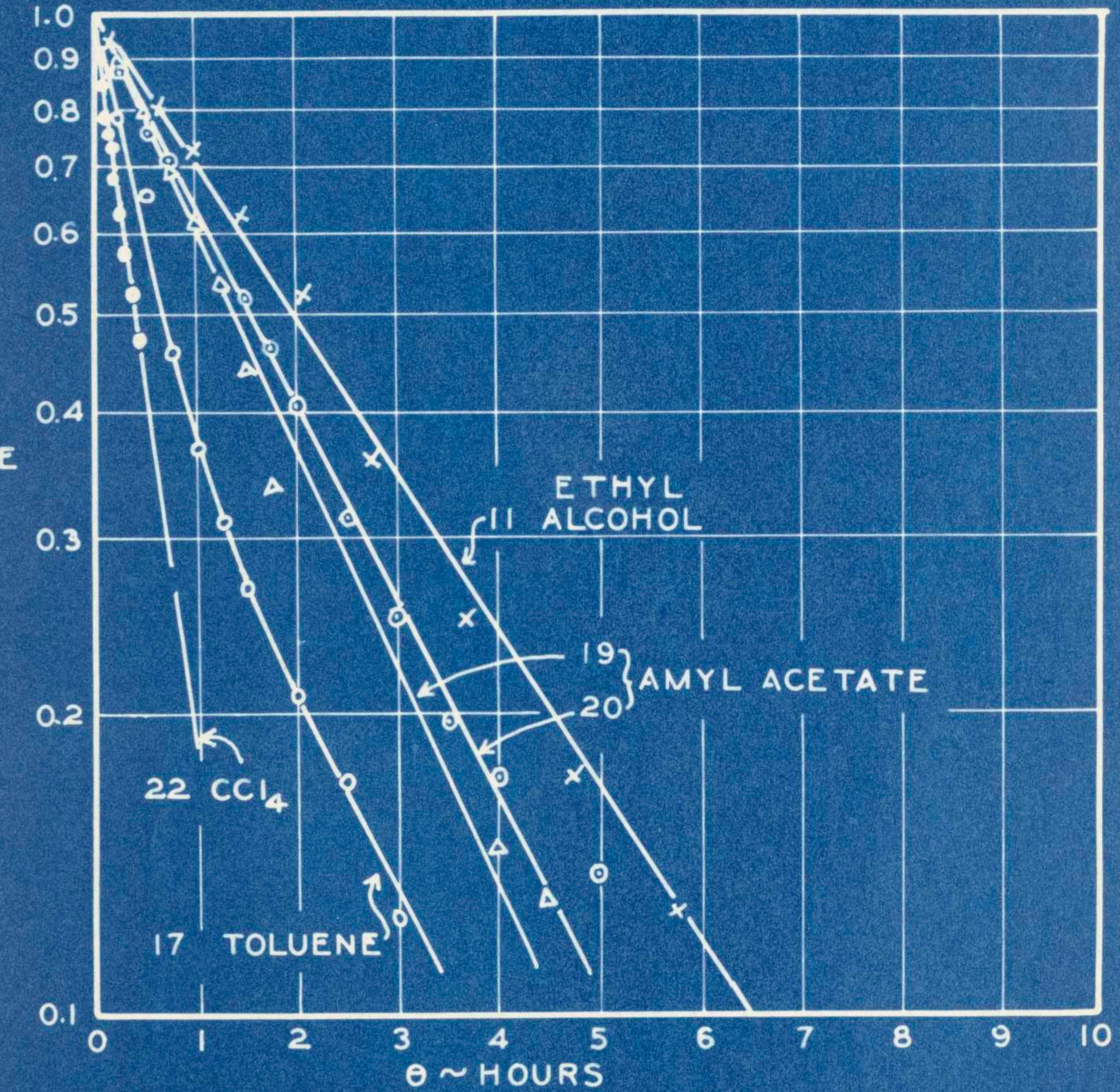
A number of experiments were carried out using the same size whiting blocks, but drying liquids other than water, and it is of interest to analyze these data by the method discussed above of plotting on semi-log paper.

Figures 33, 34, 35 and 36 show the data of runs 11, 12, 13, 14, 17, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28 and 29 plotted as E' vs. θ' for the falling rate period. In most of the above runs, however, no constant rate period occurred, and the data is shown plotted as E vs. θ. The liquids used were ethyl alcohol, carbon tetrachloride, ethyl acetate, benzol, toluol, amyl acetate, water, xylol and acetone. Inspection of these figures shows that the data of most of the runs may be well represented by straight lines but that in four

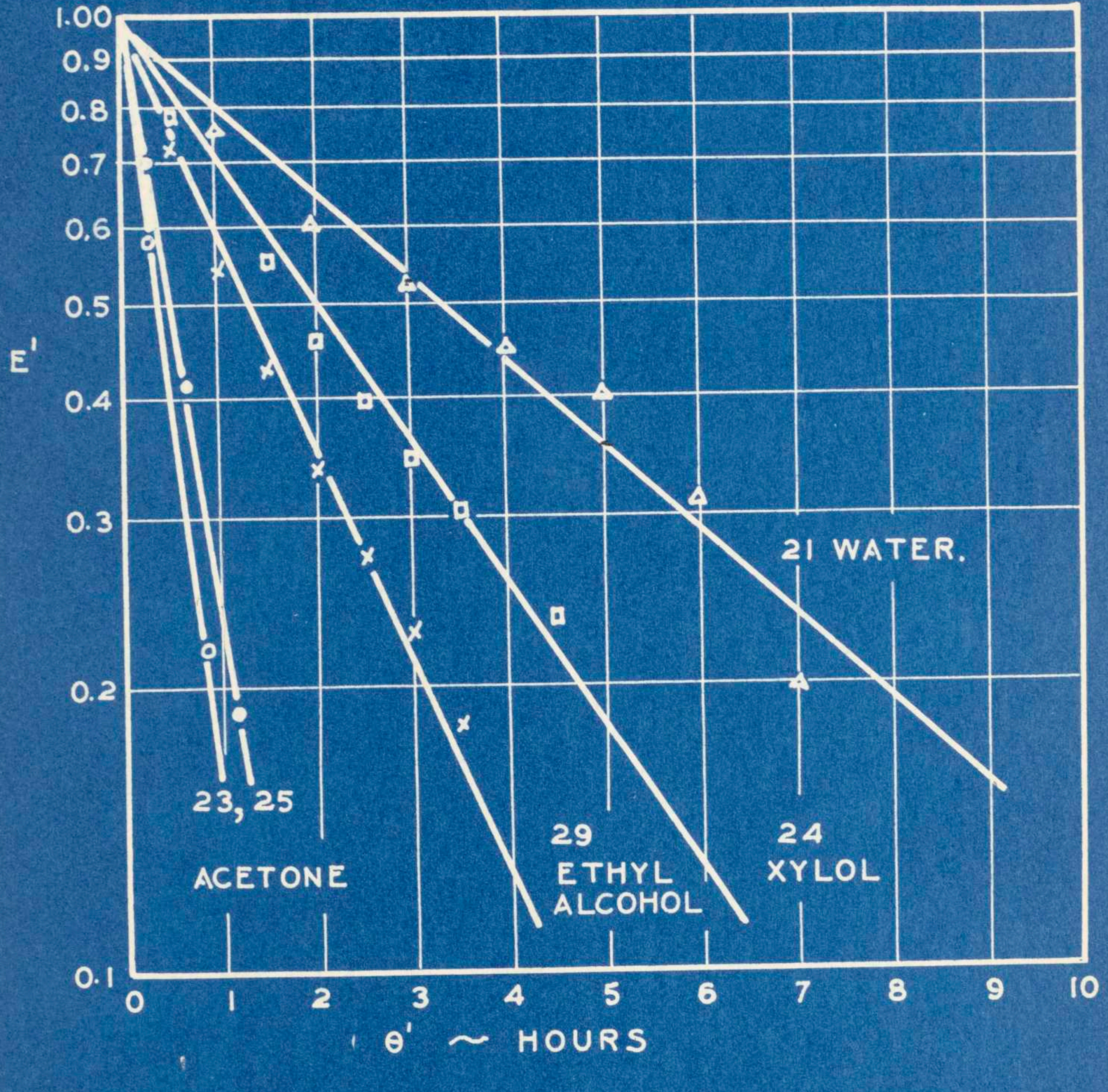
DRYING OF 3.17 CM. WHITING SLABS.



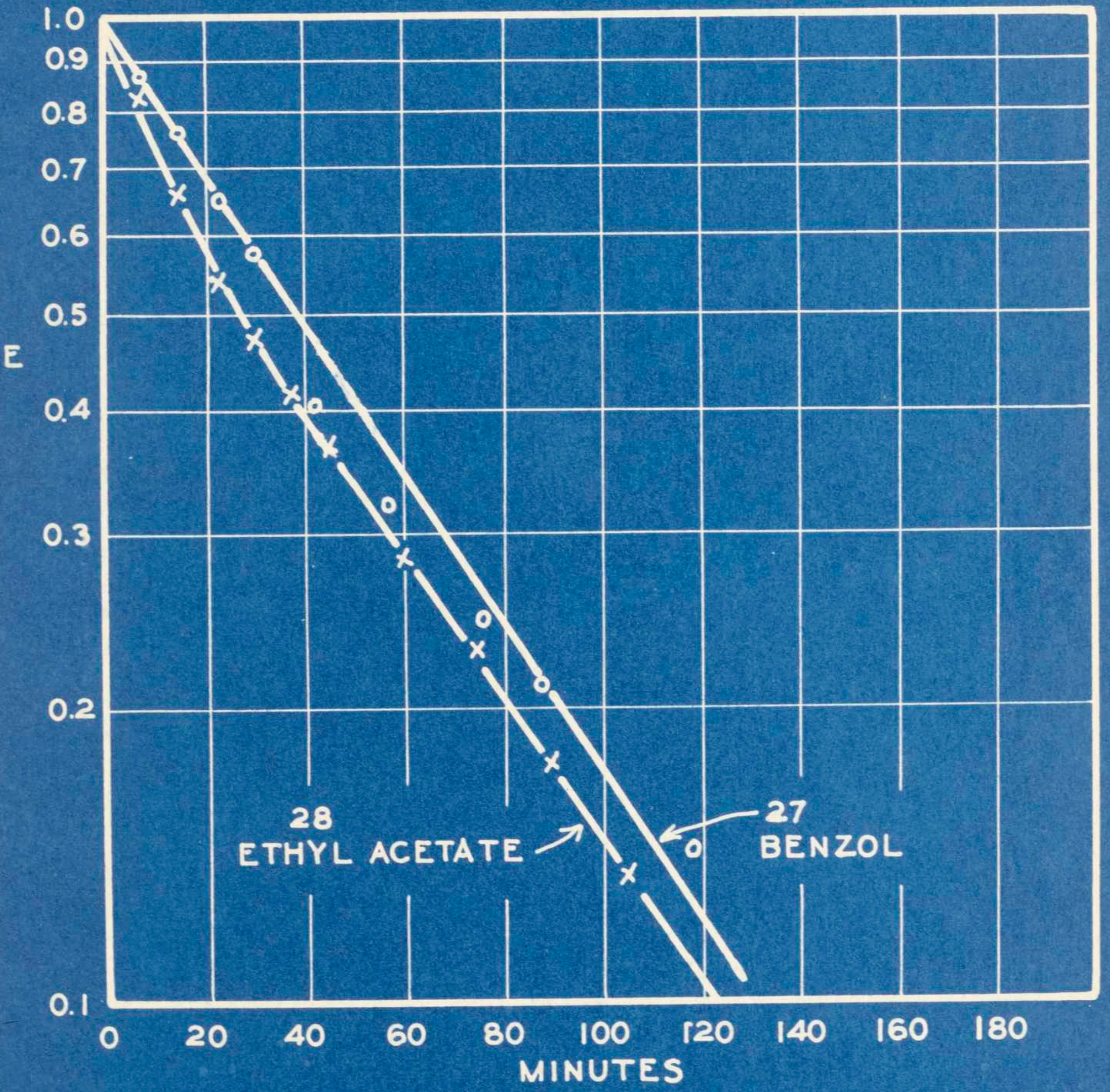
DRYING OF 3.17 CM. WHITING SLABS.



DRYING OF 3.17 CM. WHITING SLABS DURING FALLING RATE PERIOD.

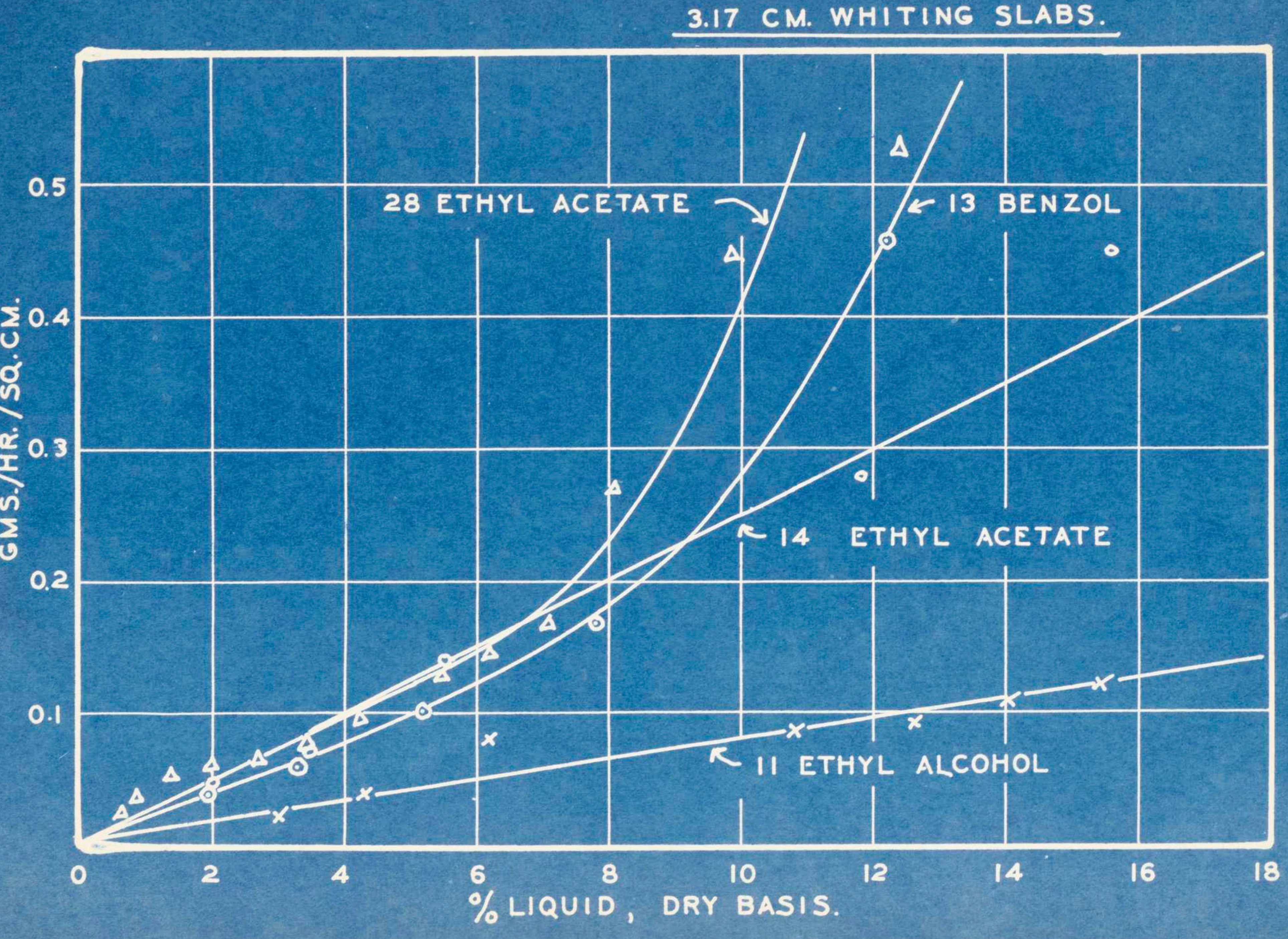


DRYING OF 3.17 CM. WHITING SLABS.

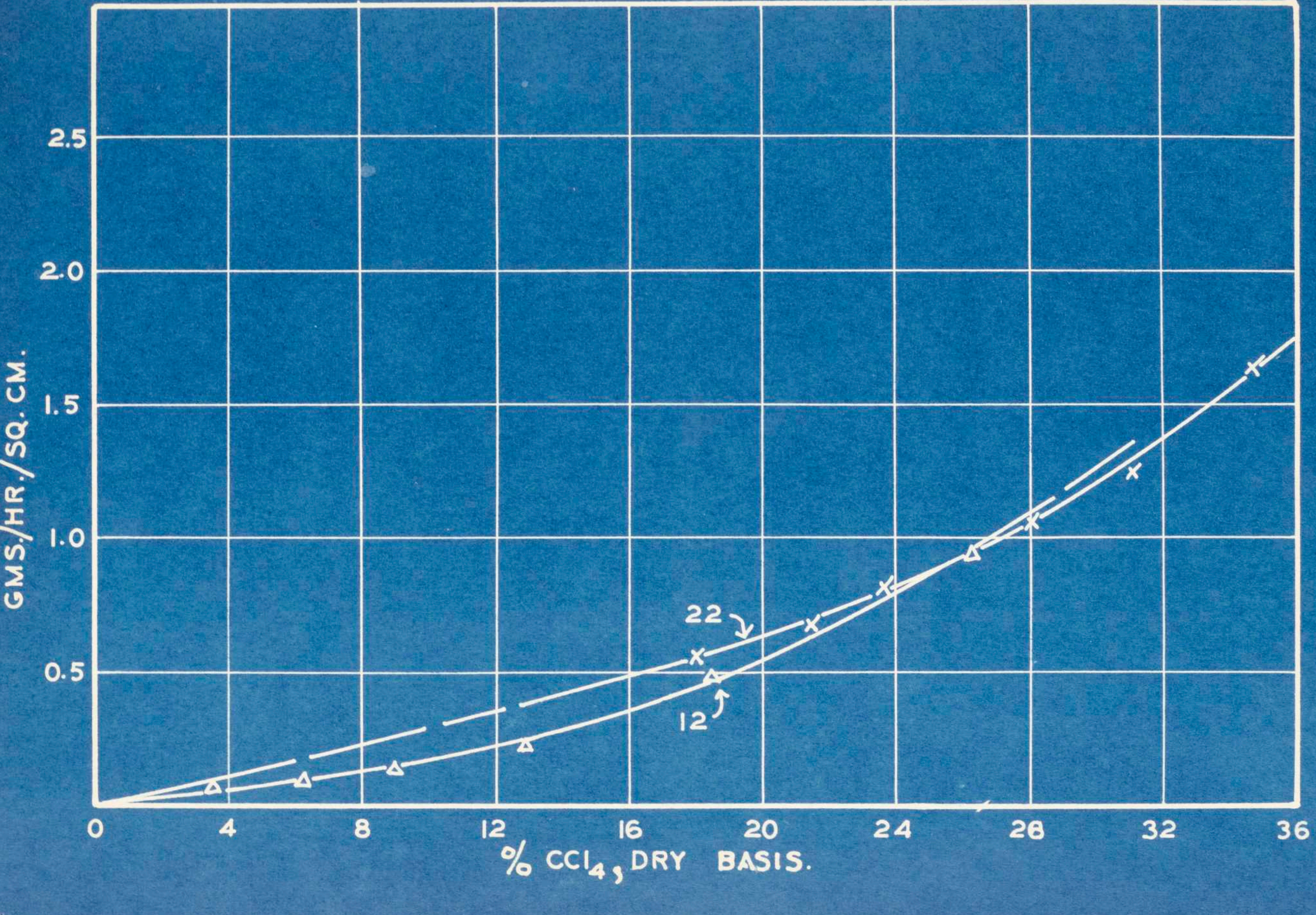


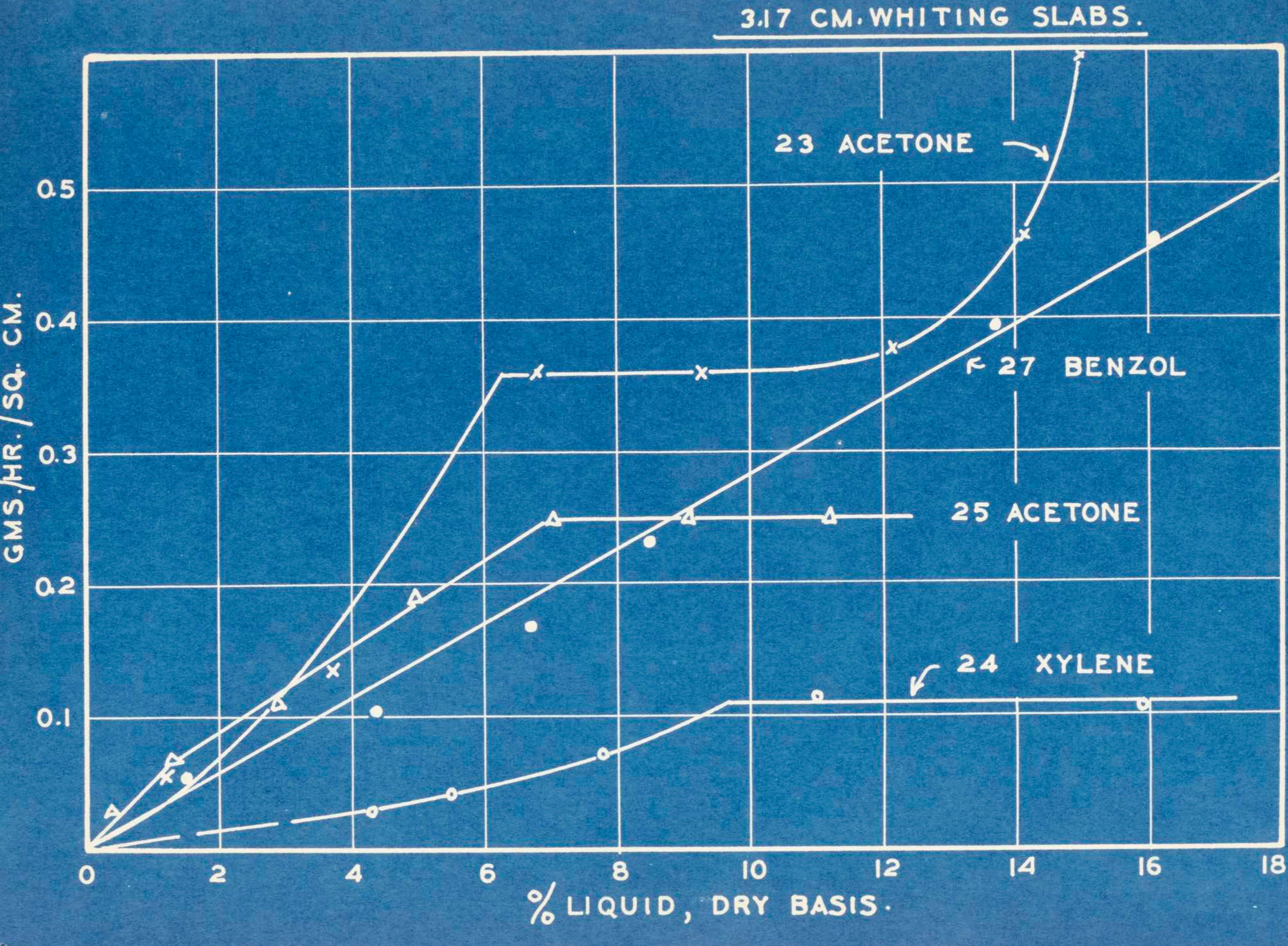
cases the lines are curved slightly concave upwards. The curvature occurs in the case of the more volatile of the several liquids used, and the shape of the curve is suggestive of the theoretical curve for internal diffusion controlling (see Fig. 2). It seems probable that a very volatile liquid would be removed from the whiting by a different mechanism than a liquid such as water, at least during the first part, or zone A, of the falling rate period. The very volatile liquid would evaporate so readily once it reached the surface that the equations for internal diffusion controlling might be expected to apply throughout the drying operation. The similarity in shape between the experimental curves and the theoretical Fig. 2 is not enough to establish the mechanism, and it would be of interest to have data on the effect of slab thickness in order to show this.

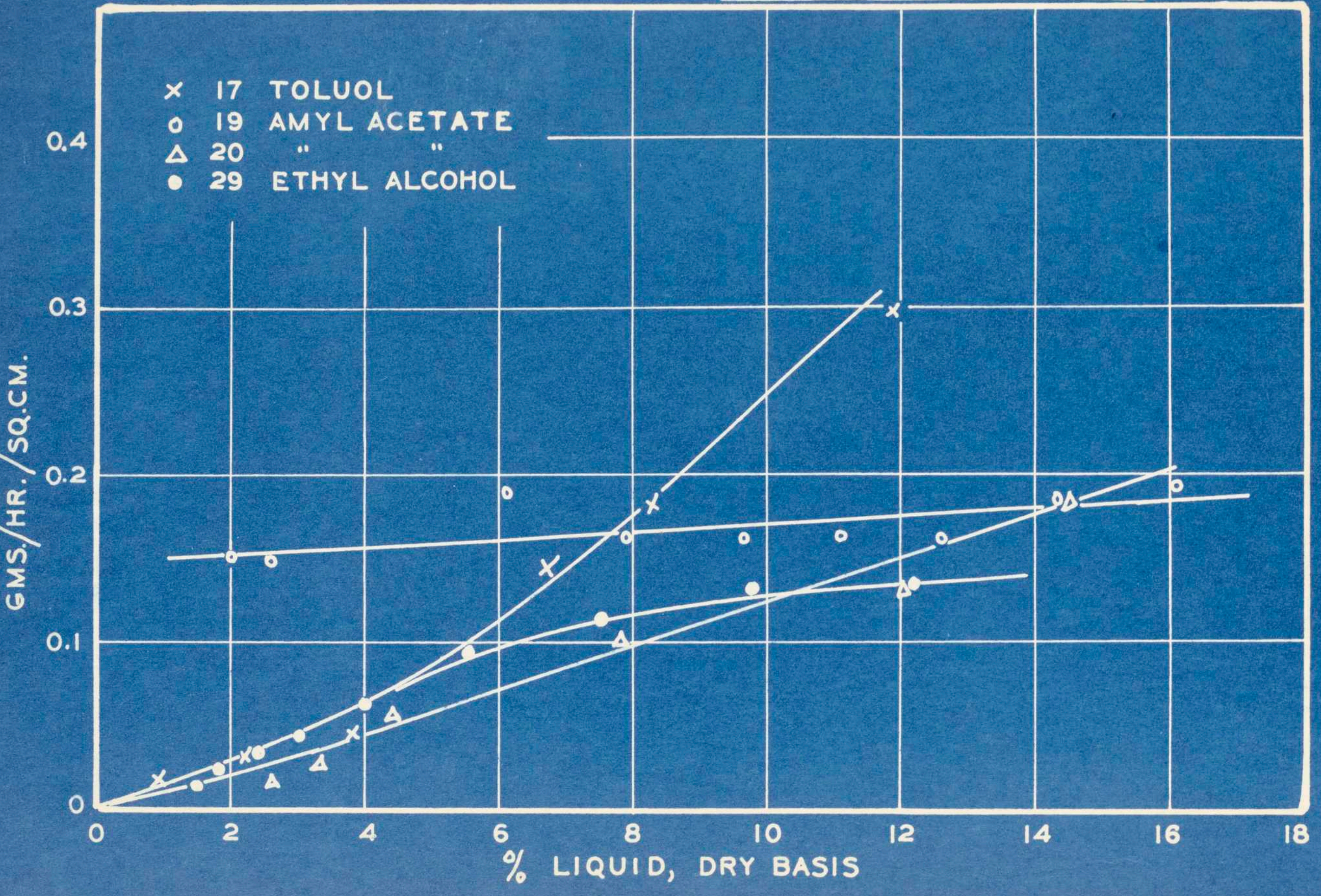
The drying rates for the above runs are shown plotted vs. percent liquid in the whiting, in Figures 37, 38, 39 and 40. Here again the data for several of the runs with very volatile liquids suggests the results obtained when internal diffusion controls, as they are seen to be concave upwards, possibly approaching a vertical asymptote. The hook before the constant rate period in the case of run 23 with acetone corresponds to the period during


3.17 CM. WHITING SLABS.
GMS./HR./SQ.CM.
0.5
0.4
0.3
0.2
0.1
0
2
4
6
8
10
12
14
16
18
% LIQUID, DRY BASIS.
28 ETHYL ACETATE
13 BENZOL
14 ETHYL ACETATE
11 ETHYL ALCOHOL

DRYING OF CCl_4 FROM 3.17 CM. WHITING SLABS.




3.17 CM. WHITING SLABS.
23 ACETONE
27 BENZOL
25 ACETONE
24 XYLENE
GMS./HR./SQ. CM.
0.1
0.2
0.3
0.4
0.5
0
2
4
6
8
10
12
14
16
18
% LIQUID, DRY BASIS.



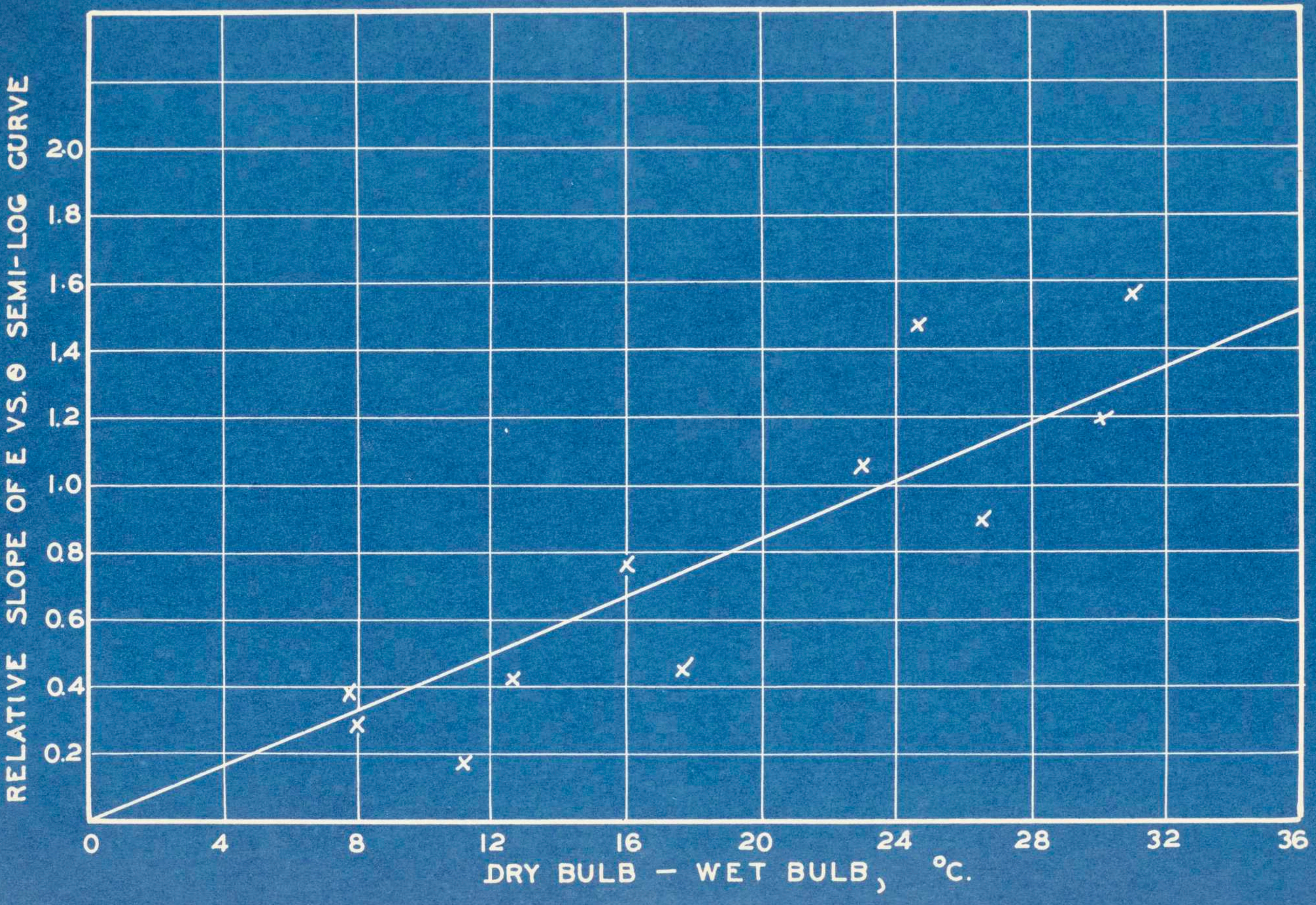
3.17 CM. WHITING SLABS.

which the acetone was being cooled down, and consequently drying at a high rate.

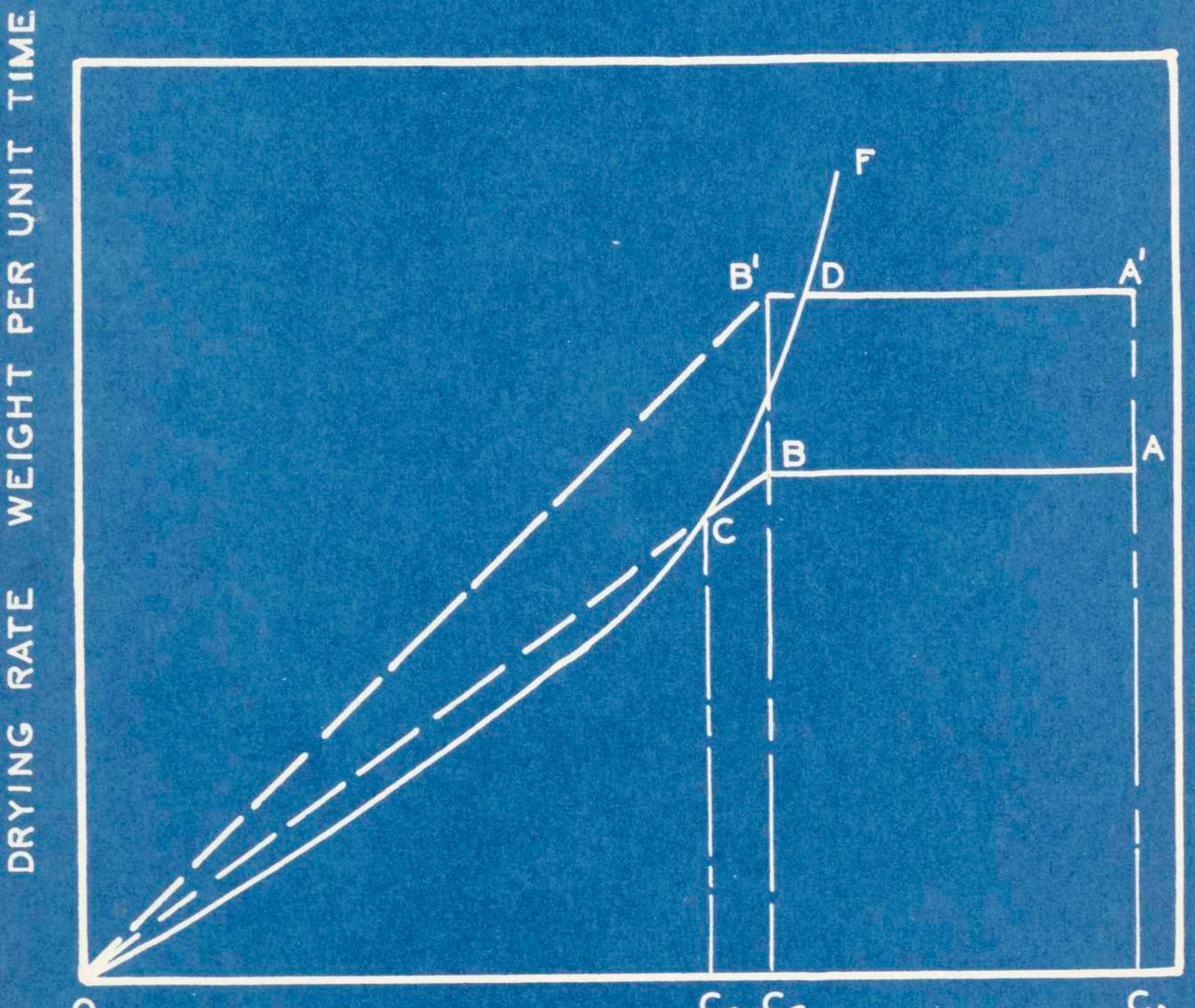
Where surface evaporation controls, and the air velocity and dimensions of the sample are the same in each run, the rate of drying might be expected to be proportional to the wet bulb depression in each case. Thus the slopes of the lines on the semi-log plots may also be expected to be proportional to the wet-bulb depression in each case. Fig. 41 shows the relative slopes of the curves of Figs. 33-36, plotted vs. the approximate wet-bulb depression as measured. The units are such that the relative slope is the reciprocal of the time in hours to reach a value of E or E' of 0.30. A general relation is apparent from this plot, although the wet-bulb depressions were measured only roughly.

Inspection of the tables of calculated data will show that of these runs discussed in this section, runs 17, 22, 23, 25 and 29 showed a continual decrease throughout the falling rate period of the overall coefficient of heat transfer H. These runs, with toluene, carbon tetra chloride, acetone, and alcohol therefore show no zone A. Runs 20, 21, 24, 27 and 28 indicated the value of H to remain constant during the first part of the

3.17 CM. WHITING SLABS WITH VARIOUS LIQUIDS.



falling rate period, i.e., the existence of zone A. The liquids in these runs were amyl acetate, water, xylene, benzol and ethyl acetate. The indication is, therefore, that with very volatile liquids the zone A may be eliminated. Fig. 42 shows diagramatically how this may happen. The rate of drying is shown plotted vs. liquid content for two different liquids which have the same diffusivity in the solid used. O E C D F represents the rate of internal diffusion, and the rate of drying can never exceed values given by this curve. Assume that the liquid content, at which the decrease in wetted area begins to affect the drying rate, is the same for both liquids and equal to C_B. The rate of drying of the less volatile will follow AB from the initial liquid content C_A at A. At B the constant rate period ends and CB represents the first linear portion of the falling rate period, or Zone A. After point C is reached the rate is limited by the rate of internal diffusion and hence follows CEO. The more volatile liquid would have a higher constant rate, following A'DB'. However, the internal-diffusion curve is met before the critical moisture C_B, and the curve D C E O followed. Under such conditions no zone A appears.


DRYING RATE WEIGHT PER UNIT TIME
F
B'
D
A'
B
A
C
O
C_C
C_B
C_A
% LIQUID CONTENT

D - EVAPORATION WITHIN THE SOLID STRUCTURE: THE DRYING OF PULP.

Case I and Case II as described in the Introduction specify evaporation of the liquid from the surface of the solid. Examples illusttrating these cases have been discussed in detail in the foregoing sections. The data on the drying of soap was discussed as an illustration of Case I, and the drying of whiting, clay and pulp during the constant rate period were given as illustrations of Case II. Case III and Case IV specify evaporation of the liquid, not at the surface, but at a point or points beneath the surface of the solid. Case III is that where the resistance to internal liquid diffusion is small, and Case IV is that where resistance to internal liquid diffusion is great, compared to the total resistance to vapor removal.

As an example of evaporation from the interior of the solid structure, the data obtained on the drying of pulp will be discussed in detail. By an analysis of the data it will be shown that the drying of paper pulp in the falling rate period is an example of this mechanism, and furthermore that it is an example of Case IV.

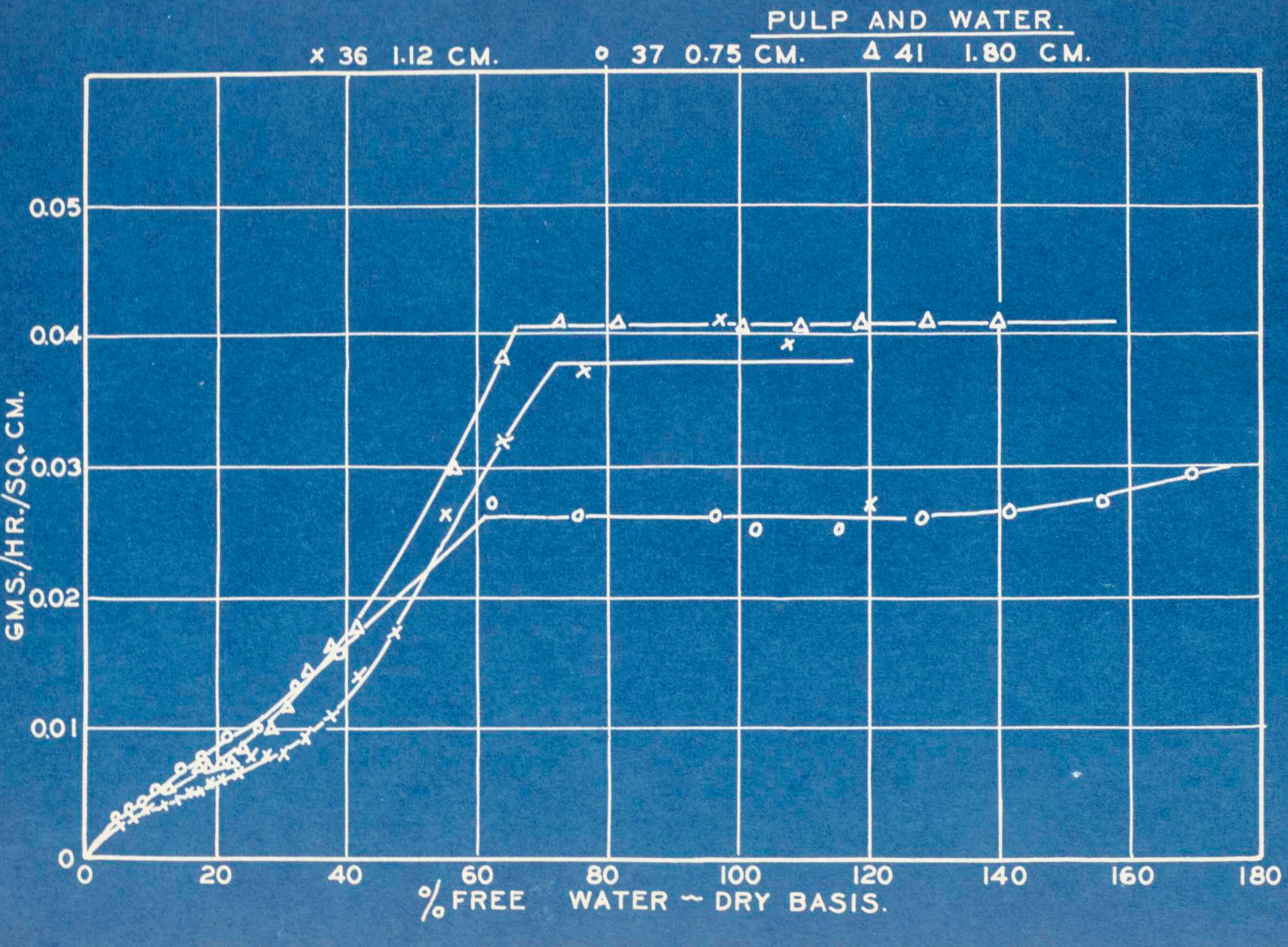
As in the case of whiting, the drying of pulp and water may be divided into a constant rate and falling rate period. (The data showing the effect of air velocity on the drying of pulp in the constant rate period has been discussed in a previous section.)

The critical moisture content, however, is found to be from 40-80% water, as compared with 4-8% for whiting. Figures 43, 44 and 45 show the rate curves for the runs made in the present investigation on pulp slabs, prepared as described under 'Method of Procedure.' In these runs the critical moisture was in every case close to 60%, the moisture contents being expressed as "free" water.

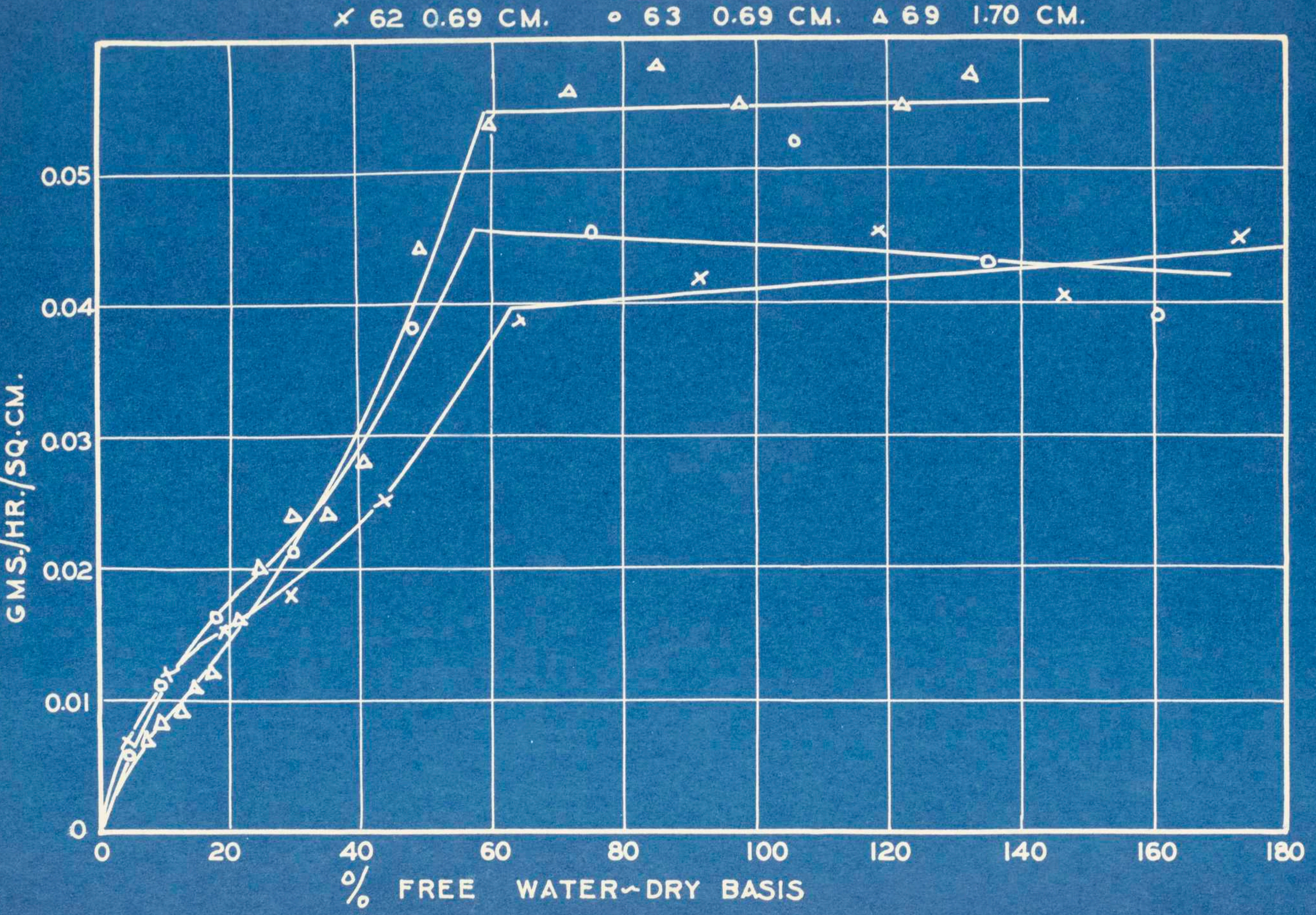
Since the rate of drying is roughly proportional to the water content, equation (26)

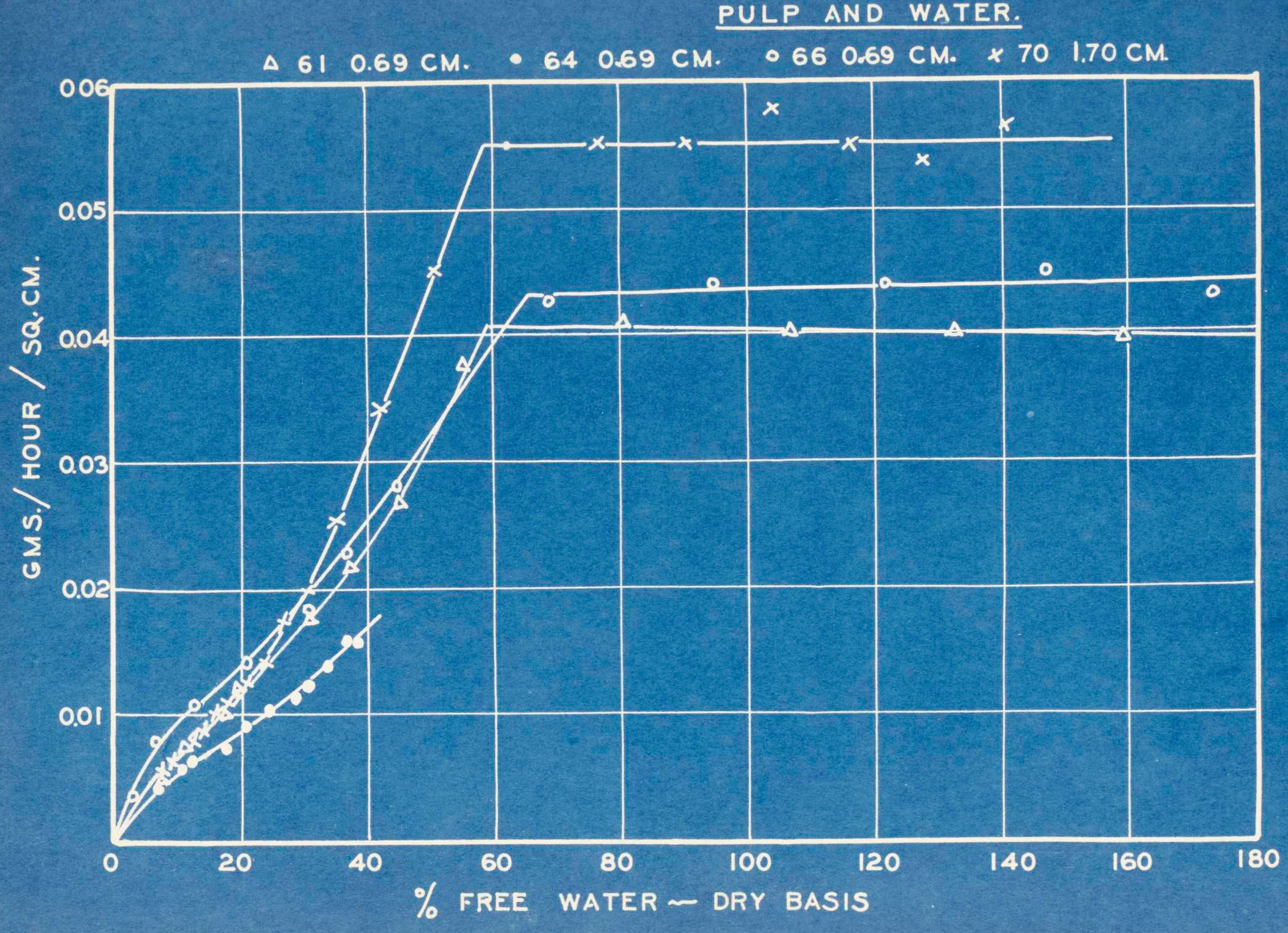
$$\ln E' = (\text{constant}) \frac{\theta'}{R}$$

might be expected to represent the data approximately, for the falling rate period. In order to test this, Figures 46 and 47 have been drawn, showing E' for the above runs on pulp, plotted on semi-log paper against θ', the time after the start of the falling rate period. Approximately straight lines result, indicating the value of this method of plotting in analyzing drying data on pulp for the falling rate period. The slopes of the lines are seen to vary approximately inversely as the slab thicknesses, although they are also affected by the drying conditions.

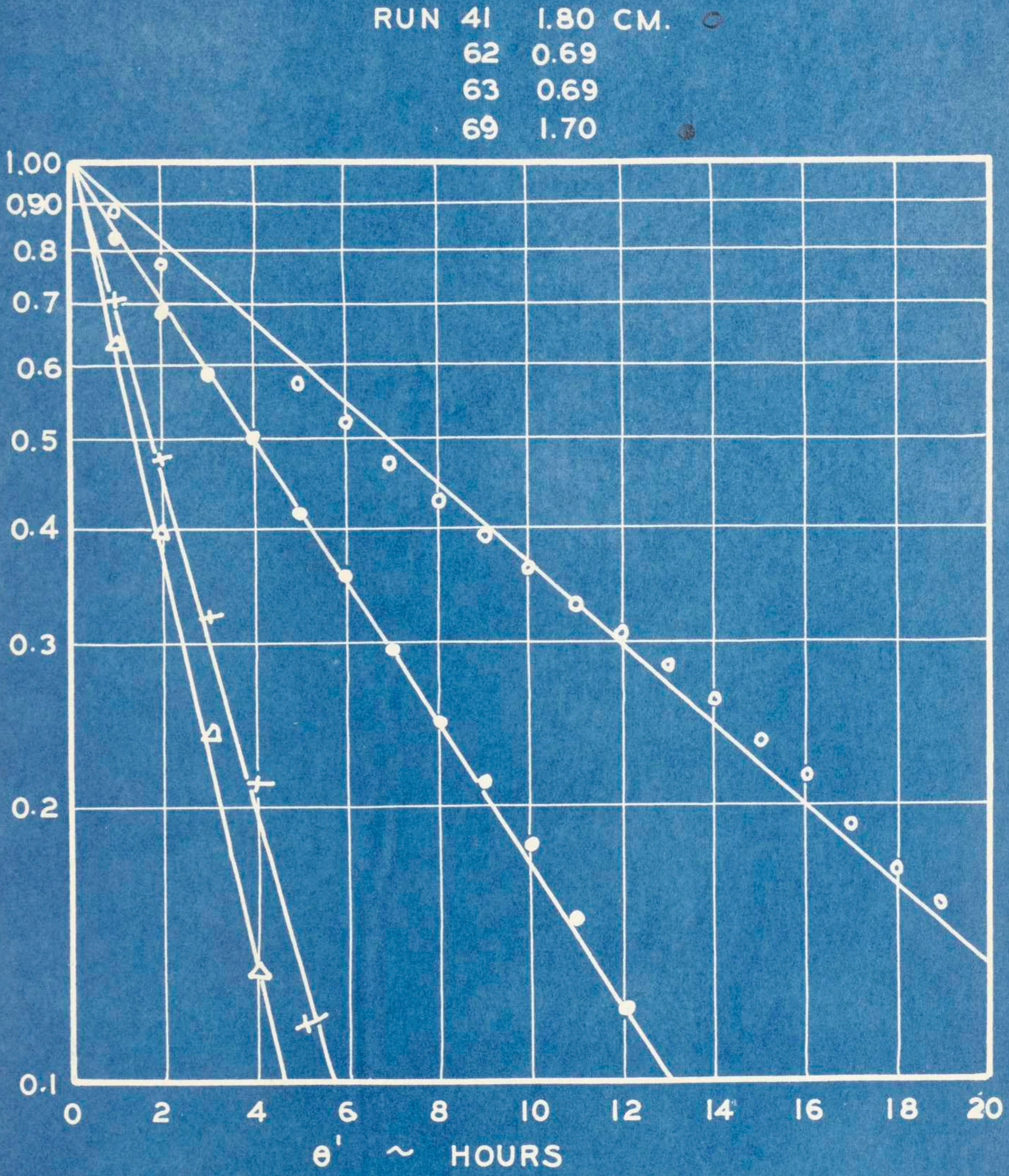

PULP AND WATER.
× 36 1.12 CM.
○ 37 0.75 CM.
Δ 41 1.80 CM.
GMS./HR./SQ. CM.
0.05
0.04
0.03
0.02
0.01
0
0
20
40
60
80
100
120
140
160
180
% FREE WATER ~ DRY BASIS.

PULP AND WATER.

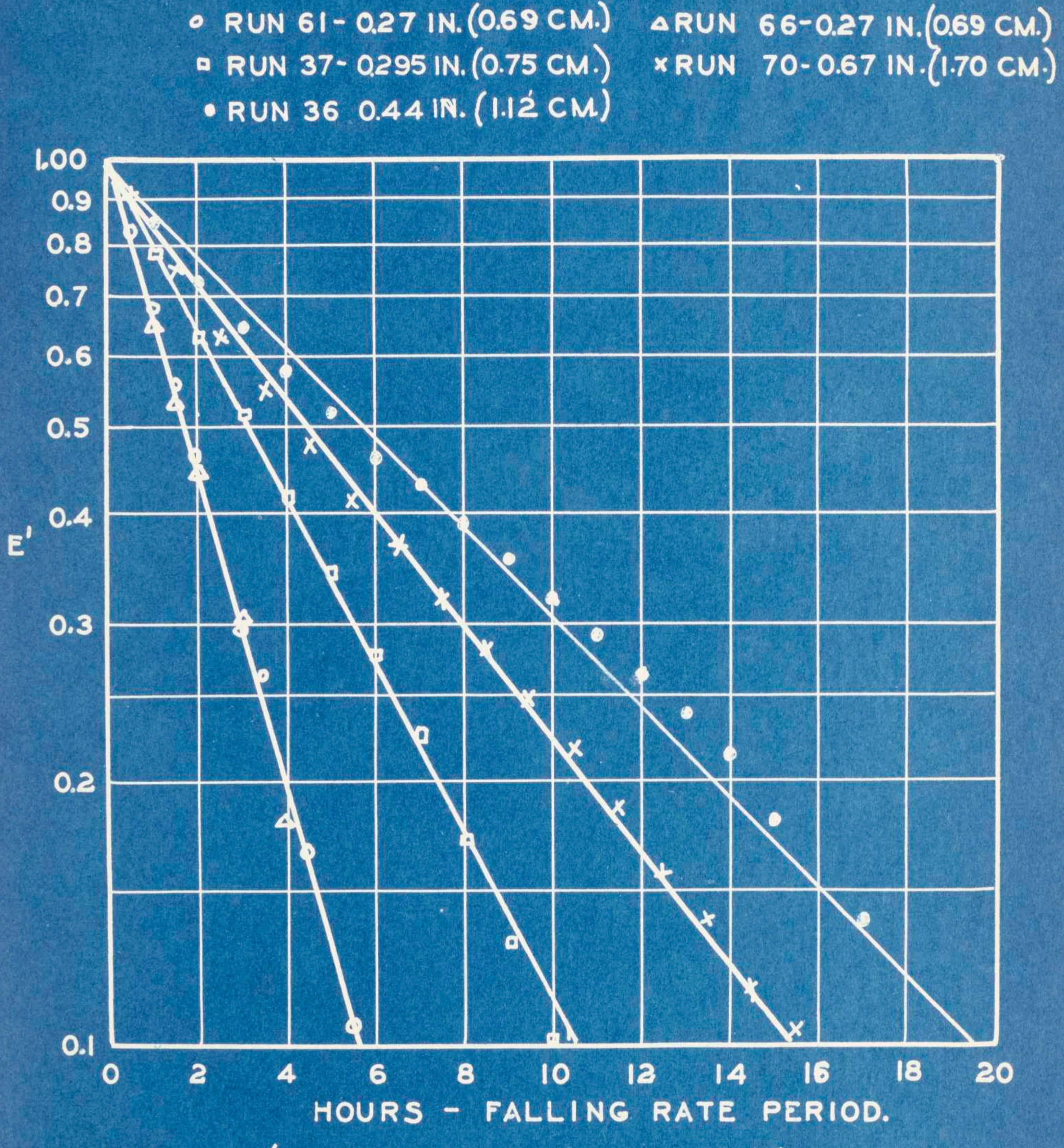



PULP AND WATER.
△ 61 0.69 CM.
● 64 0.69 CM.
○ 66 0.69 CM.
× 70 1.70 CM.
GMS./HOUR/SQ.CM.
0.06
0.05
0.04
0.03
0.02
0.01
0
20
40
60
80
100
120
140
160
180
% FREE WATER ~ DRY BASIS

PULP AND WATER.



PRESSED PULP – FALLING RATE PERIOD.



(SEMI-LOG ORDINATE SCALE)

Equation (25) may be written

$$\ln E' = (\text{constant}) \frac{\theta'}{R} \times (\text{constant rate})$$

from which it will be seen that the slab thickness divided by the product of the constant rate period drying rate and the time to reach a given value of E', should be a constant for all the runs. The following table shows the variation in the calculated values of this constant.

TABLE III

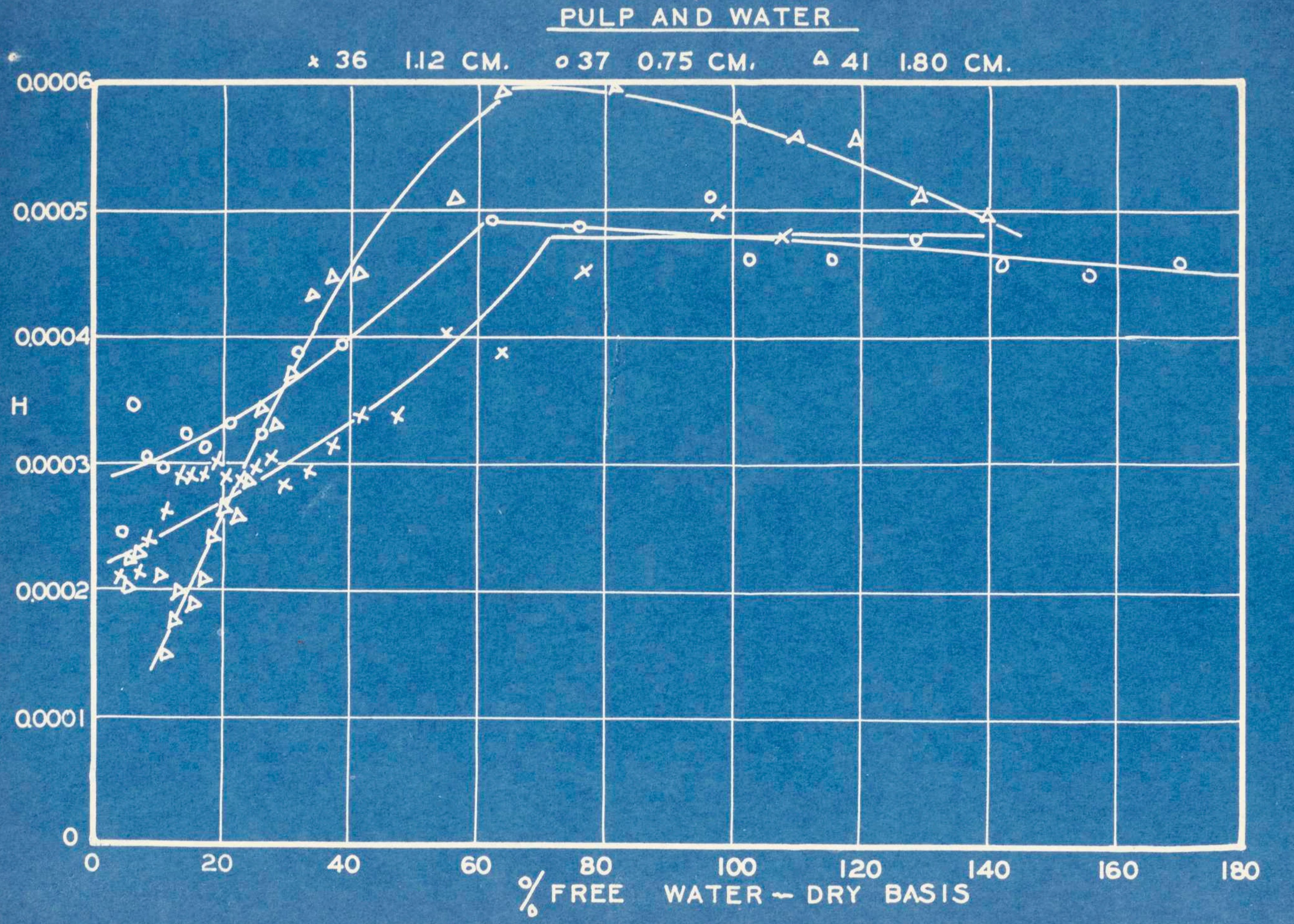
(1) Run	(2) Hours to Reach E' = 0.1	(3) Constant Rate Period Drying Rate gms./hr. per sq.cm.	(4) Thickness 2R cm.	(5) (4)/(2)	(6) (4)/(2)(3)
61	4.6	0.041	0.69	0.151	3.66
62	5.6	0.041	0.69	0.123	3.00
63	4.6	0.044	0.69	0.150	3.41
66	5.6	0.043	0.69	0.123	2.86
37	10.5	0.026	0.75	0.071	2.74
36	19.5	0.037	1.12	0.057	1.55
69	13.0	0.054	1.70	0.131	2.42
70	15.3	0.055	1.70	0.111	2.02
41	22.9	0.041	1.80	0.079	1.91
Average				0.111	2.62
Average percent deviation from average				26	22

From this it is seen that the values of the thickness divided by the time to reach a value of E' of 0.1 are nearly as constant (Column 5) as when corrected for variation in the constant rate period drying rate. This is probably largely due to the fact that variations in the constant rates are due to variations in air velocity, which do not affect the falling rate period greatly. rather than to changes in air humidity.

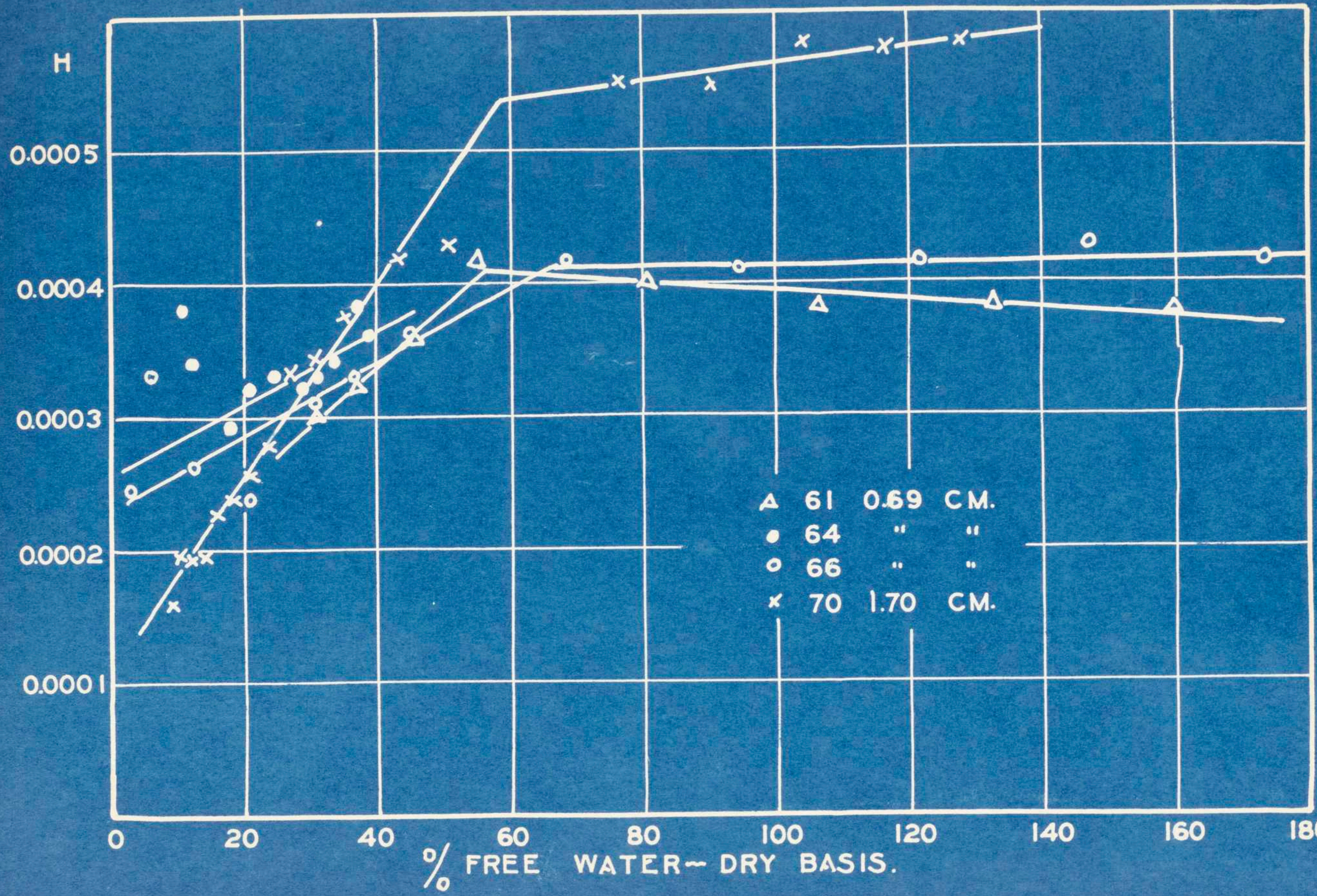
In the case of seven of the ten runs shown plotted in Figures 43, 44 and 45 thermocouples inserted in the sample enabled the overall coefficients of heat transfer from air to pulp to be calculated. The results are shown plotted vs. percent free water in Figures 48 and 49, and it is to be noted that the break in the constancy of the H curves occurs at moisture contents approximating the critical moistures. The following table shows a comparison of the critical moisture contents and the moisture contents corresponding to the breaks in the H curves:

TABLE IV

Run	Critical Moisture	Moisture Content at Break in H Curve
36	72	71
37	61	62
41	65	63
61	59	56
66	65	66
70	58	58


PULP AND WATER
× 36 1.12 CM.
○ 37 0.75 CM.
△ 41 1.80 CM.
0.0006
0.0005
0.0004
H
0.0003
0.0002
0.0001
0
0
20
40
60
80
100
120
140
160
180
% FREE WATER ~ DRY BASIS

PULP AND WATER

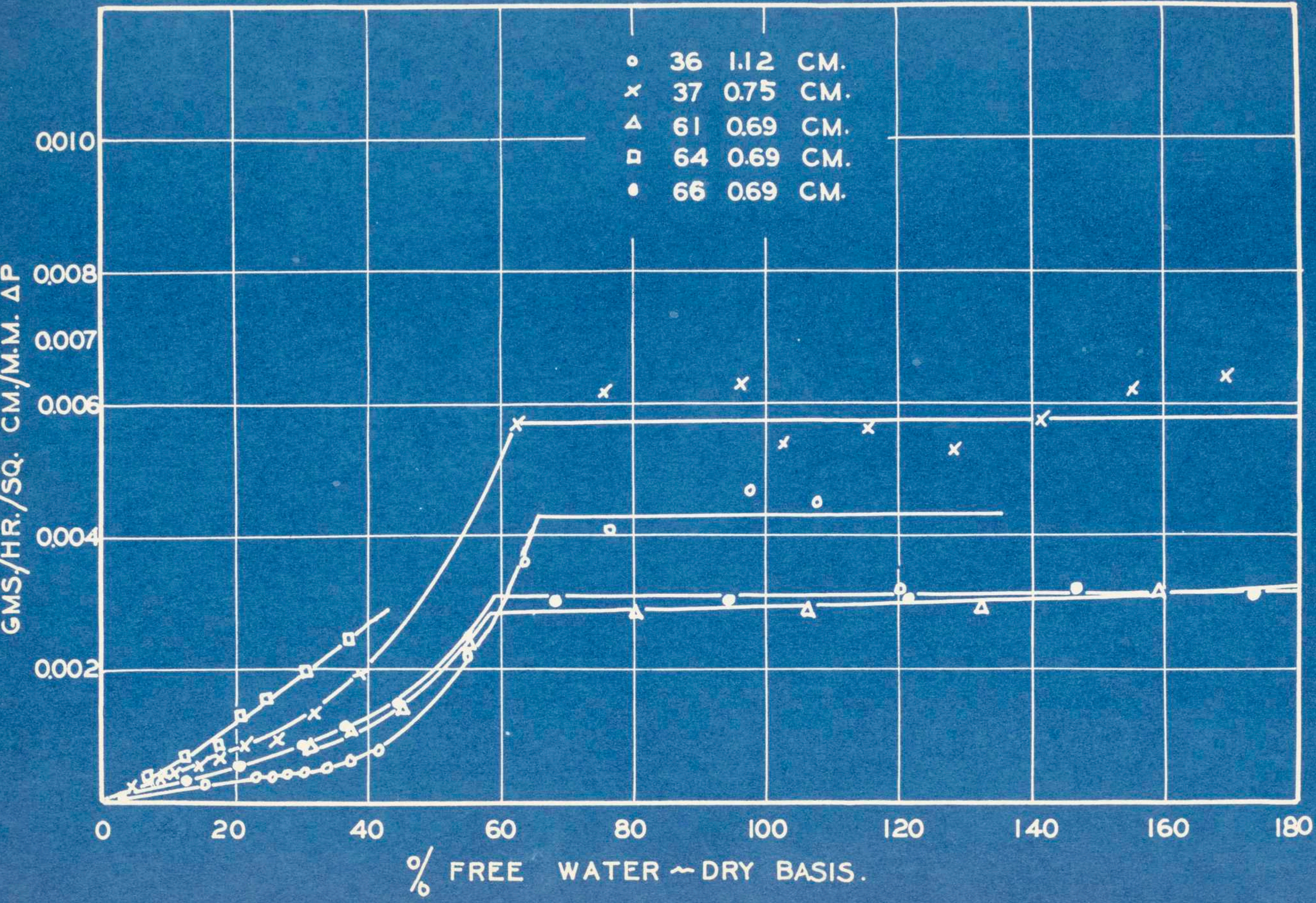


The nearly exact coincidence of the break in the H curves and the critical moisture content in each case is striking, and shows clearly that the overall resistance to heat flow starts to increase at the end of the constant rate period. Thus, no "Zone A" is apparent for these samples as was found in the case of the whiting. The increase in the overall resistance to heat flow is obviously due to the flow of heat into the solid, or, in other words, by the occurrence of the evaporation at points beneath the solid surface. During the constant rate period the evaporation takes place at the surface and the total resistance to heat flow is that of the surface air film. However, as the critical moisture is reached and passed, the evaporation begins at points beneath the surface. The heat necessary for vaporization must flow not only through the surface air film, but also through the relatively dry layer of solid between the surface and the points where evapporation proceeds. The overall resistance to heat flow, therefore, builds up and the value of H decreases. At the same time the vapor formed must diffuse, not only through the surface air film, but through the solid from the point where it originates to the surface.

Since the last of the water evaporates from the center of the slab, the resistance to heat flow at zero free water content is made up of the air film resistance and the resistance to heat flow of half the slab thickness, the latter being directly proportional to the slab thickness. Extrapolation of the H curves to zero water contents should, therefore, give values of H increasing with increasing slab thickness. Inspection of Figures 48 and 49 shows this to be the case, further substantiating the conclusion that during the falling rate period evaporation occurs within the pulp.

Since during the falling rate period the vapor formed must diffuse not only through the surface air film, but through the layer of relatively dry pulp, the overall coefficient of vapor diffusion may be expected to decrease, as well as the overall coefficient of heat transfer. In those runs where the sample temperatures were recorded, it is possible to calculate the actual driving force, Δp, and consequently the overall coefficient of vapor diffusion as gms./(hr.)(sq.cm.)(m.m. Δp.) This has been done, and the calculated results are shown plotted in Figure 50. The highest curve is for the thinnest sample and lowest for the thickest, as might be expected, but the three intermediate curves are not in order of the thicknesses of the corresponding

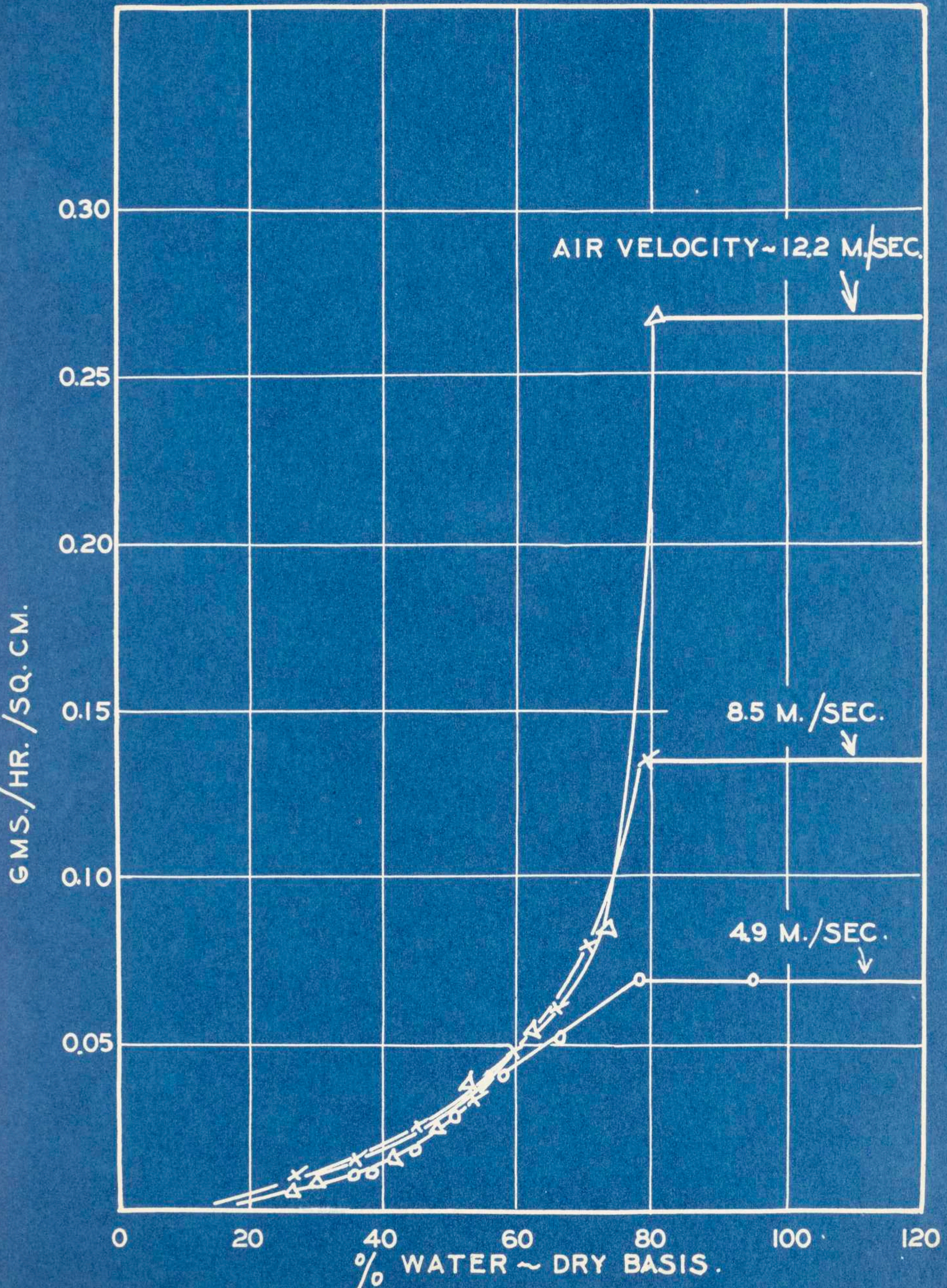
PULP AND WATER.



samples. Two of the three runs made with the same sample check well, but the third (Run 64) is much higher. In the case of this particular run the sample was dried slowly in an unheated drier down to considerably below the critical moisture before being hung on the recording balance under the usual air conditions. The retreat of the evaporation zone from the pulp surface is, no doubt, slower when the drying is slow, since the moisture gradient in the central or wet zone is less steep, and for a given water content the wet zone must, therefore, be wider, and the relatively dry surface layer must be thinner. The variation of the coefficient in the constant rate period, from run to run, as shown in Figure 48 is partly due to variations in the drying conditions, and possibly to variations in the condition of the pulp surface. Runs 61, 64 and 66 were made on the same sample of hand-pressed pulp, whereas the other two runs were made with pulp pressed hydraulically. The structure of the latter two samples was, therefore, denser than for the first.

Where drying takes place with evaporation at points beneath the solid surface, the resistance of the surface air film to heat flow, or to vapor diffusion, becomes a small part of the respective overall resistances. It would be expected, therefore, that factors affecting the surface film resistance would have only a small effect on the rate of drying. That such is actually the case is clearly shown by the results obtained by Tu[15] who determined the effect of air velocity on the drying of pulp slabs. During the constant rate period the rate of drying was found to vary greatly with the air velocity, as discussed in a previous section. During the falling rate period, however, variation of the air velocity past the pulp surface was found to have a relatively small influence on the rate of drying. Examples of the data obtained by Tu are shown in Figure 51, where the rate of drying is plotted against the water content, for three runs using air velocities of 4.9, 8.5, and 12.2 meters per second, respectively. The effect of air velocity on the drying rate is seen to become small soon after the critical moisture is reached, these data, therefore, substantiating the conclusion above, that for paper pulp the actual evaporation of liquid takes place at points within the solid structure. In the case of the run at an air velocity of 4.9 meters per second, there is some indication of a linear portion of the rate curve just after the critical moisture is passed, and it may be that at quite low air velocities pulp exhibits a "Zone A" and "Zone B" as in the case of whiting. However, the data of the present investigation, using an even lower air velocity showed little or no indication of such an effect.

PULP AND WATER ~ DATA OF T.U.

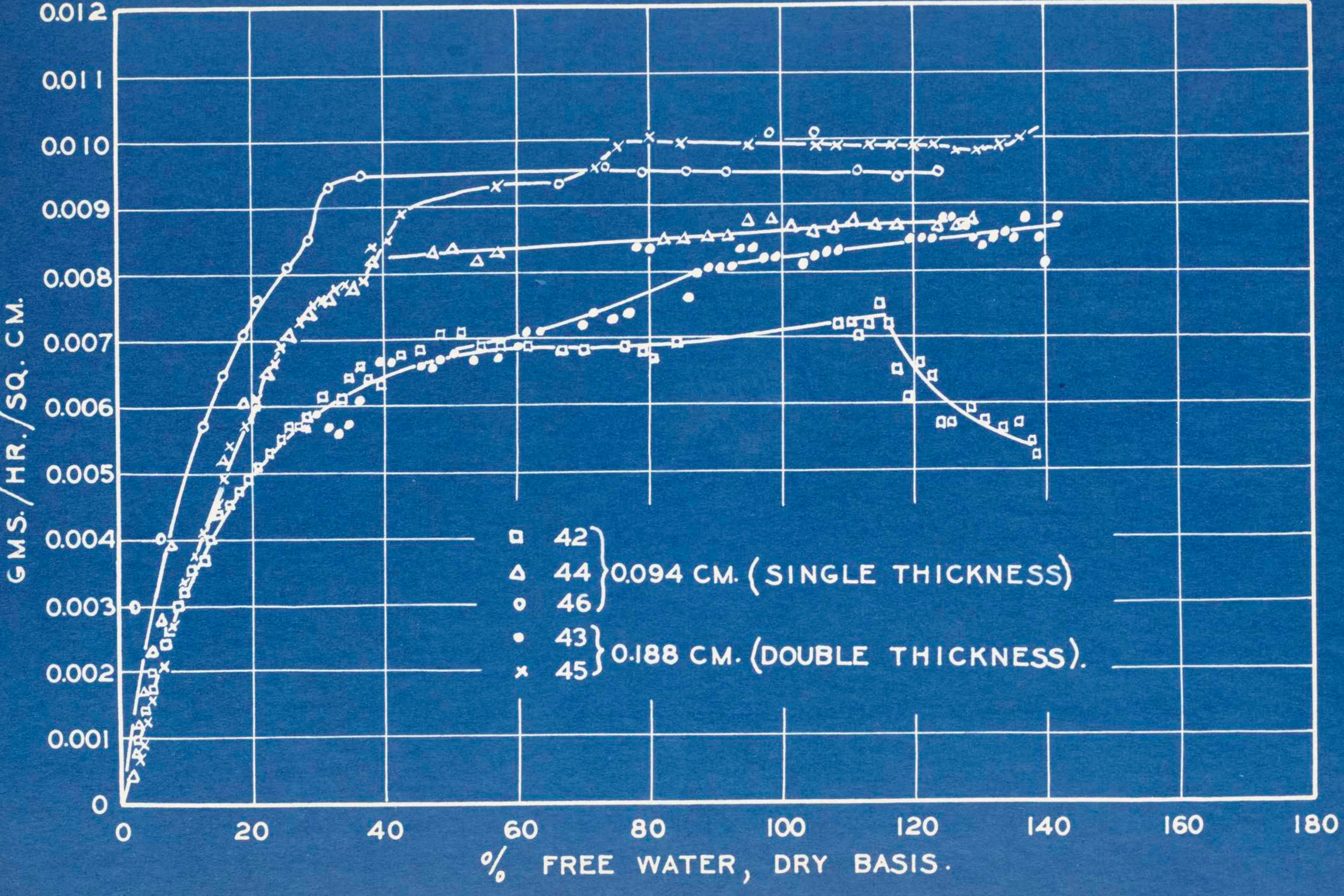


DRYING OF THIN PULP SHEETS

Several tests were made, using sheets of sulphite pulp lap as received from the pulp mill. Small rectangular sheets of the material were hung on a chemical balance and allowed to dry in that position. No heated air or forced draft was used, although the balance case was well ventilated. Frequent weighings were easily obtained without moving the sample. In two runs (43 and 45) double thicknesses of pulp were used, two identical sheets being sewed together with cotton thread. The rate of drying was calculated from the difference in weight and time elapsed between successive readings rather than by measuring the slope of the drying curves.

The results of these runs are shown in Figure 52, which shows the rate of drying plotted vs. the water content. The absence of sharp critical points is at once noticeable and is probably due to one or both of two possible causes. The pulp lap was embossed with a ribbed design so that the sheet was not of uniform thickness. The thin portions would be expected to reach the critical point first, after which the drying rate would vary over the pulp surface, explaining the rounding off of the rate curves near the critical moisture. Another possible explanation is that when the sheets were quite wet water drained to the bottom, so that the top reached the critical moisture

DRYING OF SHEETS OF SULPHITE PULP LAP.

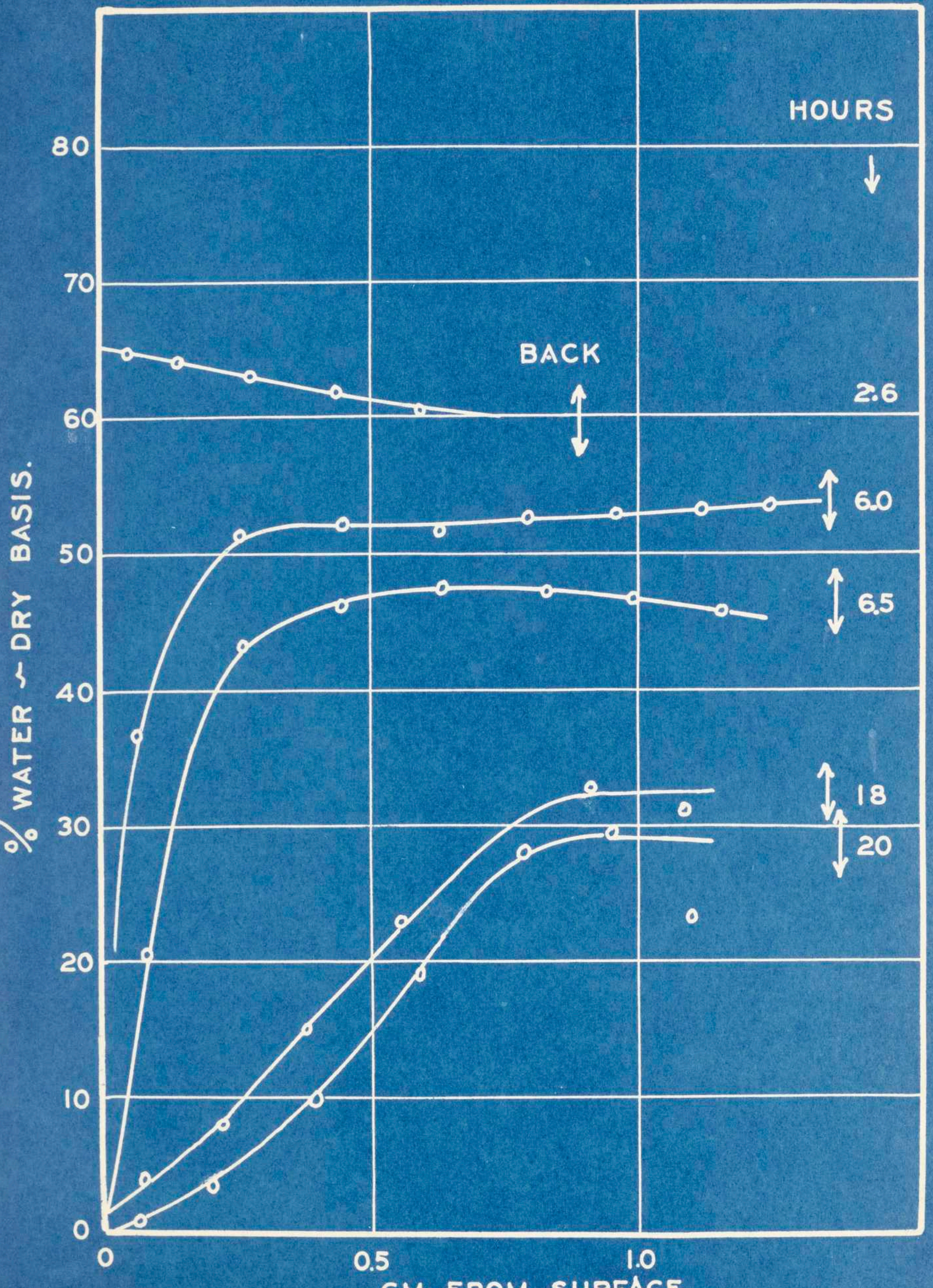


first; the result would be the same as that described above. In order to test this a sample was wetted with a strong solution of cobalt chloride, which is red when wet and blue when dry. The sample so treated was dried and observed carefully: the top was found to turn blue at almost exactly the same time as did the bottom. This experiment seemed to prove that drainage in the sample by gravity was not the explanation of the observed rounded rate curves. However. further suspicion is aroused by the fact that in the five runs shown, the sharpness of the break in the rate curve at the critical point in each case falls in the same relative order as the initial water content, and it is the latter which determines the tendency to drain by gravity. A few percent difference in the initial water content would make a considerable difference in the tendency to drain, and the sample tested with cobalt chloride may have had a relatively low initial water content. These data do show, however, that the critical for the thin sheets is approximately 40%; also, that the rates during the constant rate period do not depend on the thickness. Run 42 shows the result of cold initial water; considerable time is required to warm the sample up to the wet-bulb temperature, and during this period the rate of drying increases steadily, causing the bend in the right end of the curve for this run.

MOISTURE GRADIENTS IN PULP SLABS

Having established the fact that evaporation occurs within the pulp structure, it is of interest to inquire whether all the evaporation at a given instant takes place at the same, or nearly the same, distance from the surface; or whether the evaporation is distributed through a layer of relatively dry pulp near the surface; that is, whether the evaporation takes place at a plane continually retreating from the surface during the falling rate period, or whether there is an evaporation zone of appreciable thickness. In order to throw light on this question, data (Runs 56 and 57) were obtained on the actual moisture gradients existing in pulp slabs at different stages in the drying process. As described before, these data were obtained on small pulp blocks, coated on the edges and one face with cement, being dried from the remaining face. The blocks were cut into thin slices parallel to the face, after different lengths of time in the drier. In Figure 53, which shows the data obtained, the average total moisture content of the slices is plotted against abscissae representing the center lines of the slices, the different curves being from different blocks.

MOISTURE GRADIENTS IN PULP.



The highest curve, representing the block sliced after drying 2.6 hours shows a small gradient towards the back of the sample, due to the fact that the pulp, soaked in water after the cement was applied, was not completely wetted, so that the moisture distribution at the start was not entirely uniform. The last two points in the two lowest curves are low, probably due to the cracking of the cement, and consequent drying taking place from the back face of the block. The double arrows represent the positions of the backs of the blocks and so indicate the block thicknesses.

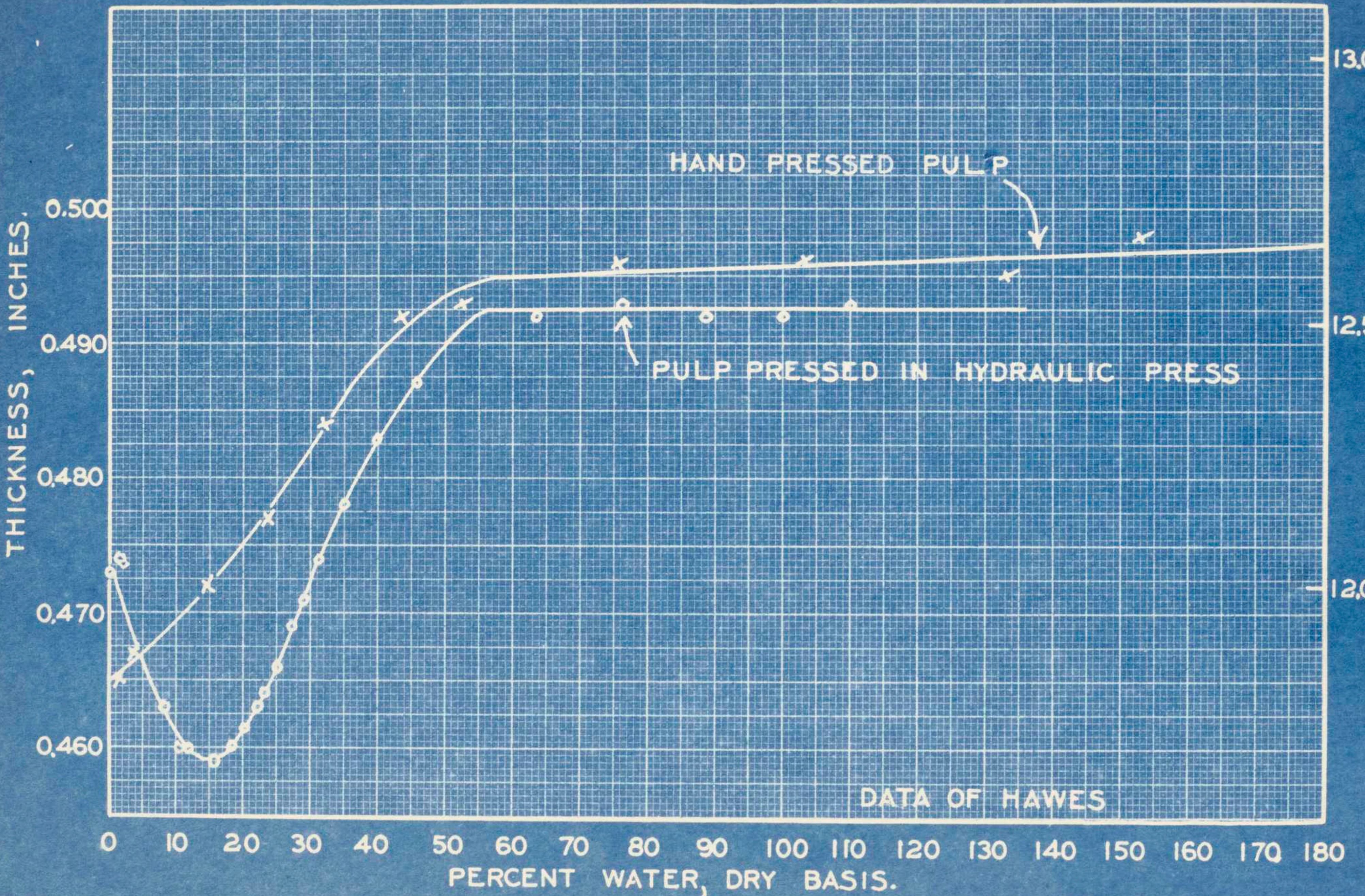
If all the evaporation were taking place at a plane a definite distance from the surface in each case, a discontinuity would be expected in the gradient curves at an abscissae representing the location of such a plane. However, since air present in the pulp would be nearly dry at the pulp surface, and approach saturation as the plane of evaporation was approached, the water content of the pulp should be nearly zero at the pulp surface, and near the plane of evaporation would approach that water content in equilibrium with saturated air. For the pulp used, the water content in equilibrium with saturated air was approximately 13.5%, and it is, therefore, evident that the discontinuity in the gradient curves described above would appear at ordinates of about 13.5% water. From the curves of

Figure 53 it is apparent that no such discontinuities occurred, in fact not even moderate increases in the slopes of the gradient curves were observed. It may, therefore, be concluded that the data obtained on moisture gradients in pulp tend to eliminate the possibility that all of the evaporation occurs at a retreating plane, or even in a narrow zone.

Instead of all of the evaporation taking place at a plane, it seems more plausible that the total evaporation should be distributed from the pulp surface in to a plane, beyond which no evaporation takes place and water diffuses by capillary flow. This inner boundary of the evaporation zone may be described as a retreating plane, and its location is indicated in Figure 53 by the intersections of the steep gradient curves with the nearly flat gradient curves in the central portions of the samples. The structure of the pulp is non-homogeneous, the sizes of the individual fibres varying greatly, as do the sizes of the spaces between the fibres. It seems reasonable to suppose, therefore, that even when the inner limit of the evaporation zone has retreated a considerable distance into the pulp slab, a small amount of evaporation is still taking place at points very near the pulp surface, probably from the surfaces of the small water wedges between the smaller fibres.

Hawes[22] has shown that between 180% and 60% water pulp being dried in room air shrinks little or not at all. Two examples of this shrinkage data obtained by Hawes on pulp are shown in Figure 54. From this figure it may be seen that at a water content corresponding to the critical point, 60%, shrinkage commences abruptly. The hand pressed pulp shows continued shrinkage from this point to dryness, but the hydraulically pressed pulp shrank to a minimum at about 15% water, and then expanded. This surprising result may possibly be explained as follows: the shrinkage is due to the retreat of the water planes into the smaller water wedges, the fibres being pulled together by the capillary action of the water as two glass plates with water between are pulled together; when the water is wholly gone the tension is no longer acting and if the structure is strong and firm as in the case of the hydraulically pressed pulp, the fibres may spring apart, causing reverse of shrinkage. It is important to note that during the constant rate period, since the shrinkage is negligible, the water lost is replaced by an equal volume of air. Some air also enters the pulp during the falling rate period, as Hawes has calculated that for one run the volume shrinkage from 47% to 0% water amounted to only 69% of the volume of the water lost. Moreover, since no large gradient is set up during the constant rate period, the large

SHRINKAGE OF PULP DURING DRYING.



amount of air entering the pulp must be fairly evenly distributed throughout the mass. It would, therefore, seem probable that the larger capillary openings throughout the pulp are emptied during the constant rate period. When these large capillaries are emptied the difficulty of diffusion of water to the surface becomes great, since it must travel by capillary flow through very small capillaries, or, since these are not long, mostly by diffusion along the surface water film on the pulp fibres. When the supply of water to the surface by such mechanisms becomes slower than the rate of removal of water from the surface by convection, evaporation begins to take place at points beneath the surface. In a large long capillary evaporation might take place at considerable distance from the surface at the same time that evaporation in a short small capillary was occurring at a point very near the surface. From the foregoing it would seem, therefore, that the drying rate of pulp is controlled by the rate of internal diffusion of water. As in the case of whiting, therefore, the internal evaporation phenomenon, with consequent decrease in the overall coefficient of heat flow, H, is caused by the slowing up of the drying rate, and not vice versa.

It should be pointed out that the argument put forward above to show that the evaporation in the case of pulp is distributed from the surface in through a relatively thick layer, and does not take place at a plane, is based primarily on the fact that the structure of the pulp is non-homogeneous. If the solid were built up of uniform particles, or rather, contain uniform capillaries, the argument would no longer hold. A metal slab honey-combed with small capillaries all at right angles to the surface and all of the same size might serve as an illustration. If, for any reason, water in the capillaries were held back from flowing to the surface, evaporation would begin to take place within the capillary tubes. However, the water-air interface would be expected to retreat from the surface at the same rate in each capillary, so that considering the slab as a whole, evaporation would be taking place at a retreating plane, and not from a zone of appreciable thickness. Indeed, in the case of the granular whiting, moisture gradient data (see Figure 29, lowest curve) showed some sign of a discontinuity indicating an approach to such conditions.

MATHEMATICAL ANALYSIS OF DRYING BY MECHANISM OF INTERNAL EVAPORATION

Although the total evaporation of water from pulp during the falling rate period may be distributed over a zone of appreciable thickness, the mechanism may be considered, for purposes of analysis, to be that of evaporation wholly at a plane retreating from the surface. Thus, x, the distance of such a plane from the surface will be the effective thickness of a relatively dry surface layer. If k_d represents the diffusion constant of water vapor through the relatively dry surface layer, the rate of drying is given by the equation

$$\frac{dW}{A d\theta} = \frac{p_s - p_a}{x/k_d + 1/K_s} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (27)$$

Assuming all the heat of vaporization to come from the air, and neglecting the sensible heat required to warm the solid, the following equation may also be written:

$$\frac{dW}{A d\theta} = \frac{1}{r}\left[\frac{t_s - t_a}{x/k_h + 1/h_c}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (28)$$

and, if $\Delta t = t_s - t_a$, and $\Delta p = p_s - p_a$, it may be shown from equations (27) and (28) that

$$x = \frac{\frac{1}{K_s}\Delta t - \frac{r}{h_c}\Delta p}{\frac{r}{k_h}\Delta p - \frac{1}{k_d}\Delta t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (29)$$

Using the data of Run 66 as an illustration, the average value of K_s was 0.00000087 gms./(sec./(sq.cm.)(m.m.Δp); the average h_c = 0.000418 cal./(sec.)(sq.cm.)(°C.), and r = 537 cal./gm. Using Hawes'[22] value of k_d of 7×10^{-8}, and the value of 0.00015 for k_n (reported by Lees and Charlton[23] for blotting paper), equation (29) may be written

$$x = \frac{\frac{1}{0.00000087}\Delta t - \frac{537}{0.000418}\Delta p}{\frac{537}{0.00015}\Delta p - \frac{1}{7\mathrm{x}10^{-8}}\Delta t}$$

$$= \frac{\Delta t - 1.12\Delta p}{3.12 \quad p - 12.43 \quad t}$$

and

$$\frac{dW}{Ad\theta} = \text{gms./(hours)(sq.cm.)} = \frac{1\ (3600\Delta t)}{537\left[\frac{x}{0.00015} + \frac{1}{0.000418}\right]}$$

Since in Run 66 actual temperatures of the solid were obtained, Δp and Δt are available at any point during the drying. Thus, it is possible to calculate both x and the drying rate, and compare with the actual values recorded. This comparison is shown below:

TABLE V

Hours	Δp m.m.	Δt °C.	x, cm. (calculated)	gms./(hr.)(sq.cm.) (calculated)	gms./(hr.)(sq.c (actual)
3		15.7	0	0.0438	0.0438
5	14.8	15.4	0.008	0.0421	0.0425
6	19.0	11.9	0.105	0.0257	0.0279
6.5	20.9	10.5	0.196	0.0190	0.0226
7	22.7	9.0	0.400	0.0119	0.0183

In view of the uncertainty as to the proper values of k_h and k_d, the agreement between the actual and the calculated drying rates is quite close. The calculated values of x, the effective distance of the evaporation "plane" from the surface, are approximately those which would be expected, although higher. The general agreement of these calculated values with the actual data may be taken as further substantiation of the former conclusion that during the falling rate period in the drying of pulp, the evaporation occurs not at the surface, but at points within the solid structure.

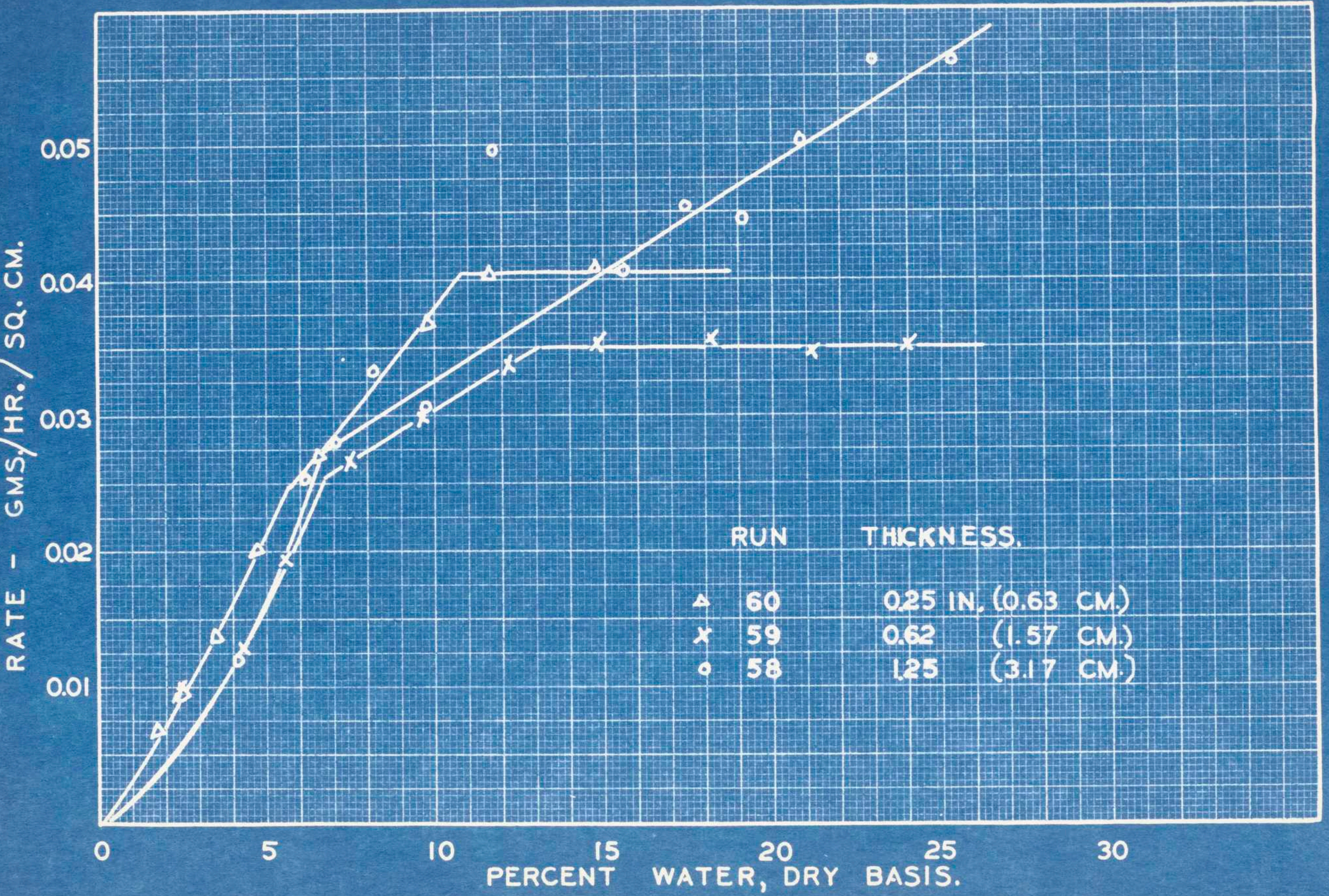
E - THE DRYING OF CLAY

Clay is perhaps one of the most important single materials which is dried commercially. The drying of ceramic wares before firing offers serious problems, not only from the point of view of the cost, but also due to the frequent difficulty of drying without injuring the product. Many clays cannot be dried without serious cracking, while others require special control of the drying conditions if spoiling by cracking is to be prevented. In recent years the Journals and Transactions of the American Ceramic Society have included numerous papers relative to the drying of clay. They have contained, however, only a limited analysis of the mechanism of drying and many of the authors have been content to deal with data obtained only in the constant rate period. For example, in one of the most thorough of these papers,[24] the authors, although distinguishing between the constant rate and falling rate periods, give no quantitative analysis of the drying rate in the falling rate period.

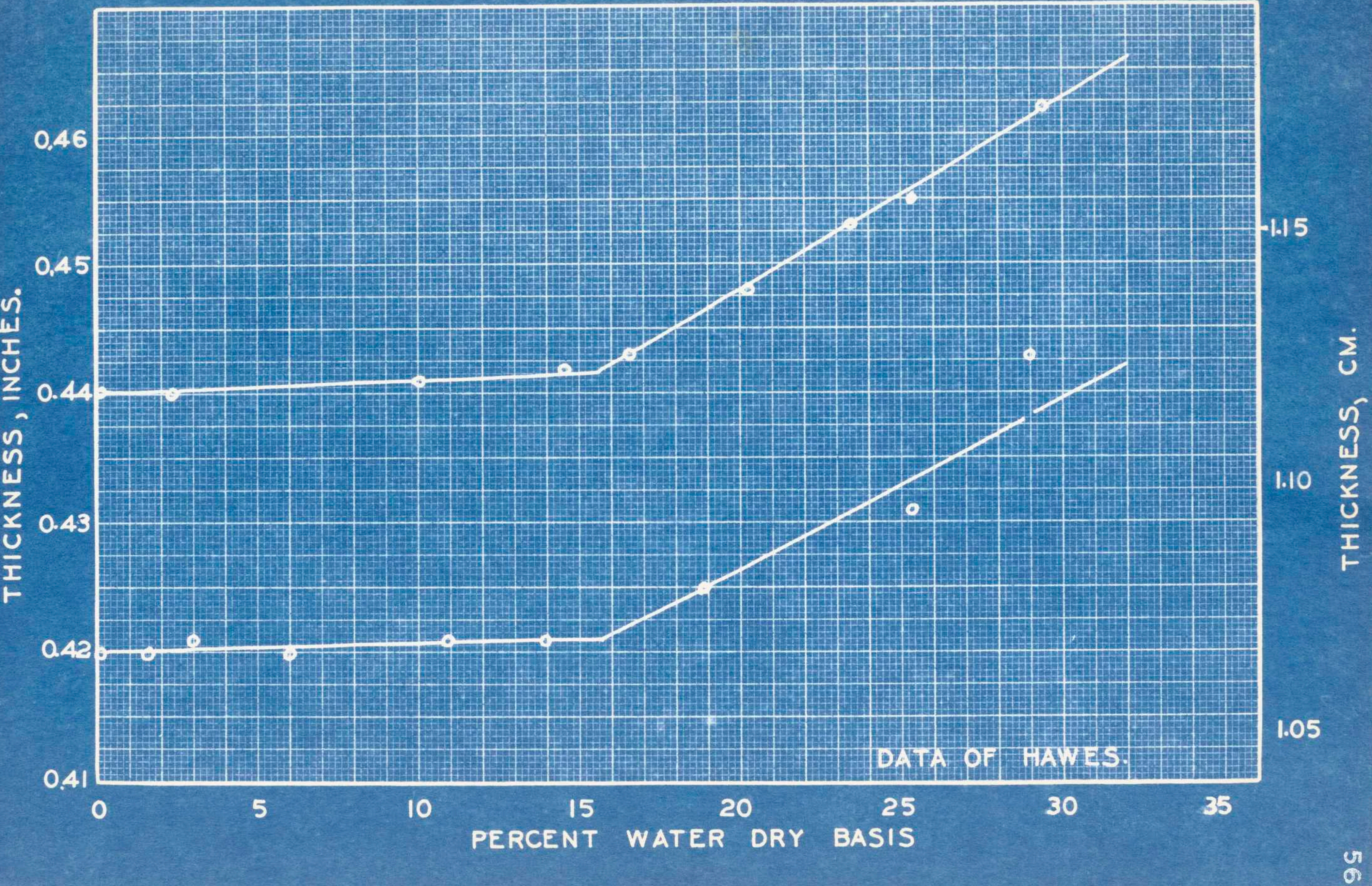
In the course of the present investigation, several experiments were made drying clay, the technique being similar to that when whiting was used, Slabs of clay, formed and held in wood frames, were dried in the tunnel drier, using the recording balance. As in the case of the whiting, a constant rate period and a falling rate period were observed. Figure 55 shows the data obtained, plotted as gms./(hr.)(sq.cm.) vs. water content, and the division into constant rate and falling rate periods may be seen clearly in the case of Runs 59 and 60. As drawn on this Figure, Run 58 shows no initial constant rate period, but the points are scattered, and could be represented nearly as well by indicating a constant rate of about 0.049 gms./hr./sq.cm. with a critical moisture content of 13%. If this were done, the critical moisture, taken from the three runs, would be 11-13%.

In connection with this observed critical moisture of 11-13%, it is of interest to note the data of Hawes[23], shown in Figure 56, on the shrinkage during drying of this same clay. The thickness of a small part of the clay is shown plotted vs. the moisture content, the data being obtained while the clay was drying in the air of the room. From this it will be seen that little shrinkage occurred at water contents below 15%, i.e., in the range corresponding to the falling rate period. Thus, the falling rate period is not due to shrinkage or to factors which cause shrinkage, but instead is found to start at approximately the same water content at which the shrinkage is completed. Since

BRICK CLAY AND WATER



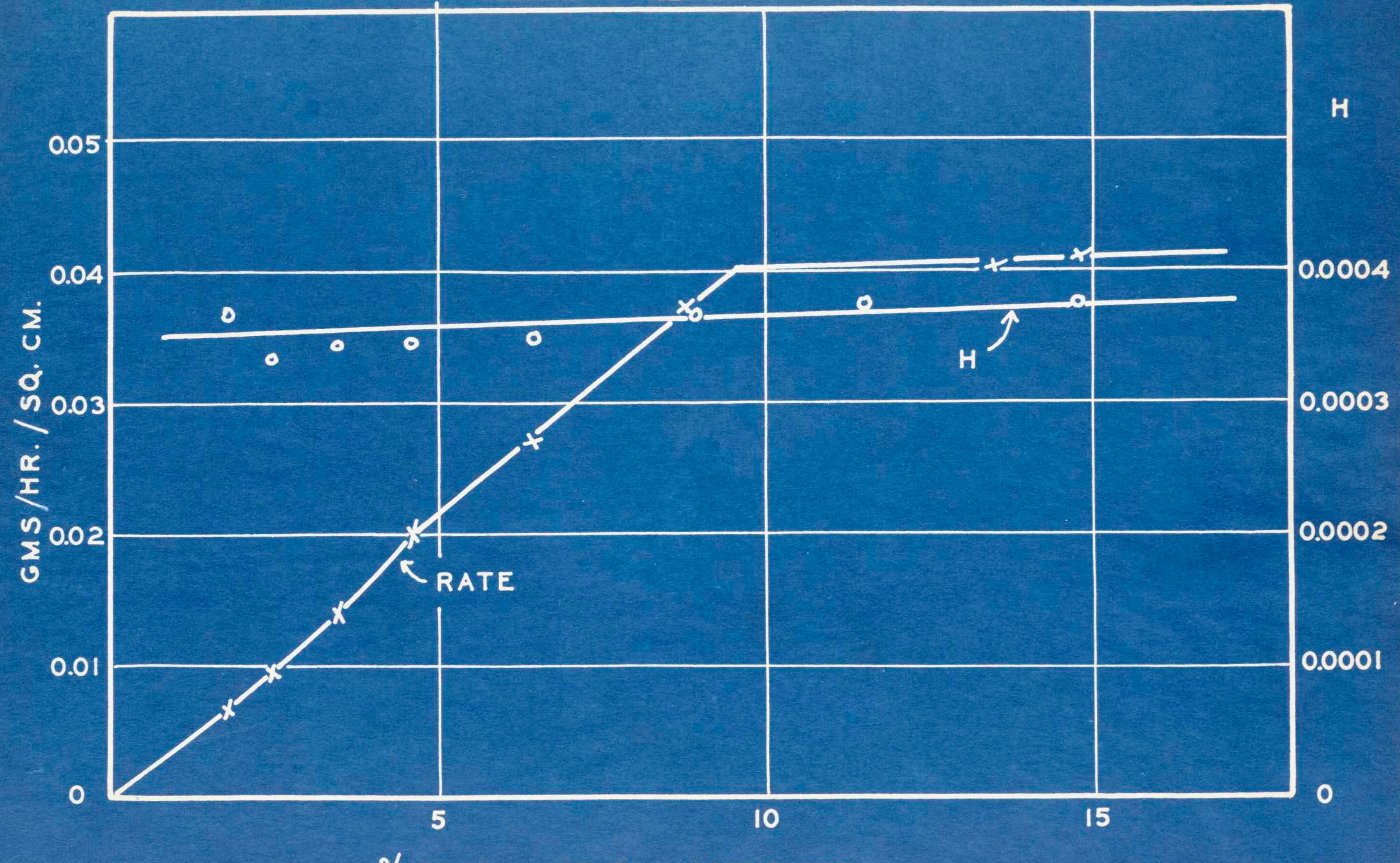
SHRINKAGE OF CLAY DURING DRYING.



the shrinkage is due to the loss of adsorbed or 'gel' water, it would appear that the 'gel' water is largely removed in the constant rate period.

Although thermocouples were inserted in each of the runs 58, 59 and 60, data on the temperature difference was obtained over the whole of the drying range only in Run 60, Figure 57 shows the data of Run 60, with both drying rate, and overall coefficient of heat transfer, H, plotted vs. water content. The slight bend in the rate curve at about 5% water corresponds to the more noticeable ones observed in Figure 55 for Runs 58 and 59. The falling rate period may be divided, therefore, into two zones, as for the whiting. The first straight portions of the falling rate period (from the critical point down to about 5% water) may be called Zone A; the lower curved portion of the same curve corresponds to Zone B. The coefficient of heat transfer as calculated for Run 60 and shown in Figure 57 is seen to remain nearly constant throughout the whole drying period. These results are supported by a single pointat 12.5 hours in Run 58, where the coefficient measured was 0.000566, whereas the average H during the constant rate period was 0.000521. Although these dataare too meagre to be conclusive, they indicate that the overall coefficient of heat flow remains constant not only during the constant rate period, and Zone A, but also during Zone B. It will be remembered that in the case

RUN 60. BRICK CLAY AND WATER - 0.63 CM.



% FREE WATER, DRY BASIS.

of the whiting the coefficient H remained constant during the constant rate period and Zone A, but fell off sharply in Zone B.

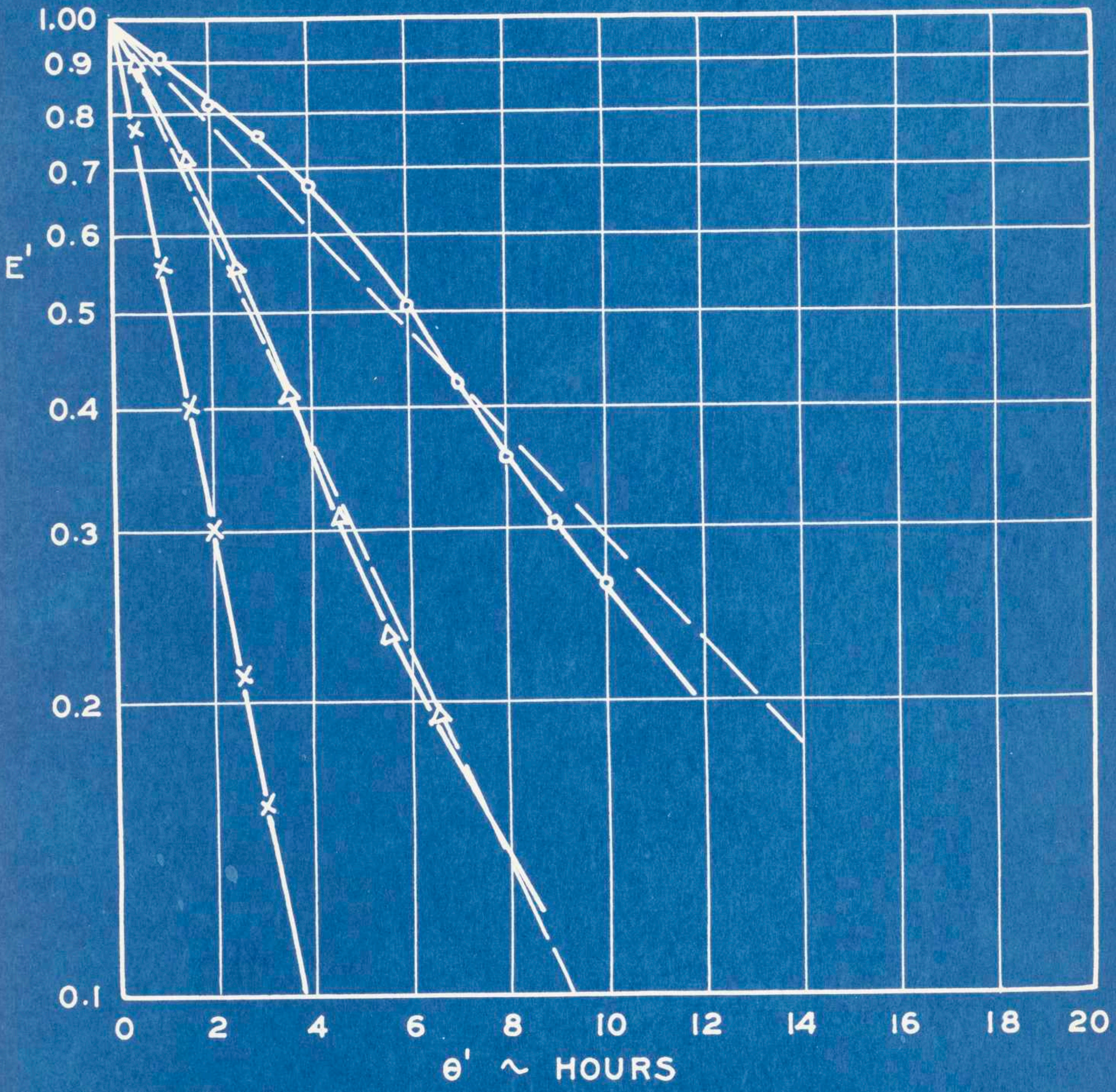
As will be shown below, Zone B in the case of clay represents a period where internal liquid diffusion controls, and is similar to Zone B for whiting. However, the retreat of the locus of evaporation, which explained the decrease in H in Zone B for whiting, is doubtless more difficult in the fine grained colloidal clay. Thus, with internal diffusion controlling the locus of evaporation might be expected to retreat to a large or small extent, depending on the porosity of the solid. The apparent constancy of H in Zone B for clay is, therefore, explained as being due, not to a fundamental difference in the drying mechanism from that of whiting, but rather to the much smaller porosity of the solid.

SEMI-LOG PLOTS OF E' vs θ' FOR CLAY DATA

As may be seen from Figure 55, the drying rate for any one of the three runs shown is roughly proportional to the water content during the falling rate period. This suggests a possible correlation of these data by plotting, on semi-log paper, E' vs. θ' for the falling rate period, as was done in the case of whiting. Figure 58

BRICK CLAY ~ FALLING RATE PERIOD.

o 58 3.17 CM., △ 59 1.90 CM., × 60 0.63 CM.



shows the result of plotting the data in this manner, and as may be seen, straight lines are approximated. The dotted lines are based on the straight line for Run 60, but with slopes inversely proportional to the thicknesses of the respective samples. The data on the falling rate period for these runs is therefore well correlated, at least down to a value of E' of 0.2, by an equation of the form

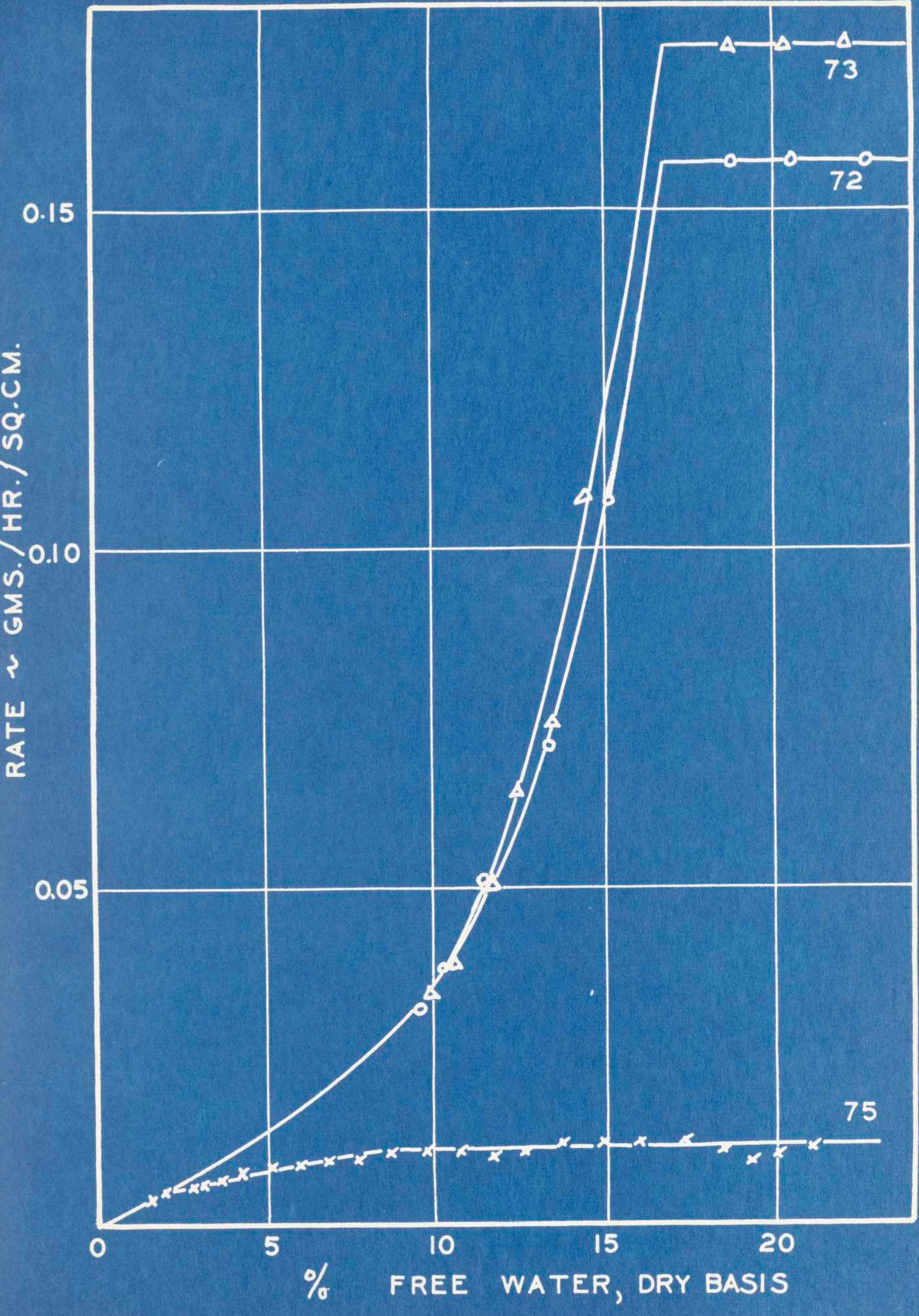
$$\log E' = (\text{constant})\,\frac{\theta'}{R}$$

The value of the constant would, of course, vary with the drying conditions.

EFFECT OF AIR VELOCITY ON THE RATE OF DRYING OF CLAY

Three runs were made using identical samples but dried in air at room temperature with widely different air velocities. The clay was formed in wood frames lined with tin foil, and the frames removed, leaving the tin foil as a smooth covering to prevent evaporation from the edges of the blocks. The wet blocks were 7.0 x 7.0 x 2.54 cm. thick in each case, and stood on edge with the faces parallel to the direction of air flow. One edge, therefore. received the full force of the air blast. impinging at right angles, and the bottom edge was in contact with the porcelain platform of the scales. Figure 59 shows the drying rates calculated from the drying curves obtained. In Run 73 the air velocity was 15.2 m./sec.; in Run 72 10.6 m./sec.; and in Run 75 no forced

BRICK CLAY AND WATER. 2.54 CM.



air convection was used, the clay being allowed to dry while resting on a scale platform open to the air of the room.

The effect of air velocity on the drying rate during the constant rate period is very marked, and is much as might be expected. The ratio of the rates during the constant rate period for the two runs at high air velocitiies might be expected to be

$$\left(\frac{15.2}{10.6}\right)^{0.6} \times \frac{8.1}{8.8} = 1.14$$

where 15.2 and 10.6 are the respective air velocities, and 8.1 and 8.8 the average wet bulb depressions in Runs 73 and 72 respectively. The observed ratio of the rates is

$$\frac{0.174}{0.157} = 1.11$$

The constant-rate rates may be compared with the results obtained in drying very wet pulp (see Figure 9) since the ratios of dry to wetted surface were similar in the two cases. The values calculated from Figure 9 are 0.026 x 8.1 = 0.21, and 0.0206 x 8.8 x 0.181 gms./(hr.)(sq.cm.) which compare fairly well with the observed values for clay of 0.174 and 0.157 respectively.

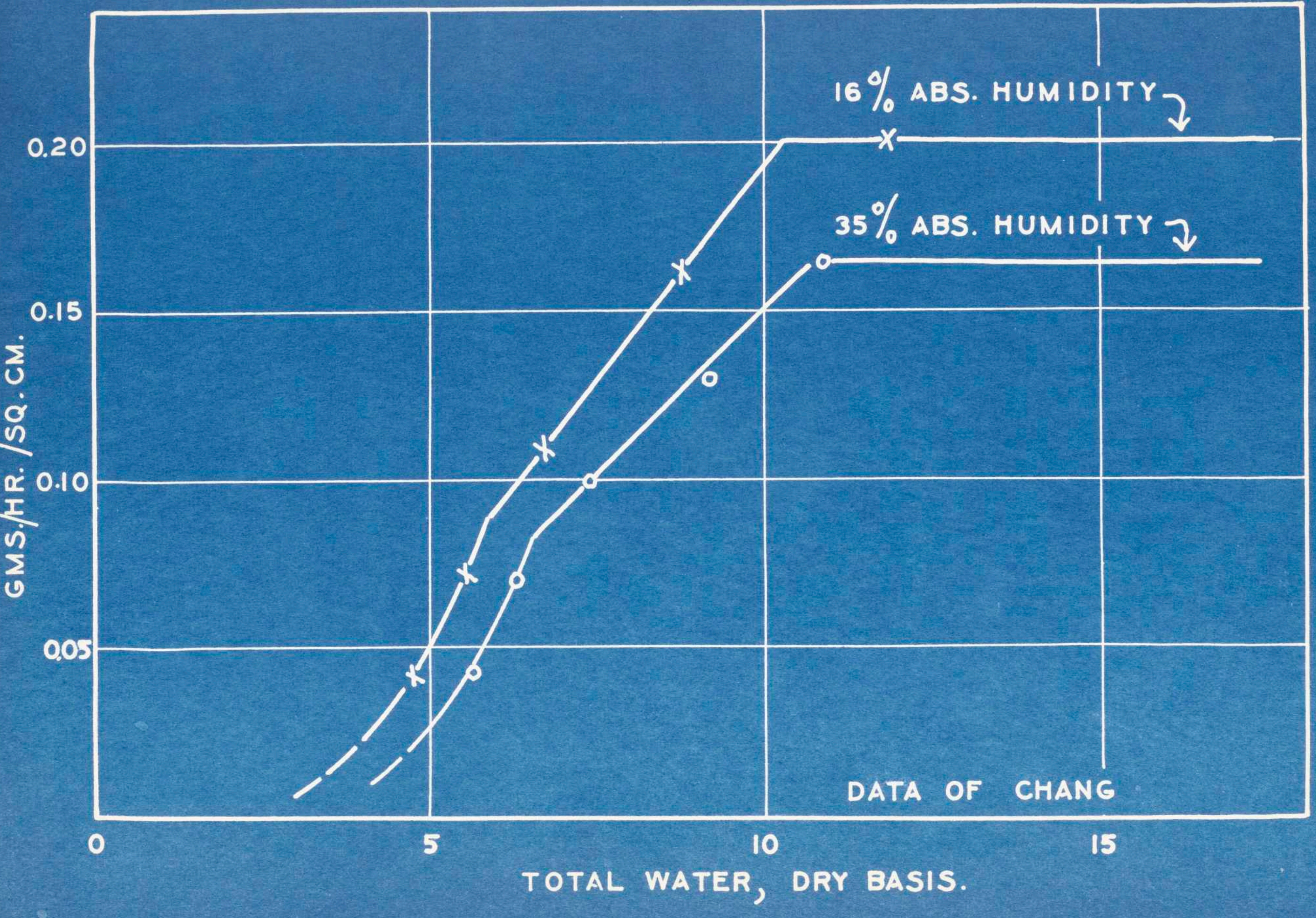
The striking and significant point brought out in Figure 59 is the near coincidence of the rate curves during the falling rate period for the two runs at high air velocities. The initial sloping linear portion, or Zone A, is not in evidence, and there is marked concavity upwards throughout the falling rate period. These curves are similar to the theoretical rate curve with internal diffusion controlling (see Figure 4), and suggest that internal liquid diffusion is controlling throughout the falling rate period for these runs at high air velocity. It is further significant that the critical water content for these runs is considerably greater than for the runs at low air velocity previously discussed. This is no doubt due to the fact that the drying rate cannot be greater than the rate of internal diffusion: the critical moisture is, therefore, that water content at which the rate of internal diffusion is equal to the constant rate rate, since there is no Zone A. At lower air velocities Zone A appears, and the straight line representing the rate in this region, rather than the constant rate line, intersects the internal diffusion curve. For example, Run 75, using no forced convection, shows evidence of a Zone A, and internal diffusion is not controlling until a very low water content is reached.

High air velocity is seen to be of great value in speeding up the drying of clay, since it not only greatly changes the drying rate in the constant rate period, but replaces the Zone A obtained at low air velocities by a falling rate period with internal diffusion controlling, during which the average drying rate is considerably greater. It is of interest to note that in Runs 72 and 73 internal diffusion is controlling at water contents below 16%, whereas in Run 75 surface evaporation is controlling from 16% water down to possibly 2% free water. Thus, identical samples of the same material may, under different conditions, dry by different mechanisms over the same range of moisture contents.

EFFECT OF HUMIDITY ON THE DRYING OF CLAY

In the course of the present investigation, no experiments were undertaken to determine the effect of varying the air humidity on the rate of drying of clay. However, in connection with the foregoing discussion it is of interest to analyze the data obtained by Chang.[25] Chang obtained data on drying clay at low air velocities, and was able to vary the air humidity over a limited range, while keeping the temperature constant. Figure 60 shows examples of the rate curves obtained by Chang, the two shown being obtained by drying 0.64 cm. slabs at 43.2° C. and with air humidities of 16% and 35% absolute, respectively. The division into constant

BRICK CLAY AND WATER 0.64 CM.



rate period, and Zone A and Zone B of the falling rate period is clear in each case. The equilibrium water reported by Chang for this clay is about 2.3% and 3.6% at humidities of 16% and 35% respectively. The difference of the two values, or 1.3%, corresponds to the horizontal distance between the lower curved portions of the two rate curves, and indicates that if the rate were plotted against free water, the curves representing Zone B in each case would coincide. This is to be expected since humidity can have little effect on the drying rate when internal liquid diffusion is controlling, as is believed to be the case in Zone B. However, the difference in equilibrium values does not explain the difference between the two curves in Zone A, and it is evident that in this range the difference in humidity does affect the drying rate. Internal liquid diffusion, therefore, cannot be controlling in this range, and the conclusions from the whiting data are substantiated: that in Zone A the controlling factor is the rate of evaporation from the surface.

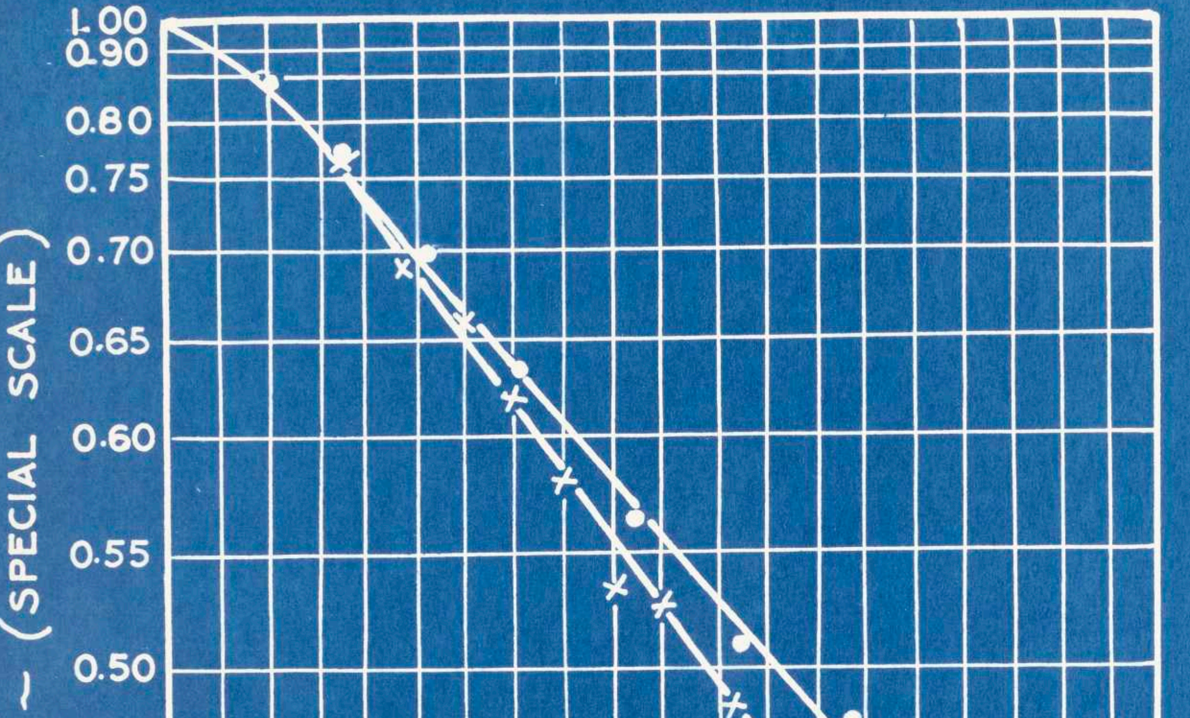
COMPARISON OF FALLING RATE PERIOD DATA ON CLAY WITH THE THEORETICAL DIFFUSION EQUATIONS

Since it is believed that internal liquid diffusion is controlling during the falling rate period in Runs 72 and 73, a comparison of this data with the theoretical diffusion equations previously derived would seem logical. It will be remembered that the data on soap was plotted as E vs. $\theta/(2R)^2$ on special plotting paper, the ordinate scale being so changed as to make a straight line represent the relation between E and τ. Since the clay data shows a constant rate period, E' will be plotted vs. θ', on the same special plotting paper. Figure 61 shows the data plotted in this way, and it may be seen that nearly straight lines result, except for a slight curvature at large values of E'. Approximate values of the diffusion constant K for clay may be obtained from this plot by comparison with the theoretical relation between E and τ. For example, from the theoretical equation for surface resistance negligible τ is found to be 0.285 when E = 0.40. From Figure 61 the corresponding time is seen to be 153-174 minutes, or an average of 164 minutes.

$$\text{Hence } \tau = \frac{K \times 164 \times 60}{(1.27)^2} = 0.285$$

and $K = 4.7 \times 10^{-5}$ in c.g.s. units.

BRICK CLAY ~ 2.54 CM. SLABS.
USING HIGH AIR VELOCITY.



MOISTURE GRADIENTS IN A SLAB DURING THE CONSTANT RATE PERIOD

When the data of Runs 72 and 73 were compared with the theoretical relation for cases of internal diffusion controlling, a discrepancy appeared in the form of a slight curvature at high values of E', of the line representing the data on the special co-ordinate plot. It seems probable that this is due to the existence of the initial constant rate period, at the end of which conditions are not the same as assumed to hold initially for the derivation of the theoretical relation. It seems desirable, therefore, to present a quantitative analysis of the conditions existing in a slab, especially with reference to the moisture gradients, during and at the end of the constant rate period. Although the data on clay show the importance of this analysis, the derivations are general, and apply to drying of other solids.

Assuming the diffusion constant K' to be independent of the moisture concentration; the rate of drying is given by the equation

$$\frac{dW}{A\ d\theta} = -K'\left(\frac{dT}{dx}\right)_s \ldots\ldots\ldots\ldots(30)$$

where K' = diffusion constant where concentrations are expressed on a weight basis, = $K\rho$

T = gms. water per gm. dry solid

x = distance of the point from the center line of the slab.

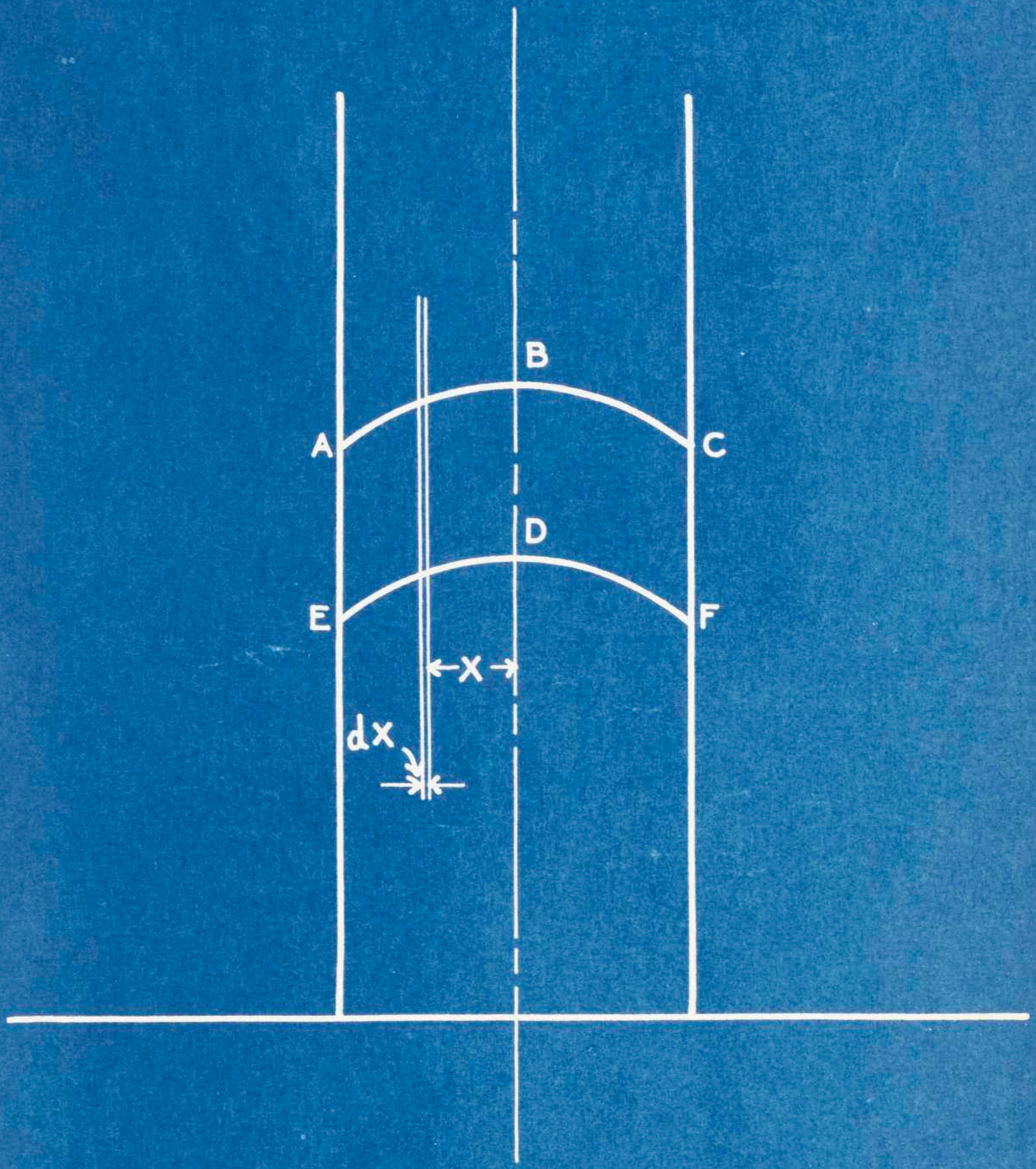
Subscript "s" refers to conditions at slab surface, and "m" refers to conditions at the center line. Figure 62 represents the cross section of a slab, with ordinates representing the moisture concentrations at different times during the constant rate period. Let ABC represent the gradient at any instant and EDF the new gradient after a finite length of time. Since no moisture crosses the center line, the slope of the gradient curve is zero at that point. Furthermore, since the rate of drying is constant, then from (30), above, the slopes at A, E, C and F are equal. Now the area ABCFDE represents the moisture lost, and since the rate of drying is constant, the areas between successive gradients separated by equal lengths of time, will be the same. The constant rate period is, therefore, an example of a steady state process in that the rate and the slopes of the gradient curves are constant. Successive gradient curves, such as ABC and EDF, are of the same shape and parallel.

Hence $\left(\frac{\partial T}{\partial \theta}\right)_x = \text{constant}.$

Therfore, from the fundamental equation for diffusion in a slab (see Appendix II)

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{K'}\frac{\partial T}{\partial \theta} = \text{constant} = c$$

FIG 59



MOISTURE GRADIENTS DURING CONSTANT RATE PERIOD.

$$\therefore \frac{\partial T}{\partial x} = c\,x + \text{constant}$$

and since $\frac{\partial T}{\partial x} = 0$ when $x = 0$, this second constant disappears.

Integrating again,

$$T = c_2\,x^2 + c_3$$

and since $T = T_m$ when $x = 0$;

$$c_3 = T_m$$

and since $T = T_s$ when $x = R$,

$$c_2 = -\frac{(T_m - T_s)}{R^2}$$

whence

$$T = T_m - \left(\frac{T_m - T_s}{R^2}\right) x^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots(31)$$

which is the equation of the moisture gradient in a slab during the constant rate period, and shows the gradient to be a parabola. Furthermore, it follows that the slope of the gradient curve is given by

$$\frac{dT}{dx} = -\frac{2\,(T_m - T_s)}{R^2}\,x \quad \ldots\ldots\ldots\ldots\ldots\ldots(32)$$

and at the surface of the slab

$$\left(\frac{dT}{dx}\right)_s = -\frac{2(T_m - T_s)}{R} = \frac{1}{K'}\left(\frac{dW}{A\,d\theta}\right)$$

whence $K' = \frac{R}{2(T_m - T_s}) \left(\frac{dW}{A\, d\theta}\right)$ ....(33)

The last equation suggests that with data on the rate of drying and moisture gradients during the constant rate period, the diffusion constant K'(= K x density) could be calculated.

The data of Troop and Wheeler[26] afford possibility of the calculation of the diffusion constant by this method. These authors report data on the drying of clay in a thermostat, which was used to maintain the temperature of the clay as nearly constant as possible. Cylinders of clay 12.7 x 2.54 cm. dia. were placed in hollow copper shells of the same inside dimensions, and the whole placed in a thermostat with only the faces at one end of each cylinder exposed to a current of air. Identical samples were sliced every six hours, and the moisture gradients obtained; the data covering only the constant rate period, however. For example, one run at 70° C. and 90% relative humidity gave values of $T_m - T_s$, of 0.056, 0.054 and 0.047, 0.051 and 0.043, after 6, 12, 24, 29 and 36 hours, respectively. The average of these values is 0.050 and the average rate of drying was 2.86 gms. per 24 hours. Therefore, substituting in (33) above,

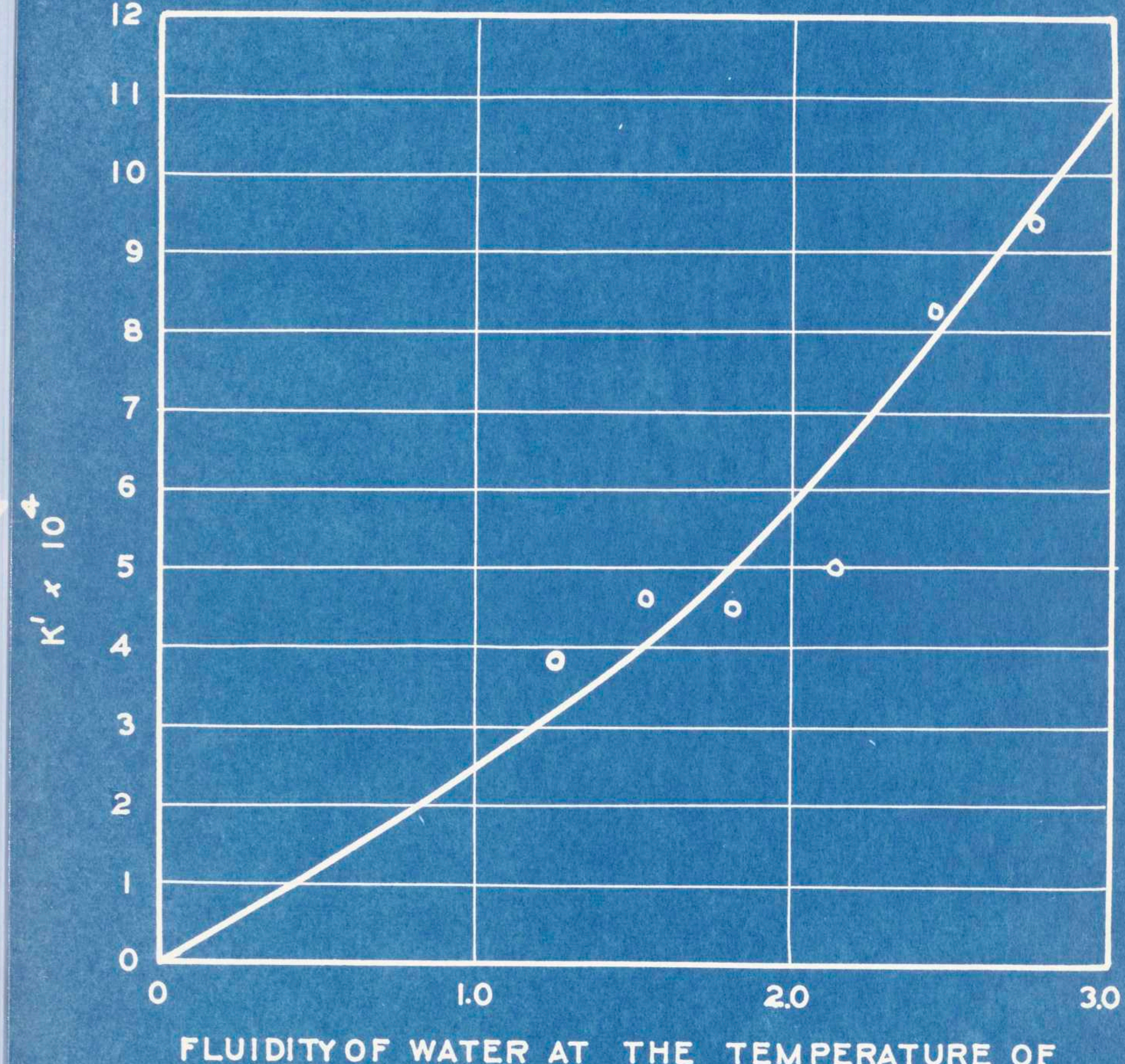
$$K' = \frac{12.7}{2 \times 0.050} \times \frac{2.86}{24 \times 3600 \times 0.785 \times 2.54^2} = 8.3 \times 10^{-4}$$

Since the data were obtained using a sample having such a small ratio of dry to wetted surface (0.045), the cooling effect of the evaporation was relatively small. and the temperature of the clay approached that of the thermostat. Since K' doubtless depends largely on the viscosity of the liquid diffusing, a relation might be expected between the values of K' from the above calculation and the viscosity or fluidity of water at the temperature of the thermostat. The results are plotted in Figure 63, which indicates that such a relation does exist.

The value of K calculated from Figure 61 for the clay used in the present investigation was 4.7×10^{-5}, and since the density was approximately 1.6, $K' = 1.6 \times 4.7 \times 10^{-5} = 0.74 \times 10^{-4}$. The temperature of the clay in Runs 72 and 73 was not determined, but the corresponding fluidity was doubtless in the vicinity of 0.8. A comparison of this value of 0.75×10^{-4} at a fluidity of 0.8, with the data of Troop and Wheeler shows that their clay would have about twice the diffusion constant at the same fluidity.

DIFFUSION CONSTANTS OF WATER IN CLAY

CALCULATED FROM THE DATA OF TROOP AND WHEELER ON MOISTURE GRADIENTS DURING THE CONSTANT RATE PERIOD.



FLUIDITY OF WATER AT THE TEMPERATURE OF THE THERMOSTAT.

The thesis of K. Chang[25] also included data on moisture gradients in a clay cylinder, the two ends being exposed. However, as the clay became very hard and extremely difficult to cut when partly dry, Chang obtained data on the moisture gradients only during the first 100 minutes of the drying process. Since the initial moisture distribution was uniform, in each run there must be an initial stage of transformation from the uniform to the parabolic gradient. The parabolic gradient is approached more and more closely as the drying proceeds, and T_m-T_s increases from zero, approaching an asymptote which would correspond to the final or equilibrium parabolic gradient. It is this asymptotic or equilibrium value of T_m-T_s which should be used with equation (33) to get K'. Since Chang's data were obtained so soon after the start of the drying, the values of T_m-T_s increase with time; for example, in Run 1 of Chang's thesis, they are 0.045, 0.055, 0.065, 0.065, 0.070 after 20, 40, 60, 80 and 100 minutes, respectively. Thus, the values of K' calculated from Chang's data are high, being 11 to 13×10^{-4} at fluidities of water of 1.2 - 1.5. The data of Troop and Wheeler are not subject to a large error due to this cause, as their gradients were obtained 6-36 hours after the start, and T_m-T_s does not show a tendency to increase with time.

RELATION BETWEEN RATE OF DRYING AND CRACKING OF CLAY

It follows from the derivation of the parabolic moisture gradient in a clay slab during the constant rate period that the greatest slope of the gradient curve is at the solid surface. Since the shrinkage is a direct function of the water content, it follows that the shrinkage is always greatest at the surface.

Since the clay is non-compressible, the surface plane must remain of the same gross area as the corresponding parallel plane at the center, with consequent appearance of cracks in the surface; or else the edges of the slab must curve sufficiently to allow for the difference in shrinkage at the surface and at the center. The ability of the slab edges to curve and thus eliminate surface cracks will depend on the ratio of thickness to surface area. Thus a slab being dried only from the two faces, and having a very large face area compared to its thickness would have no chance to take up the different shrinkage by distortion, and would crack easily. Another slab of the same material, but quite thick as compared to its face area could take up the differential shrinkage by distortion (from a cylinder to a barrel-shaped bar, if drying were from the two circular faces).

For any given shaped object the differential shrinkage is a function of T_m-T_s, which in turn is directly proportional to the rate of drying in the constant rate period. Thus, for a given shape the tendency to crack is directly proportional to the rate of drying. It seems possible that data on the shrinkage and the elongation of a break of a given clay would make possible the prediction of the maximum rate of drying without cracking of the large slab where no distortion was possible. Where distortion helps prevent cracking, the plasticity of the clay is doubtless an important factor, since the rate of change of form must correspond to the rate of shrinkage or cracking will result.

CALCULATION OF THE DIFFUSION CONSTANT FROM THE RATE CURVE

The value of the diffusion constant K may also be obtained by comparison of the actual with the theoretical rate curves. For example, in the case of Runs 72 and 73 for clay (see Figure 59) the rate was approximately 0.030 gms./hr./sq.cm. when E was 0.5. From Figure 4 it is seen that the corresponding theoretical value of $dE/d\tau$ is 1.254.

$$\text{Now } \frac{dW}{A\,d\theta} = \frac{dE}{d\theta} \times T_o \times R \times \rho = \frac{dE}{dT} \times \frac{K}{R} \times T_o \times \rho$$

$$K = \frac{0.030 \times 1.27}{3600 \times 0.17 \times 1.6 \times 1.254} = 3.1 \times 10^{-5}$$

as compared with 4.7×10^{-5} obtained from Figure 61.

F - THE DRYING OF WOOD

The drying of wood offers a commercial field where the theoretical equations for internal liquid diffusion might be expected to apply. Tuttle[27] compared data on moisture gradients in a 5.08 cm. slab of Sitka spruce with the theoretical equation (1), and calculated the diffusion constant of water through the wood. This value of K was then used with the theoretical drying equation (2) to predict the drying curve for a similar 5.08 cm. spruce slab. The predicted curve was found to compare well with experimental data obtained in drying such a slab. It is believed that the special plot method described above is a considerable improvement over Tuttle's method of finding K from experimental data, since not only are the required calculations much less, but little knowledge of the mathematics involved is necessary.

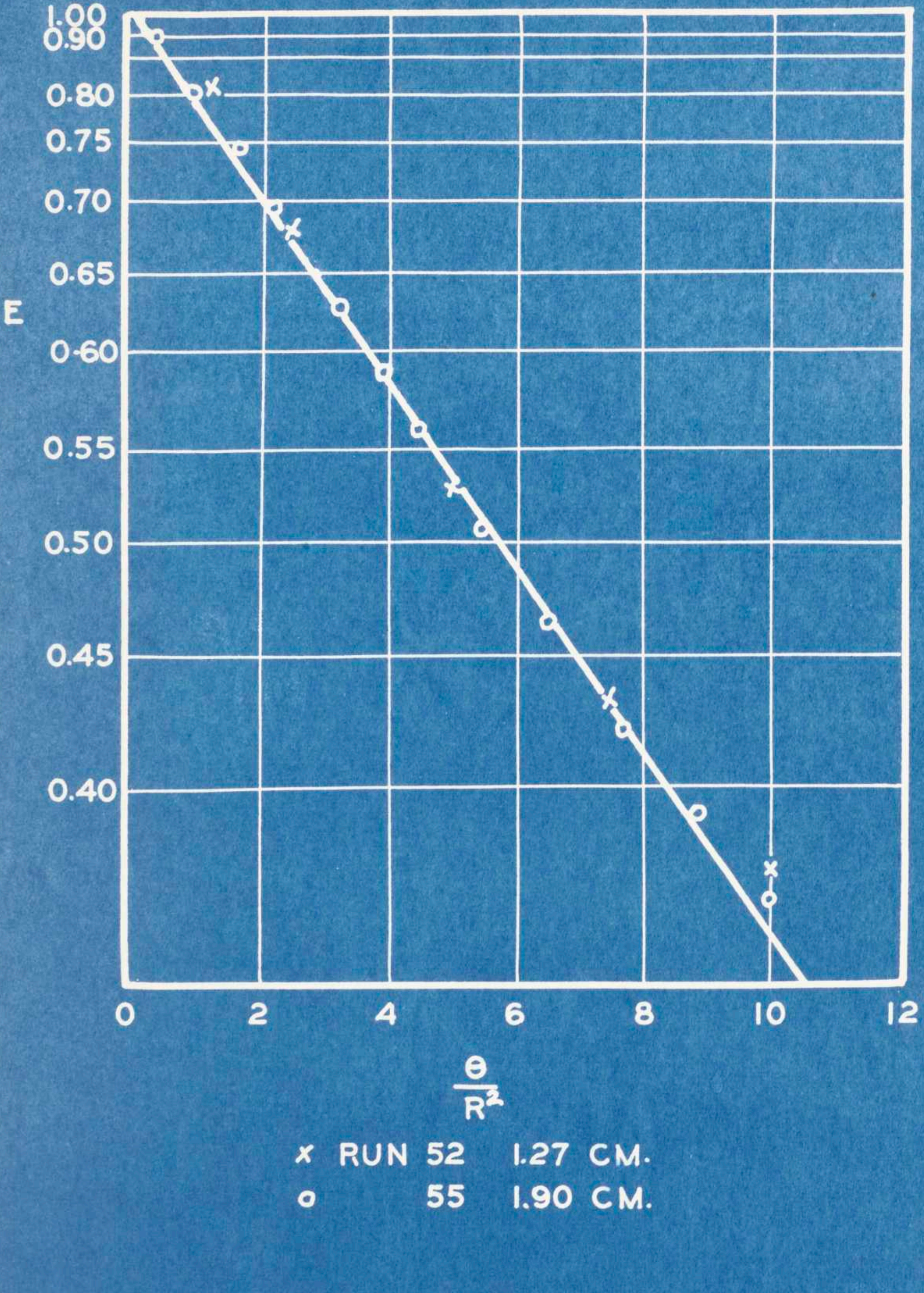
The data of only one experiment are shown by Tuttle, and that in the form of a plot, so it is impossible to use his data to compare the actual with the theoretical effect of slab thickness on the drying time. In this single experiment reported, the initial water content was 51 percent, and the equilibrium water content 8%, E was, therefore, 0.60 at 33.8% water, which from the plot corresponded to about 28 hours. From Figure 2, $E = 0.60$ when $\tau = 0.126$

$$\tau = 0.126 = \frac{K\theta}{R^2} = \frac{28 \times 3600 \times K}{(2.54)^2}$$

where $K = 1.05 \times 10^{-6}$ in c.g.s. units. This is an approximate value of K for the Sitka spruce used, diffusion across the grain, the calculation assuming that the data follows the experimental relation as indicated by the plot shown by Tuttle, and that $E = 0.60$ at 28 hours is a representative point.

In the present investigation several runs were made drying white wood (poplar) slabs 0.41, 0.69, 1.27 and 1.90 cm. thick, respectively. The first two sets of four runs each (Runs 48-55) are believed to be faulty due to the fact that the samples were not soaked under water long enough before the start of the experiment to assure an even moisture distribution through the wood. The result was that the initial moisture contents varied from 17% with the thick slab to 147% with the thin slab. Since at the start, therefore, there existed an appreciable moisture gradient from the surface in towards the center, the equations previously derived could not be expected to fit the data. In spite of this, however, the data on Runs 52 and 55 using slabs 1.27 and 1.90 cm. thick, and containing 49.4 and 39.7% free water, respectively, when plotted on the special plotting paper give excellent

DRYING OF POPLAR WOOD.



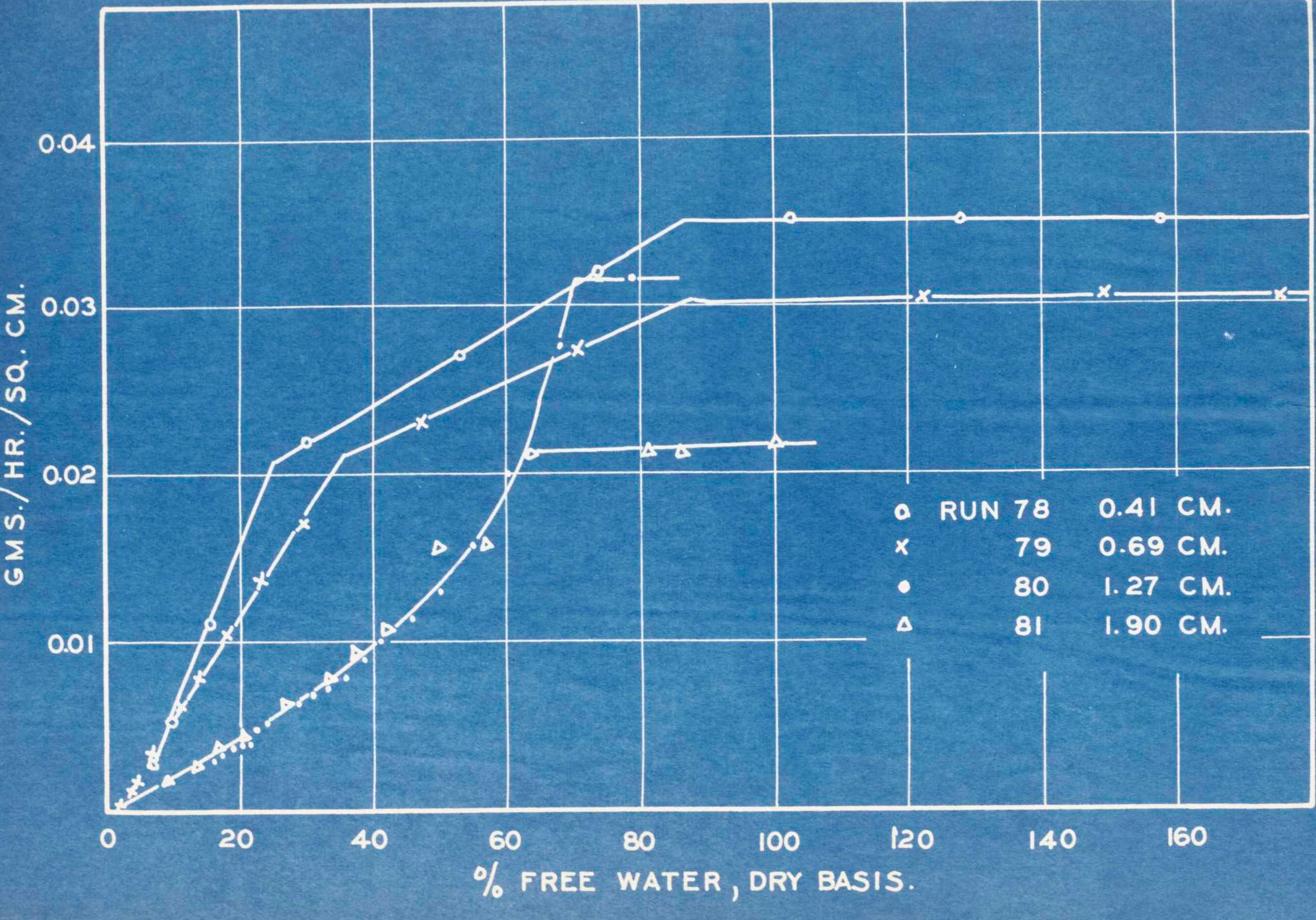
results. As may be seen from Figure 64, the curves are practically linear down to values of E of less than 0.40, and the lines representing the runs almost coincide, although there is more than a two-fold variation in the term R^2. The value of K may be calculated as above. Again arbitrarily taking the point at E = 0.60 as a representative point, we have

$$\tau = 0.126 = \frac{K\theta}{R^2} = 3.72 \times 3600 \times K$$

whence $K = 9.4 \times 10^{-6}$, which compares well with the value of 8.05×10^{-6} obtained from Tuttle's data on spruce.

In order to obviate the difficulty of obtaining uniform moisture distribution in the samples before the start of the runs, the four wood slabs used above were soaked under water nearly four months before being used in Runs 78-81 inclusive. Even then the initial moisture contents varied from 90-265% water, but since the wood was so very wet and swollen, it is believed that a fairly uniform moisture distribution was possible in each slab, even though the water contents were different in the slabs of different thickness. Figure 65 shows the rate curves calculated from the data of these runs. In each case a constant rate period appeared, and in the case of the two thinner slabs, the falling rate period is clearly divisible into Zone A and Zone B. The rate curves in Zone

DRYING OF POPLAR WOOD



B fall approximately inversely in order of the slab thicknesses, except for the near coincidence of the curves for Runs 80 and 81, and in this region internal liquid diffusion is controlling. It is interesting to note the appearance of a Zone A in the runs with the two thinner slabs, and the absence of a Zone A in the case of the thicker slabs. This is no doubt due to the fact that with the thicker slabs, the internal diffusion curve is reached before the surface water concentration drops to that point where Zone A appears; with the thinner slabs the internal diffusion curves are so much farther to the left at the same rate that the surface water concentration drops to a low enough value to cause the appearance of a Zone A before the internal diffusion curves are reached.

It has been shown in the discussion of the data on drying clay that an increase in air velocity may be the cause of the disappearance of the Zone A. From the above it is seen that an increase in slab thickness may cause the same effect. The explanation in each case is that conditions are changed so the internal diffusion curve is reached before the surface water concentration can drop to a value low enough to cause the appearance of a Zone A.

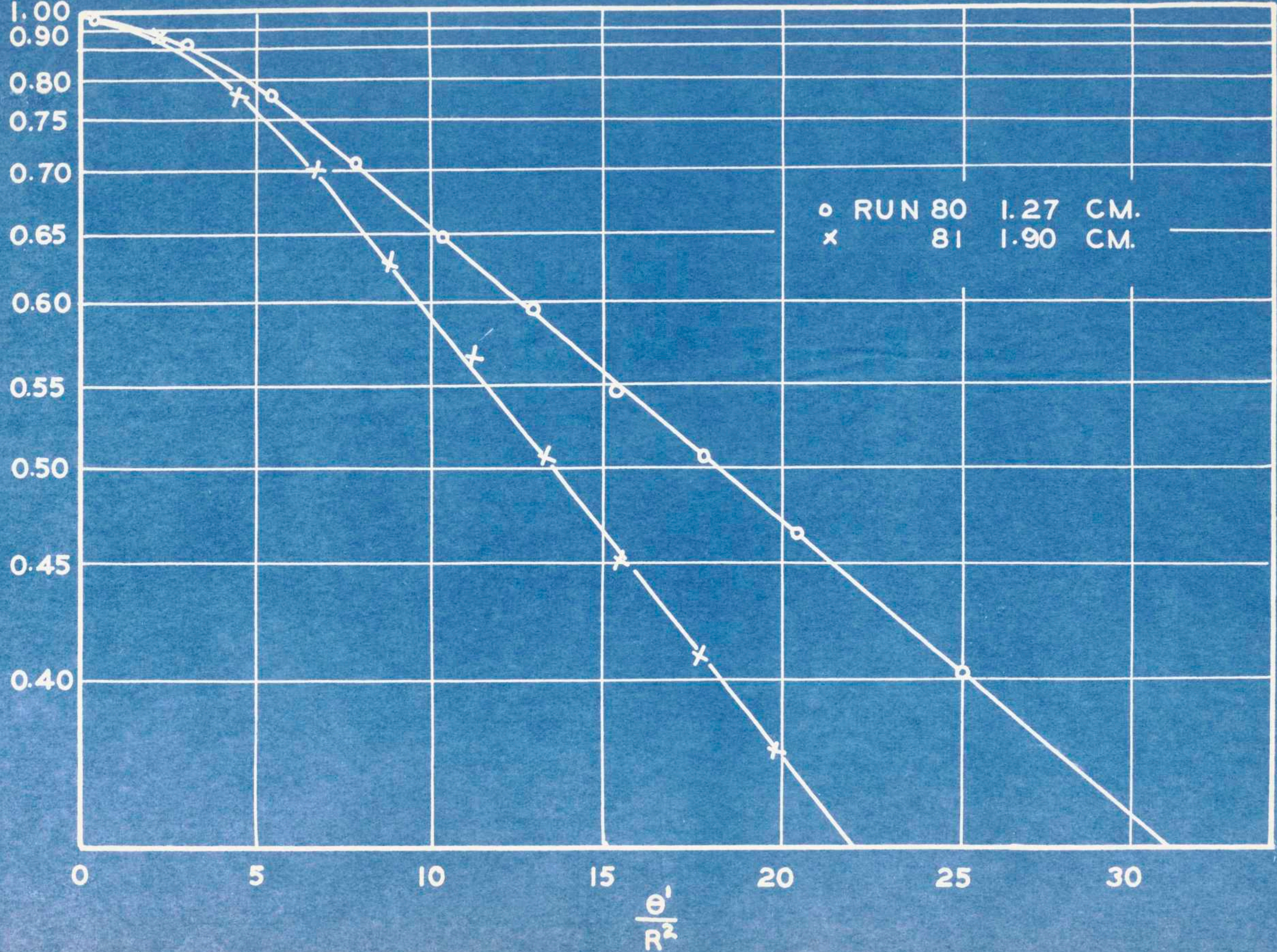
The data of Runs 80 and 81 have been plotted on the special coordinate paper, as E' vs. θ'/R^2 as shown in Figure 66. The curves are seen to be linear except at high values of E', and it is suspected that during the constant rate period in each case a gradient was set up from center to surface, so that the initial drying rate in the falling rate period was less than that called for by the theoretical relation, which was based on the assumption of an initial uniform liquid distribution. As in the case of the clay, therefore, the first portions of the curves have relatively low slopes. The curves for the two runs do not check each other well, probably because the wood structure in the two slabs was changed by the swelling when soaked. The approximate value of K may be calculated from these curves, as was done above. At $E' = 0.40$ the average value of $\theta'/R^2 = 21.6$; the corresponding theoretical value of Υ is 0.285;

$$\Upsilon = 0.285 = K \times 3600 \times 21.6$$

whence $K = 3.67 \times 10^{-6}$, which may be compared with the value of 8.05×10^{-6}, obtained by Tuttle for spruce.

It would be of interest to use the above equations and method of analysis in the correlation of data on the absorption of water and other liquids by wood. The reverse of the drying process should be amenable to the same mathematical analysis, and a correlation of

DRYING OF POPLAR WOOD.

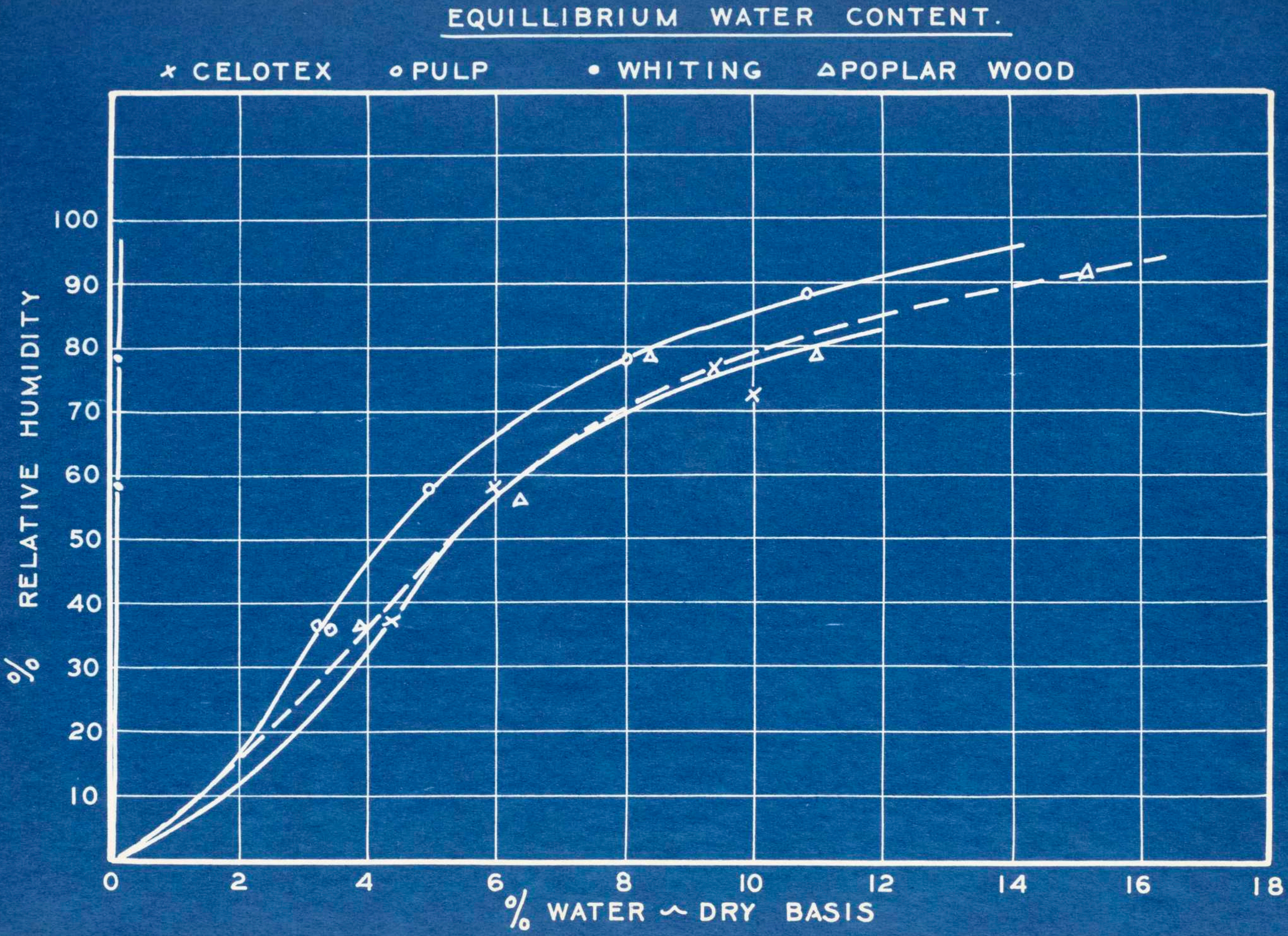


such data might throw light on the problems involved in soaking wood with liquid preservatives.

G - EQUILIBRIUM MOISTURE DATA

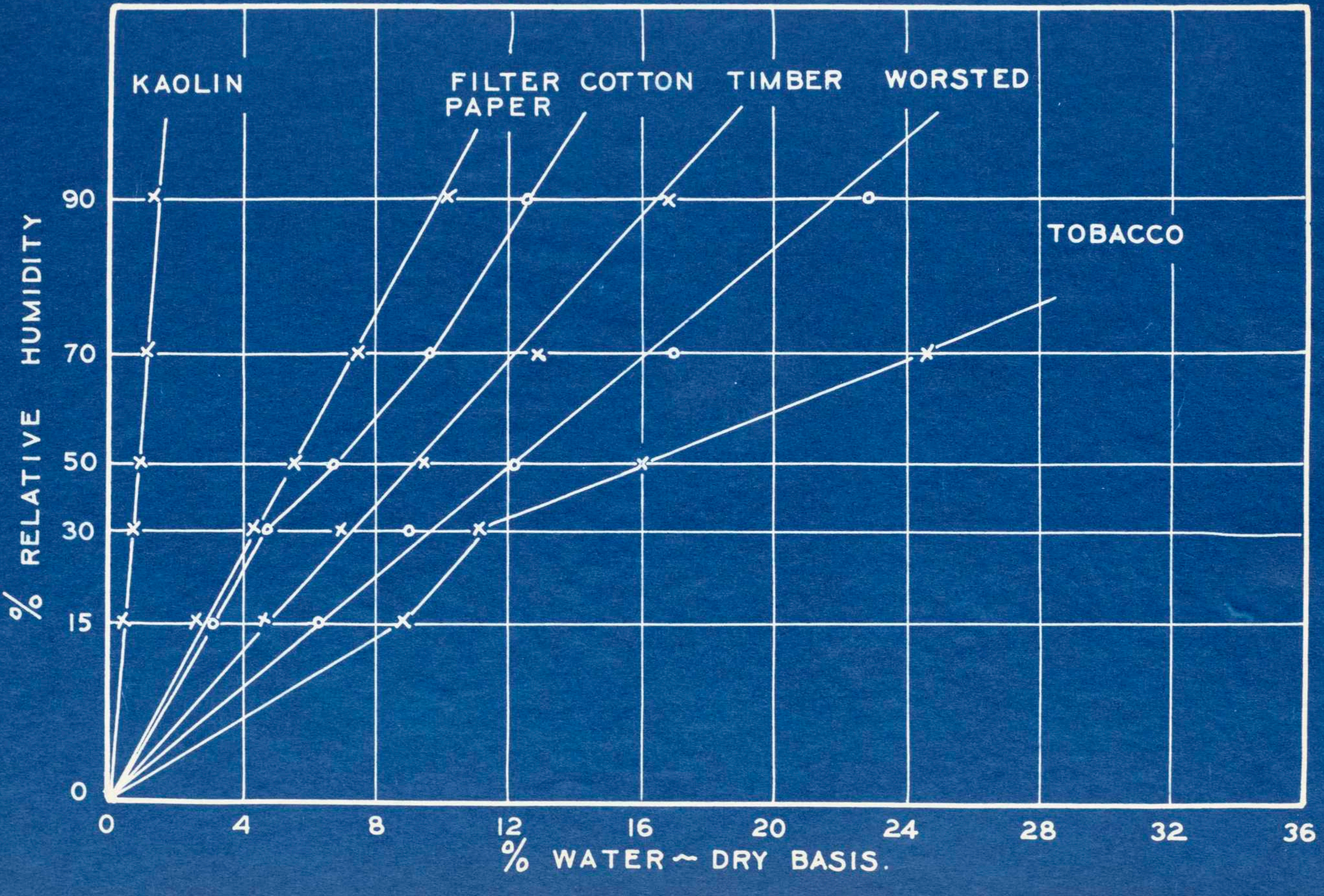
Equilibrium moisture data for several of the materials dried were obtained by the method used by Wilson and Fuwa.[11] It was found, however, that instead of three days, one to three weeks were necessary to bring the sample to constant weight. For this reason several months were required to obtain the data on the four materials tested. The results are shown plotted in Figure 67, which shows the typical sigmoid curve representing percent relative humidity as a function of water content. It is to be noted that whiting showed an almost imperceptible hygroscopic moisture, even at high relative humidities, so the total water is nearly identical with the free water. Even pulp contains only 2-3% equilibrium water under the conditions prevailing in the tunnel drier.

The similarity in shape of the various equilibrium curves, such as those of Figure 67, suggests a method of correlating such data similar in principle to the "special plot" method of using equation (2). Figure 68 shows equilibrium data from the literature,[29] plotted as


EQUILLIBRIUM WATER CONTENT.
× CELOTEX
○ PULP
● WHITING
△ POPLAR WOOD
% RELATIVE HUMIDITY
100
90
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
% WATER ~ DRY BASIS

EQUILLIBRIUM WATER CONTENT.

DATA FROM INTERNATIONAL CRITICAL TABLES.



in Figure 67 , but with the ordinate scale so changed as to force a typical sigmoid curve to become a straight line. Other similar curves will also approximate straight lines, as shown. Such a plot is of value in constructing an approximate equilibrium curve with limited data, for since all the curves must pass through the origin, another single point is sufficient to fix the location of the straight line relation in Figure 68, and hence the approximate equilibrium curve on a linear coordinate plot as in Figure 67 .

PART IV

CONCLUSIONS

CONCLUSIONS

The general conclusions reached as a result of the present investigation have been described in the Abstract. However, a number of conclusions have been collected and tabulated below.

1. Under constant drying conditions, solids in general dry in two stages, a constant-rate period and a falling-rate period. The point at the end of the first and at the beginning of the latter is called the critical point, and the liquid content of the solid at the critical point is called the critical liquid content.
2. In general, the critical liquid content does not correspond to the liquid content of the solid in equilibrium with nearly saturated air.
3. During the constant rate period, the rate of drying is governed by the rate of removal of vapor from the solid surface. When all of the surface of the solid is wetted, the rate of drying corresponds to the rate of evaporation from a free liquid surface.
4. Under the same drying conditions, the rate of drying in the constant rate period is the same for the whiting, clay and pulp tested, providing the ratio of the dry to the wetted surface of the solid is the same in each case.

5. The ratio of dry to wetted surface of the solid is an important variable affecting the solid temperature and hence the drying rate. Unless this factor is constant, the total rate of drying is not necessarily proportional to the wetted surface.
6. During the constant rate period the solid temperature remains constant. If the whole surface is wetted, the solid temperature is the same as the wet-bulb temperature of the air; if there is dry surface adjoining the wet, the solid temperature will be everywhere greater than the wet-bulb temperature.
7. Radiation to the solid from surroundings at a higher temperature may increase the rate of drying very materially. Radiation from surroundings at the air temperature caused an increase in the drying rate in the experiments described of only 4-5%, but radiation from surroundings at 200-400° C. may increase the rate of drying several fold.
8. The data on drying of whiting during the constant rate period using different liquids are too meagre to be correlated on the basis of the physical properties of the liquids. What data was obtained indicate that the coefficient K_g (gms./hr./sq.cm./m.m.Δp) varies inversely as the molecular weight of the liquid evaporating.

9. The velocity of air past the surface of the solid has a very marked effect on the drying rate during the constant rate period. Data on very wet pulp in the constant rate period shows the rate of vaporization to vary directly as the 0.6 power of the air velocity past the surface.

10. The falling rate period is in general divisible into two zones called "Zone A" and "Zone B". Zone A is that period immediately after the critical point, during which the rate of drying is a linear function of the free liquid content of the solid. Zone B follows Zone A, and is distinguishable by the plot of rate of drying vs liquid content, being convex to the axis representing liquid content.

11. The overall coefficient of heat flow from air to solid remains constant during Zone A of the falling rate period, and is the same as the value found during the constant rate period. It follows that during Zone A the evaporation of liquid is at the solid surface.

12. During Zone A of the falling rate period the curve of rate of drying vs. liquid content is not similar to the theoretical curve rate, and furthermore the rate is not inversely proportional to the slab thickness; it is concluded that internal diffusion of liquid is not controlling in this range.

13. During Zone B of the falling rate period the curve of rate of drying vs. liquid content is similar in shape to the theoretical rate curve; and the data indicates strongly that in this region the rate is inversely proportional to the slab thickness; it is concluded that in this zone internal liquid diffusion is controlling.

14. The overall coefficient of heat flow from air to solid decreases sharply in Zone B for the case of whiting, but for clay no such decrease is apparent. Thus, in Zone B for whiting evaporation occurs beneath the solid surface; for clay evaporation is at the surface in Zone B. It is concluded that when internal liquid diffusion is controlling evaporation may occur at the surface or within the solid, depending on the porosity.

15. The occurrence of a "Zone A" is dependent on the value of the rate during the constant rate period and on the relation between internal diffusion and liquid content. Thus, if the liquid content, at which the rate of internal diffusion is equal to the constant rate period drying rate is reached before the surface liquid concentration falls to such a value as to cause a decrease in drying rate due to decreased wetted surface, then no Zone A" appears.

16. In the drying of paper pulp the overall coefficient of heat flow from air to solid remains constant during the constant rate period, but falls off sharply at the critical point, and decreases continually throughout the falling rate period. It is concluded that for the case of pulp, evaporation occurs at points beneath the solid surface throughout the falling rate period.

17. Variations in air velocity have little or no effect on the rate of drying of pulp in the falling rate period.

18. From the data on moisture gradients in pulp during drying, it is concluded that evaporation in the pulp is not at a plane, or a relatively thin zone, but is distributed from the surface in to a plane parallel to the surface beyond which no evaporation takes place.

19. The liquid gradient in a slab during the constant rate period may be represented by a parabola on a plot of liquid concentration vs. slab thickness. If the initial liquid distribution is not parabolic, the parabolic gradient is approached more and more closely as time goes on.

20. The mathematical theory and Fourier series derived and commonly applied to the conduction of heat in solids may be applied to the diffusion of liquids through solids. The equations so derived apply in general to the drying of solids where internal liquid diffusion is controlling.

21. The theoretical equations apply to the drying of soap, if proper allowance is made for the change of diffusion constant with moisture content.

22. For practical calculations, the change of liquid content with time in the falling rate period is found to be well represented by the equation

$$\log E' = - C \theta'$$

where E' is the ratio of the free liquid content to the free liquid content at the critical point, θ' is the time after the start of the falling rate period, and C is a constant. Thus, the data on the drying of clay and pulp wet with water and of whiting with several liquids, is found to be well correlated by an equation of this form.

PART V

APPENDICES

APPENDIX I

THEORETICAL ANALYSIS OF RATE OF DRYING FOR CASE WHERE EQUILIBRIUM CONTROLS

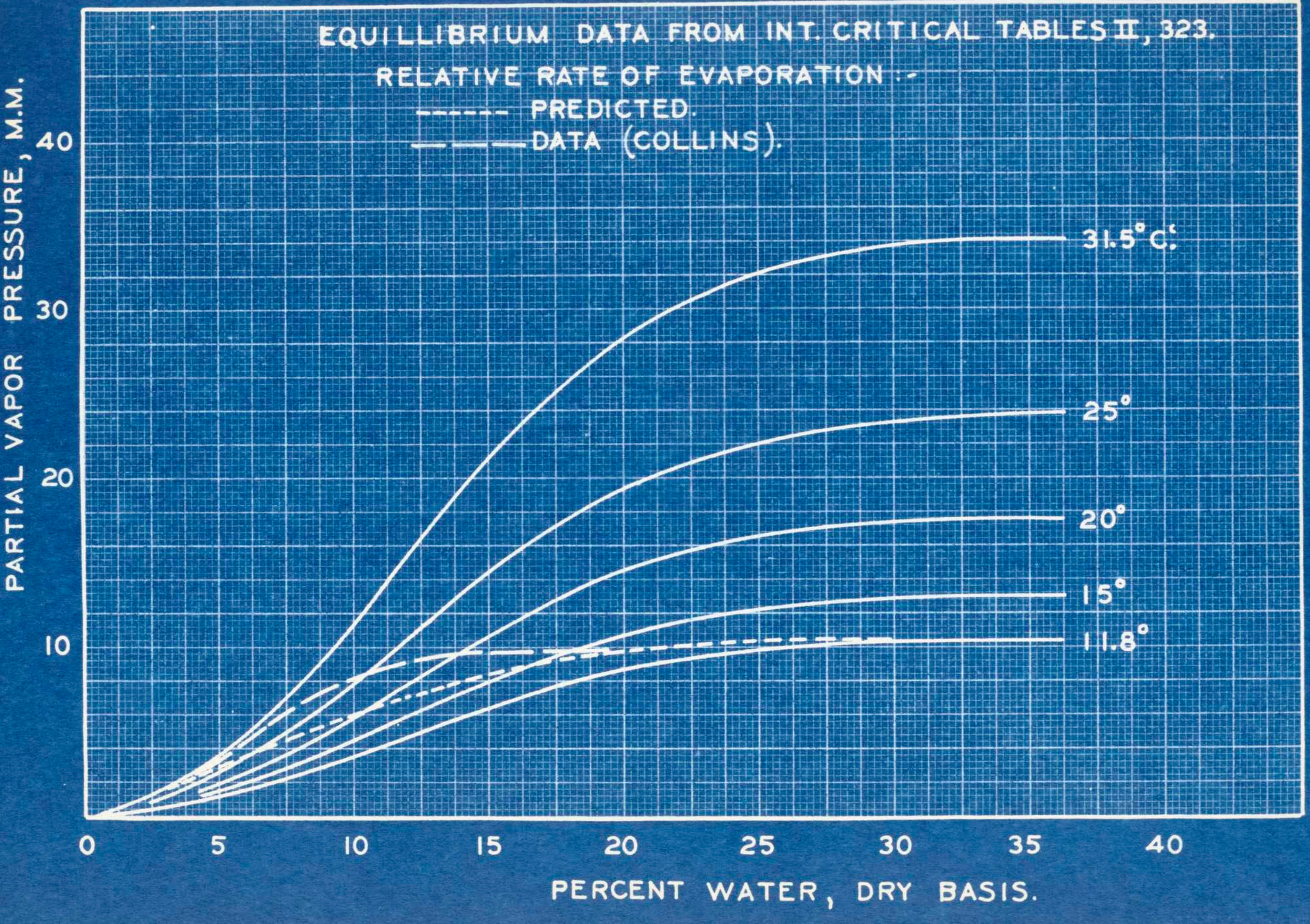
In the discussion of the possible causes of the decrease in drying rate after the critical point is passed, it was shown that the decreased vapor pressure of water at low water contents was not in general important as a factor influencing the drying rate, However, it is interesting to see the possible effect of the partial pressure of water over the solid in the extreme case where this factor controls the drying rate. Such might be expected to be the case for the case of a very thin sheet of homogeneous material of such a structure that the surface area when wet is the same as when dry. Under these conditions no Zone A or Zone B would be expected to occur, and except for a decrease in vapor pressure of water over the solid, the rate of drying would be expected to continue constant to dryness.

When a solid is very wet, the partial pressure of water over the wet solid is equal to the vapor pressure of water at the same temperature. However, as indicated by the equilibrium moisture curves, the partial pressure decreases with water content and is zero at zero water content. The equilibrium curves do not vary greatly with temperature, so that the partial pressure of water over a solid at a given water content is found by multiplying the corresponding percent relative humidity by the vapor pressure of water. Figure 69 shows the partial vapor pressure of water over wool calculated in this way plotted vs. water content of the wool, for several different temperatures.

Under the conditions specified, these curves in Figure 69 represent p_s, and if p_a represent the partial pressure of water in the air, then the rate of drying should be proportional to $p_s - p_a$ or Δp. Thus, with dry air, and if the solid temperature remained constant the curves shown would represent the relative rate of drying.

However, the solid is at the wet-bulb temperature during the constant rate period, and is at the dry bulb temperature when dry. For example if the air is at 31.5° C. and dry, therefore having a wet-bulb temperature of 11.8° C., the Δp during theconstant rate period will be 10.4 mm, and the Δt during the same period will be $31.5-11.8 = 19.7°$ C. Since from the conditions specified H will remain constant, Δt will be proportional to the heat flow, which in turn will be very nearly proportional to the rate of drying and to Δp. Under these conditions the relation between Δt and Δp is given by

WORSTED WOOL FABRIC.



$$\Delta t = \frac{19.7}{10.4} \Delta p$$

and since $\Delta p = p_s - p_a = p_s$

and $\Delta t = t_a - t_s = 31.8 - t_s$

therefore, the position is fixed of the curve representing the partial pressure of the water over the solid during the drying process. Thus, for the conditions specified it is possible to construct the curve of relative drying rate vs. water content, and is shown dotted on Figure 69. With data on the rate of drying during the constant rate period, and data on the equilibrium water content it is thus possible to predict the curve of drying rate vs. water content.

The dashed curve on Figure 69 represents the data of Collins (M.I.T. Thesis, 1928) on the drying of a thin piece of wool fabric. The curve is drawn so that the constant rate period rate coincides with the horizontal part of the partial pressure curve for 11.8° C. Since the data was obtained using dry air at 31.5° C., the resulting curve showed dashed should coincide with the predicted curve shown dotted. The fact that the two curves do not check indicates that either the equilibrium data used is not correct for the wool used, or else that other factors than the decreasing partial pressure of water over the wool affect the drying rate.

APPENDIX II

DERIVATION OF EQUATION FOR MOISTURE CONCENTRATION IN SLAB

(SURFACE RESISTANCE TO VAPOR DIFFUSION NEGLIGIBLE)

NOMENCLATURE

v = moisture concentration per unit volume, at a distance x from the surface, and at a time θ from the start of drying.

θ = time from start

x = distance of point from surface

R = one half slab thickness

K = diffusion constant of moisture through solid.

From Newton's Law of Diffusion

$- k \frac{dv}{dx} ds\, d\theta$ represents the moisture diffusing across an element dS in time $d\theta$.

The total amount of water diffusing is the surface

integral

$$- K\, d\theta \iint_{(s)} \frac{dv}{ds}\, ds$$

which is equal to the volume integral

$$- K\, d\theta \iiint \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} \right) dx\, dy\, dz$$

The amount of water in the element $dx\, dy\, dz$

at a time θ is $dx\, dy\, dz$ and after an interval $d\theta$

this amounts to

$$\left(\upsilon + \frac{v}{\theta}\, d\theta\right) dx\; dy\; dz$$

and, therefore, the loss of moisture is

$$-\left(\frac{\partial v}{\partial \theta}\, d\theta\right) dx\; dy\; dz$$

and the total loss of moisture is

$$-\, d\theta \iiint \frac{\partial v}{\partial \theta}\; dx\; dy\; dz.$$

Equating the amount lost to the water diffusing

$$\iiint \left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} - \frac{1}{k}\,\frac{\partial v}{\partial \theta}\right) dx\; dy\; dz = 0$$

This is true for any region and hence the integrand must vanish at any point

$$\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2} = \frac{1}{k}\,\frac{\partial v}{\partial \theta}$$

In the case of the slab, v is independent of y and z, whence

$$\frac{\partial^2 v}{\partial x^2} = \frac{1}{k}\,\frac{\partial v}{\partial \theta}$$

which is the fundamental differential equation for the drying of a slab.

In order to solve this equation, let $v = X\Theta$ where X is independent of θ and Θ independent of x

$$\text{then } \Theta \frac{\partial^2 X}{\partial x^2} = \frac{X}{K} \frac{\partial \Theta}{\partial \theta}$$

$$\text{or } \frac{1}{X} \frac{\partial^2 X}{\partial x^2} = \frac{1}{K\Theta} \frac{\partial \Theta}{\partial \theta}$$

each side of which must be a constant, since the left side does not change as θ is varied, and the right side remains constant as x is varied.

$$\text{Let } \frac{1}{X} \frac{\partial^2 X}{\partial x^2} = - r^2$$

then $X = C_1 \cos r x + c_2 \sin rx$ and let

$$\frac{1}{K} \frac{\partial \Theta}{\partial \theta} = r^2$$

$$\text{then } \Theta = C_3 e^{-r^2 k\theta} + C_4 e^{r_2 k\theta}$$

and the general solution is

$$v = \sum_{r=0}^{r=\infty} (A_r \cos rx + B_r \sin rx)(C_r e^{-r^2 k\theta} + D_r e^{r^2 k\theta})$$

The conditions are

$v = 0$ when $x = 0$ (1)

$v = 0$ when $x = 2R$ (2)

$v = 1$ when $\theta = 0$ (3)

$v = 0$ when $\theta = \infty$ (4)

Conditions (1) and (2) follow from the assumption that the surface resistance to vapor diffusion is negligible; conditions (3) and (4) from the assumption that v is unity at the start and zero after infinite time, or in other words, from the definition of v as the ratio of the free water concentration at any time to the initial free water concentration at the point in question

i.e., $v = \Delta$ (see main table of nomenclature)

From (1), above, $0 = \sum_{r=0}^{r=\infty} C_r e^{-r^2 k\theta} + D_R e^{r^2 k\theta}$

and from (4) $D_r = 0$

$$\therefore 0 = \sum_{r=0}^{r=\infty} C_r e^{-Kr^2\theta} \text{ for all values of } \theta$$

hence $C_r = 0$ for all values of r

$$\therefore v = \sum_{r=0}^{r=\infty} e^{-r^2 k\theta} B_r \sin rx$$

from (3) $1 = \sum_{r=0}^{r=\infty} B_r \sin Kx$

but a Fourier series for 1 between 0 and 2R may be written as follows

$$1 = \sum_{r=0}^{r=\infty} \left\{1-(-1)^{r}\right\} \frac{2}{r\pi} \sin \frac{2r\ xR}{\pi}$$

which from above $= \displaystyle\sum_{r=0}^{r=\infty} B_r \sin r\,x$

hence $B_r = \left\{1-(-1)^{r}\right\} \dfrac{2}{r\pi}$ where $K = \dfrac{2R\Omega}{\pi}$

$$\text{whence } v = \sum_{r=0}^{r=\infty} \left\{1-(-1)^{r}\right\} \frac{2}{r\pi}\, e^{\frac{-r^2 \pi^2 K\theta}{4R^2}} \sin \frac{rx\pi}{2R}$$

or if $\tau = \dfrac{K\theta}{R^2}$

$$v = \sum_{r=0}^{r=\infty} \left\{(1-(-1)^{r}\right\} \frac{2}{r\pi}\, e^{-\left(\frac{\pi}{2}\right)^2 r^2 \tau} \sin \frac{rx\pi}{2R}$$

or

$$v = \frac{4}{\pi}\left[e^{-\left(\frac{\pi}{2}\right)^2 \tau} \sin \frac{x\pi}{2R} + \frac{1}{3}\, e^{-9\left(\frac{\pi}{2}\right)^2 \tau} \sin \frac{3x\pi}{2R} + \ldots\ldots\ldots \right]$$

and since the total concentration change is 1,

$\therefore$ v = Δ = ratio of free water concentration to the initial free water concentration at the point in question.

$$= \frac{4}{\pi}\left[e^{-(\frac{\pi}{2})^2\tau}\sin\frac{x\pi}{2R} + \frac{1}{3}\,e^{-9(\frac{\pi}{2})^2\tau}\sin\frac{3x\pi}{2R} + \frac{1}{5}\,e^{-25(\frac{\pi}{2})^2\tau}\sin\frac{5\pi x}{2R} + \right]$$

APPENDIX III

CORRECTION TO DERIVATION OF GENERAL DRYING EQUATION GIVEN BY WALKER, LEWIS AND MCADAMS[2]

The equations derived by Lewis for the case of drying with internal diffusion controlling have already been discussed. These equations are given in the chapter on Drying in Walker, Lewis and McAdams' "Principles of Chemical Engineering", together with their deviations, which are based on the assumption of a linear moisture gradient from center line to surface of the slab. The general equation derived is

$$-\frac{dy}{d\theta} = \frac{8\alpha\beta y}{L(4\alpha+\beta L)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

where y = moisture concentration, weight per unit volume

θ = time

L = total slab thickness

α = coefficient of diffusion through the stock.

β = coefficient of surface evaporation.

Using this equation the surprising result was obtained that shrinkage influences the rate of drying <u>when surface evaporation is controlling.</u> Since this conclusion is obviously in error, it is of interest to search out the error in the derivation. This is found in the statement "Since the average concentration of free moisture (y) appears on both sides of Equation (4), it is allowable to substitute for y the weight ratio of free moisture on the dry basis, (T-E)". Since it is y that appears on one side of the equation and dy on the other, the above statement is only true when there is a constant relation between T-E and y. Now it is assumed that

$$L = L_e\left[1 + a\,(T-E)\right]$$

where L_e is the thickness corresponding to the equilibrium water content. If ρ is the dry density, the relation between y and T may be written

$$y = T\rho\,\frac{L_e}{L}$$

$$= \frac{T\rho}{\left[1+a(T-E)\right]}$$

$$\frac{dy}{d\theta} = \rho\left\{\frac{\left[1+a(T-E)\right]dT/d\theta - aT\,dT/d\theta}{\left[1+a(T-E)\right]^2}\right\} = -- \frac{\rho\,(1-aE)\,dT/d\theta}{\left[1+a(T-E)\right]^2}$$

Therefore, from (4)

$$-\frac{dy}{d\theta} = -\frac{\rho\,(1-aE)dT/d\theta}{\left[1+a(T-E)\right]^2} = \frac{8\alpha\beta\,y}{L(4\alpha+\beta L)} = \frac{8\alpha\beta(L_e/L)T}{L\,(4\alpha+\beta L)}$$

$$-\frac{dT}{d\theta} = \frac{8\alpha\beta T L_e \left[1+a(T-E)\right]^2}{L^2 (4\alpha + \beta L)(1 - aE)}$$

$$= \frac{8\alpha\beta T}{L_e (4\alpha + \beta L)(1-aE)}$$

$$-\frac{d(T-E)}{d\theta} = \frac{8\alpha\beta T}{L_e (4\alpha + \beta L)(1-aE)}$$

which is the general equation, replacing

$$-\frac{d(T-E)}{d\theta} = \frac{8\alpha\beta(T-E)}{(4\alpha + \beta L) L} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

as given in the book referred to.

Application to Case I. Diffusion rapid compared with rate of surface evaporation, 4α large compared with βL. For these conditions the general equation derived above, becomes

$$-\frac{d(T-E)}{d\theta} = \frac{2\beta T}{L_e (1-aE)}$$

It is to be noted that when the derivation is corrected as above, the resulting equation for Case I no longer shows the rate of drying to vary as shrinkage occurs.

Application to Case II - Diffusion slow compared to surface evaporation, 4α small compared to βL. For these conditions the general equation derived above becomes

$$-\frac{d(T-E)}{d\theta} = \frac{8\alpha T}{L L_e (1-aE)}$$

When shrinkage is neglected, $L=L_e$, and $a = 0$, and the integrated equation is

$$\log_{10} \frac{T_o}{T} = \frac{8\alpha\theta}{2.3 L^2}$$

And when shrinkage is appreciable,

$$-\frac{d(T-E)}{d\theta} = \frac{8\alpha T}{L_e^2 \left[1+a(T-E)\right](1-aE)}$$

Runs 1, 2, 3, 4 and 5
Argo Laundry Starch and Water

Starch paste formed in wood frames.
Laboratory balance used. Samples
hung from roof of drier.
All wood frames 14.2 x 14.2 cm.

Time, Hours	1	2	3	4	5	Dry Bulb ° C.	Wet Bulb ° C.
0	216.2	412.7	537.6	723.1	907.0		
1.67					883.0		
1.78		397.9		695.4			
1.95	190.1		514.6				
3.75					860.9	25.5	10.7
3.86		382.6		670.0			
4.04			494.7				
11.00					774.3	28.0	17.7
11.11		326.3		583.0			
11.28			426.1				
22.75					699.7	28.7	17.8
22.86				535.8			
23.04			387.2				
30.67					675.5	30.0	18.9
30.78				516.9			

Run No.	1	2	3	4	5
Thickness, cm.	0.63	1.27	1.90	2.54	3.18
T_{ave}	41.9	51.2	66.4	78.3	87.3
Net dry, gms.				366.5	494.0

Runs 1-5 Starch and Water

Calculations

Run	1	2	3	4	5
% water, dry basis, at start	(71)	(71)	(71)	76.0	65.9
Gms./hr., constant rate period	(13)	7.8	9.7	11.7	14.5
Gms./hr./sq.cm., " " "	0.033	0.0193	0.0240	0.0290	0.036
Ratio dry to wetted surface	0.09	0.18	0.27	0.36	0.45

Run. 6. Borax Soap and Water

"Babbitt's Best Borax" laundry soap put through meat grinder, sprinkled with water, again put through grinder, kneaded, and pressed into wood frame.
Initial water content 16.8% wet basis.
Dimensions 14.2 x 14.2 x 0.64 cm.
Laboratory balance used. Sample hung from roof of tunnel drier.
Air temperature 23-30°C.
Net original weight (wet) 148.9 gms.

Time, Hours	Loss, Grams	Time, Hours	Loss, Grams
0	0	572.5	15.7
1.92	0.9	593.5	15.8
6.67	2.6	646	16.9
20.5	4.8	669.5	17.0
41.5	6.2	694	17.1
48.3	7.4	720	18.1
89.7	8.2		
119.	9.8		
140.5	10.4		
161.5	11.0		
169.	10.8		
188.5	11.6		
209.5	11.8		
236.5	12.0		
257.5	12.1		
292.3	13.1		
308.5	12.7		
330.	13.4		
357.5	14.1		
379.5	14.0		
406.5	14.6		
425.5	14.5		
453.	14.7		
478.	14.8		
497.5	15.0		
524.5	15.3		
545.5	15.6		

Run 6 Soap and Water

Calculations

Time,hours	% water, dry basis	E
0	20.2	1.00
1.92	19.5	0.965
6.67	18.1	.895
20.5	16.3	.807
41.5	15.2	.751
48.3	14.2	.704
89.7	13.6	.671
119	12.2	.609
140.5	11.8	.584
161.5	11.3	.56
169	11.5	.568
188.5	10.8	.535
209.5	10.7	.528
236.5	10.5	.52
257.5	10.4	.515
292.3	9.6	.475
308.5	9.9	.491
330	9.4	.463
357.5	8.8	.435
379.5	8.9	.44
406.5	8.4	.415
425.5	8.5	.42
453	8.3	.411
478	8.2	.408
497.5	8.1	.40
524.5	7.8	.388
545.5	7.6	.376
572.5	7.5	.372
593.5	7.4	.368
646	6.55	.324
669.5	6.46	.32
694	6.4	.316
720	5.6	.276

Run 7. Borax Soap and Water

Dimensions 14.2 x 14.2 x 1.27 cm.
Procedure and conditions as in
Run 6.
Original net weight (wet) 292.7 gms.

Time, hrs.	Loss, gms.	Time, hrs.	Loss, gms.
0	0	768	23.5
2.58	1.5	794	23.9
7.33	3.6	819	23.9
21.2	4.5	838	23.7
42.2	6.2	883	24.2
49.0	8.0	910	24.2
90.4	9.5	931	24.3
119.7	10.7	983	25.1
141.2	11.8	1006	25.8
162.2	12.5	1051	26.2
169.7	12.9	1151	26.2
189.2	13.4	1174	26.7
210.2	14.1	1226	27.0
237.2	14.8	1267	26.7
258.2	14.7	1321	27.5
293.	15.9	1387	28.4
309.2	15.6	1436	28.4
330.5	16.7	1488	28.7
358	17.2	1556	29.1
380	17.6	1658	29.9
407	18.5	2014	31.2
426	18.4	2060	30.6
454	18.8	2280	32.0
478.5	18.6	2352	32.0
498	19.6		
525	20.0		
546	20.4		
573	20.0		
594	21.4		
647	22.5		
670			
694			
720			
742			

Run 7 Soap and Water

Calculations

Time, Hours	% water, dry basis	E
0	20.2	1.00
2.58	19.6	.97
7.33	18.7	.926
21.2	18.4	.91
42.2	17.7	.87
49.0	16.9	.836
90.4	16.3	.805
119.7	15.8	.78
141.2	15.4	.76
162.2	15.1	.745
169.7	14.9	.736
189.2	14.7	.726
210.2	14.4	.713
237.2	14.1	.70
258.2	14.2	.70
293	13.7	.676
309.2	13.8	.68
330.5	13.3	.66
358	13.1	.65
380	13.0	.64
407	12.6	.623
426	12.6	.625
454	12.5	0.617
478.5		0.621
498	12.2	0.60
525		0.592
546	11.8	0.585
573		0.592
594	11.4	0.564
647		0.541
670	11.0	0.545
694		0.542
720		0.516
742	10.7	0.528
768		0.522
794		0.514
819	10.3	0.514
838		0.519
883	10.3	0.508
910		0.508
931		0.506
983	9;9	0.490
1006		0.475
1051		0.467
1151	9.45	0.467
1174		0.457
1226	9.14	0.451
1267		0.457
1321	8.9	0.441
1387		0.422
1436	8.55	0.422
1488		0.416
1556	8.26	0.408
1658		0.392
2014	7.4	0.366
2060		0.378
2280	7.1	0.349
2352		0.349

Run 8. Borax Soap and Water.

Dimensions 14.2 x 14.2 x 1.90 cm.
Procedure and conditions same as in Run 6.
Original net weight (wet) 434.9 gms.

Time, Hours	Loss, Grams.
0	0
2.4	0.8
7.2	3.4
21	4.7
42	6.6
48.8	7.6
90.2	10.4
119.5	10.8
141	11.6
162	12.2
169.5	13.0
189	13.6
210	14.2
237	15.1
258	15.3
292.8	16.5
309	15.7
330.3	17.6
358	18.4
380	18.9
407	19.1
426	19.4
454	19.5
478.5	20.5
498	20.8
525	21.3
546	21.8
573	22.1
594	23.9
647	23.8
670	24.8
694	24.8
720	26.3
742	25.3
768	26.4
794	26.5
819	27.4
838	26.0
883	28.9
910	26.7
931	28.8
983	28.6
1006	30.6
1051	29.4
1151	30.4
1174	29.7
1226	30.8
1267	32.0
1321	32.6
1387	32.2
1436	32.2
1488	33.0
1556	34.0
1658	34.7
2014	36.7
2060	37.1
2280	37.3
2420	38.5
2715	40.8
3720	43.3

Run 8 Soap and Water

Calculations

Time, Hours	% water, dry basis	E
0	20.2	1.00
2.4	20.0	.99
7.2	19.3	.953
21	18.9	.935
42		.923
48.8	18.4	.909
90.2		.857
119.5	17.2	.855
141		.841
162	16.8	.833
170		.821
189	16.4	.814
210		.805
237	16.0	.794
258		.791
293	15.7	.774
309		.785
330	15.5	.755
358		.749
380	15.0	.741
407		.739
426	14.8	.735
454		.733
479	14.6	.72
498		.715
525	14.3	.709
546		.702
573	14.1	.697
594	13.6	.672
647		.673
670		.66
694	13.4	.66
720		.64
742	13.2	.653
768		.639
794	12.9	.637
819		.626
838	13.0	.644
883		.606
910	12.8	.635
931		.606
983	12.3	.609
1006	11.7	0.581
1051		0.598
1151	11.8	0.585
1174		0.594
1226	11.7	0.578
1267		0.561
1321	11.2	0.555
1387		0.56
1436	11.3	0.56
1488		0.548
1556	10.8	0.535
1658		0.526
2014	10.1	0.497
2060		0.493
2280	9.9	0.49
2420	9.6	0.473
2715	8.9	0.449
3720	8.2	0.407

Run 9. Borax Soap and Water.

Dimensions 14.2 x 14.2 x 2.54 cm.
Procedure and conditions as in
Run 6.
Original net weight (wet) 567.2 gms.

Time, Hours	Loss, grams
0	0
2.08	1.5
6.83	2.5
20.7	4.8
41.7	5.9
48.5	9.7
89.8	10.1
119.2	10.7
140.7	12.5
161.7	12.4

This sample used to obtain moisture gradients, being cut into blocks at intervals starting at 166 hours.

Run 9

Moisture Gradients in Soap

Square chunks about 3.3 x 3.3 cm. cut from sample No.9 at intervals, and sliced parallel to the drying face. The loss in weight of each slice was noted when left in the drier until a constant weight was reached. Slices number from face (No. 1) in towards center. The edges of the square hole in the main sample were covered with tin foil after the chunk was cut in each case.

Table I. --After 166 hours.

Slice No.	Slice Thickness, m.m.	Water, gms.	Dry Weight, gms.	% Water Dry Basis
1	1.9	0.207	2.098	9.87
2	1.9	0.346	2.334	14.82
3	1.9	0.443	2.668	16.61
4	1.9	0.441	2.542	17.32
5	1.9	0.386	2.195	17.62
6	1.9	0.447	2.432	18.41
7	1.9	0.392	2.152	18.22
8	1.9	0.414	2.290	18.09
9	1.9	0.427	2.373	18.02
10	1.9	0.418	2.306	18.10
11	1.9	0.323	1.872	17.27
12	1.9	0.351	2.140	16.42
13	2.5	0.367	3.350	10.97

Run 9.

Moisture Gradients in Soap. (cont.)

Table II.--After 382.7 hours.

Slice No.	Slice Thickness, m.m.	Water, gms.	Dry Weight, gms.	% Water Dry Basis
1	1.9	0.345	3.352	10.29
2	1.9	0.295	2.097	14.08
3	1.9	0.436	2.747	15.88
4	1.9	0.371	2.145	16.51
5	1.9	0.310	1.888	16.42
6	1.9	0.479	2.731	17.57
7	1.9	0.369	2.121	17.40
8	1.9	0.408	2.331	17.51
9	1.9	0.388	2.250	17.26
10	1.9	0.296	1.923	15.40
11	1.9	0.292	1.948	15.00
12	1.9	0.321	2.370	13.56
13	2.5	0.319	3.256	9.80

Table III.--After 1152 hours.

Slice No.	Slice Thickness, m.m.	Water, gms.	Dry Weight, gms.	% Water Dry Basis
1	1.9	0.211	3.181	6.64
2	1.9	0.254	2.128	11.92
3	1.9	0.332	2.405	13.79
4	1.9	0.267	1.820	14.67
5	1.9	0.462	2.380	14.60
6	1.9	0.353	2.295	15.39
7	1.9	0.415	2.739	15.15
8	1.9	0.329	2.047	16.03
9	1.9	0.379	2.489	15.20
10	1.9	0.376	2.496	15.06
11	1.9	0.251	1.716	14.63
12	1.9	0.364	2.769	13.13
13	2.5	0.251	3.519	7.15

Run 10. Borax Soap and Water.

Dimensions 14.2 x 14.2 x 3.18 cm.
Procedure and conditions as in Run 6.
Original net weight (wet) 746.2 gms.

Time, Hours	Loss, gms.	Time, Hours	Loss, gms.
0	0	670	28.4
2.2	1.4	694	29.0
7.0	3.1	720	30.3
20.8	7.2	742	30.7
41.8	7.9	768	29.8
48.6	9.3	794	32.5
90	11.1	819	32.2
119.3	12.2	838	32.5
140.8	13.7	883	34.8
161.8	14.6	910	33.6
169.3	15.3	931	33.9
188.7	16.8	983	35.9
210	16.5	1006	34.2
237	17.0	1051	35.6
258	17.8	1151	36.8
292.8	19.1	1174	35.8
309	18.9	1226	38.5
330	19.7	1267	39.4
358	20.9	1321	39.4
380	22.5	1387	40.6
407	23.7	1438	40.6
426	21.4	1488	41.8
454	22.2	1556	43.0
478	24.2	1658	42.7
498	25.0	2014	45.2
525	26.7	2060	48.1
546	26.3	2280	48.2
573	26.2	2420	52.0
594	26.3	2715	51.8
647	28.9	3720	58.8

Run 10 Soap and Water

Calculations

Time, Hours	% water, dry basis	E	Time, Hours	% water, dry basis	E
0	20.2	1.00	426	16.7	.829
2.2	19.9	0.989	454		.823
7.0	19.7	0.976	478	16.3	.807
20.8	19.0	.943	498		.800
41.8		.938	525	15.9	.788
48.6	18.7	.926	546		.891
90		.912	573	16.0	.892
119.3	18.2	.903	594		.891
140.8		.891	647	15.5	.77
161.8	17.8	.884	670		.774
169.3		.878	694	15.5	.769
188.7	17.5	.865	720		.759
210		.868	742	15.2	.755
237	17.5	.865	768		.763
258		.868	794	15.0	.741
293	17.1	.848	819		.743
309		.85	838	15.0	.741
330	17.0	.843	883		.723
358		.834	910	14.8	.732
380	16.6	.82	931		.73
407		.811	983	14.4	.714
1006		0.727			
1051	14.5	0.716			
1151		.706			
1174	14.4	.715			
1226		.683			
1267	13.8	.685			
1321		.685			
1387	13.6	.677			
1436		.677			
1488	13.5	.667			
1556		.657			
1658	13.3	.660			
2014		.640			
2060	12.4	.616			
2280		.614			
2420	11.8	.585			
2715		.587			
3720	10.7	.531			

Runs 11, 12, 13, 14, and 15.

Whiting and Alcohol CCl_4, Benzol, Ethyl Acetate, Water.
Each 3.18 cm. thick and 7.0 x 7.0 cm., formed in wood frames. Laboratory balance used. Samples hung from roof of drier.

Time, Minutes	Total Weight plus Tare, gms.					Dry Bulb, ° C.
	11 Alcohol	12 CCl_4	13 Benzol	14 Eth. Acet.	15 Water	
0	329.5	332.6	299.7	320.3	334.7	31
9	326.7	317.9	291.7			
15				307.5		
17	324.7					
22		308.3	280.5		333.0	32
27		291.8				
37	321.2			296.4		
44			271.0			
46		280.0				
52					330.0	31
59	317.8			284.7		
67						
74			265.5			
76		271.7				
87					327.5	31.5
89	313.5					
102				279.5		
109			261.3			
116		265.5				
124	309.0					
127					323.3	31
142				275.8		
149			258.3			
156		260.0				
164	302.1					
180					318.9	32
195				272.8		
202			255.1			
209		255.0				
217	297.4					

Runs 11, 12, 13, 14, and 15 (cont.)

Time,	Total Weight plus Tare, gms.					
Minutes	11	12	13	14	15	Dry Bulb°C.
247					313.6	25
262				271.4		
269			254.4			
278		252.6				
284	294.2					
313					309.4	32
328				271.3		
331			254.2			
340		252.6				
346	292.2					
362					304.7	31
377				271.4		
384			254.2			
393		252.6				
399	290.6					
417					300.3	32
432				271.4		
439			254.6			
448		252.9				
454	290.0				284.0	31
1400				271.4		
1410			254.3			
1426		252.7				
1430	286.7					
	286.8	252.7	254.3	271.4	283.5	
Tare	40.4	40.3	40.0	40.1	40.8	

Run 11 Whiting and Alcohol

Calculations

Time, Minutes	% alcohol, dry basis	Gms/hr. /sq.cm.
0	17.3	
9	16.2	
17	15.4	0.122
37	14.0	0.108
59	12.6	0.093
89	10.8	0.087
124	9.0	
164	6.2	0.082
217	4.3	0.040
284	3.0	0.021
346	2.2	
399	1.5	
454	1.3	
1429		
1524		
2899	0	

Run 12 - Whiting and Carbon Tetrachloride

Calculations

Time, Minutes	% CCL_4, dry basis	Gms./hr. /sq.cm.	E
0	37.7		1.00
9	30.7		.813
14	26.2	0.94	.696
29	18.5	0.485	.49
51	12.9	0.224	.342
81	9.0	0.134	.238
116	6.1	0.097	.161
156	3.5	0.070	.093
211	1.1		.03
276	0		0

Run 13 Whiting and Benzol

Calculations

Time, Minutes	% benzol, dry basis	Gms/hr. /sq.cm.	E
0	20.7		1.00
9	17.0		0.841
22	12.2	0.459	0.589
44	7.8	0.169	0.376
74	5.2	0.101	0.252
109	3.3	0.061	0.158
149	1.9	0.043	0.09
202	0.4		

Run 14 Whiting and Ethyl Acetate

Calculations

Time, Minutes	% et.acet. dry basis	Gms./hr. /sq.cm.	E
0	21.1		1.00
15	15.6	0.45	0.739
37	11.8	0.28	0.51
67	5.5	0.14	0.272
102	3.5	0.07	0.165
142	1.9	0.044	0.09
195	0	0.023	

Run 15 Whiting and Water

Calculations

Time, Minutes	% water, dry basis	Gms./hr. /sq.cm.
0	21.1	
22	20.4	
52	19.2	0.051
87	18.1	0.051
127	16.4	0.051
180	14.6	0.051
247	12.4	0.051
309	10.7	0.046
363	8.7	
417	6.9	
1393	0.2	

Run 16. Whiting and Water.

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame. Laboratory balance and indicating potentiometer used.
Net dry weight 243.0. Total face area 89 sq.cm.
Resting on drier floor.

Time, Minutes	Loss, gms.	Dry Bulb, °C.	Wet Bulb, °C.	ΔT °C.
0	0			
2		32.4		7.5
6				7.8
9		32.5		7.8
18		32.3	22.1	7.9
20	1.8			
22		32.4	22.2	8.1
34		32.5	22.2	8.2
35	3.6			
49	5.2	32.5	22.3	8.3
60				8.4
91	9.1	32.6	22.4	8.2
114	11.3	33.0	22.5	8.4
159	14.4	33.5	23.0	8.6
243		34.0	23.2	8.7
250	21.3			
279		34.0	23.3	8.9
344	28.5	34.2	23.4	8.9
374	30.7	34.7	23.6	8.0
576	44.5	35.5	23.9	6.9
1322	53.0	34.5	23.7	0.9
∞	54.6			

Run 16 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./hr. /sq.cm.	H
0	22.5		
1	19.6	0.0652	
2	17.6	0.054	0.00096
3	15.9	0.0506	0.00088
4	14.1	0.0506	0.00087
5	12.2	0.0506	0.00086
6	10.3	0.0506	0.00086
7	8.5	0.0461	0.00083
8	6.9		
10	3.8		

Run 17 Whiting and Toluene

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 220.6 gms. Total face area 89 sq.cm.

Time, Minutes	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0	0			
3		38.8	22.6	4.4
15	8.6			11.9
28		39.1	23.2	11.7
30	14.0			11.7
45	21.9			10.4
60	25.5			8.5
63		39.8	23.2	
75	27.8			6.8
90	29.6			5.5
120	31.9			4.2
150	33.4			3.8
180	35.3	41.1		3.6
240	37.2			3.3
288		41.6	23.9	3.[illegible]
300	38.6			2.9
360	40.1			2.5
413		41.6	24.3	
420				1.7
480	40.2			1.5
540	40.2			1.3
598				
600		41.1	23.7	
∞	40.2			

Run 17 Whiting and Toluene

Calculations

Time, Minutes	% toluene, dry basis	Gms./hr. /sq.cm.	H	E
0	18.2			1.00
15	14.3			0.787
30	11.9	0.298	0.000696	0.653
45	8.3	0.182		0.456
60	6.7	0.145	0.000616	0.367
75	5.6			0.31
90	4.8			0.265
120	3.8	0.045	0.000383	0.208
150	3.1			0.171
180	2.2	0.033	0.000362	0.124
240	1.4			0.077
300	0.9	0.017	0.000187	0.041
360				
420				
480				
540				
598				

Run 19 Whiting and Amyl Acetate

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 235.3 gms. Total face area 89 sq.cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0	0			
0.25	4.5	39.4	26.8	14.9
0.5	8.8	40.0	27.5	12.1
0.75	12.9			10.3
1.00	16.4			9.3
1.25	19.7			8.4
1.5	23.8			7.6
1.75	28.2			7.3
2.0				7.0
3.0				5.7
4.0	36.3	41.5	29.8	3.3
4.5	37.0			2.8
5.0	37.7			2.6
5.5	38.4			
6.0	38.9	41.6	28.8	2.2
7.0	39.7			2.1
8.0	40.5			
9.0	41.1			1.7
10.0	41.4			
∞	42.5			

Run 19 Whiting and Amyl Acetate

Calculations

Time, Hours	% amylacetate, dry basis	Gms./hr. /sq.cm.	H
0	18.1		
0.25	16.1	0.193	
0.50	14.3	0.186	
0.75	12.6	0.163	
1.0	11.1	0.163	
1.25	9.7	0.163	
1.50	7.9	0.163	
1.75	6.1	0.191	
2			
3			
4	2.6	0.015	
4.5	2.3	0.015	
5	2.0	0.015	
5.5	1.7		
6	1.5		
7	1.2		
8	0.85		
9	0.6		
10	0.5		

Run 20 Whiting and Amyl Acetate

Thickness 3.18 cm.
Dimensions 6.6 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 238.5 gms. Total face area 89 sq.cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δ t ° C.
0	0			
0.25	5.5			8.3
0.5	11.2	38.5	29.7	6.9
0.75	13.4			6.4
1.0				6.1
1.25				5.7
1.5	22.0	38.5	32.0	5.6
1.75	24.8			5.3
2.0	27.3			5.0
2.5	31.6			4.2
3.0	34.3	38.3	32	3.3
3.5	36.9			2.3
4.0	37.9			1.9
5.0	39.5			1.3
6.0	40.4	37.4	30.6	1.2
7.0				
8.0	41.5	38.0		1.1
∞	45.8			

Run 20 Whiting and Amyl Acetate

Calculations

Time, Hours	% amylacet. dry basis	Gms./hr. /sq.cm.	H	E
0	19.2			1.00
0.25	16.9			0.88
0.50	14.5	0.1852		0.756
0.75	13.6			0.708
1.00		0.1313		
1.50	10.0			0.52
1.75	8.8			0.46
2.0	7.8	0.1020		0.405
2.5	6.0			0.31
3.0	4.4	0.0562		0.25
3.5	3.7			0.195
4.0	3.3	0.0247		0.174
5.0	2.6			0.138
6.0	2.3	0.0146		0.12
7.0				
8.0	1.8			

Run 21 Whiting and Water

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 225.5 gms.
Total face area 89 sq.cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Dry bulb - wet bulb ° C.	Δt ° C.
0				
0.25	0.4	29.6	9.4	6.8
0.5	1.3	32.0	10.1	7.9
0.75	2.3	32.5	10.2	7.9
1.0	3,3	33.5	10.4	8.3
1.5	5.9			
2.0	7.8	35.5	11.0	8.8
2.5	9.5			
3.0	11.3	36.3	11.2	8.9
3.5	13.0			
4.0	14.6	36.5	11.2	9.1
5	17.7	37.0	11.2	9.0
6	21.4	37.2	11.2	9.0
7	24.7	36.8	11.1	9.0
8	27.9	36.3	11.0	8.9
9	31.3	36.3	11.0	8.6
10	34.5	36.3	11.0	8.5
11	37.7	36.0	11.0	8.0
12	40.7	36.4	11.0	7.0
13	42.5	36.5	11.0	4.8
14	43.5	37.2	11.2	3.6
15	44.4	37.0	11.1	2.5
16	45.0	36.0	10.8	2.4
17		36.3	10.7	2.3
18		37.5	11.1	2.2
19	46.1	38.2	11.2	2.0
20		38.0	11.2	1.9
21	47.5	39.0	11.1	1.8
22		39.0	11.9	1.7
23	48.9	39.0	11.9	1.4
∞	49.9			

Run 21 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./hr. /sq.cm.	H	E'
0	22.1			
0.25	22.0	0.0371	0.000812	
0.50	21.6	0.0529	0.000997	
1.00	20.7	0.0472	0.000848	
2	18.7	0.0405	0.000655	
3	17.1	0.0405	0.000665	
4	15.7	0.0394	0.000637	
5	14.3	0.0382	0.000645	
6	12.6	0.0382	0.000631	
7	11.2	0.0382	0.000625	
8	9.8	0.0365	0.000610	
9	8.3	0.0365	0.000637	
10	6.8	0.0360	0.000637	
11	5.4	0.0337	0.000665	1.00
12	4.1	0.0270	0.000637	0.755
13	3.3	0.0150	0.000574	0.607
14	2.8	0.0107	0.000540	0.525
15	2.4	0.0084	0.000501	0.451
16	2.2	0.0047	0.000269	0.401
17				0.312
18				0.197
19	1.7			

Run 22 Whiting and Carbon Tetrachloride

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Laboratory balance and indicating potentiometer used.
Net dry weight 229.3 gms.
Total face area 89 sq.cm.

Time, Minutes	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δ t ° C.
0	0			
5				18.0
6	15.0			
8	20.0			19.0
10	23.0			19.3
11.5	25.0			19.3
14	30.0			19.2
17.5	35.0	36.4	11.5	18.8
21.5	40.0	36.3		18.1
26	45.0			17.2
32	50.0			15.3
36		36.4	11.8	14.1
∞	94.2			

Run 22   Whiting and CCl_4

Calculations

Time, Minutes	% CCl_4 dry basis	Gms./hr. /sq.cm.	H	E
0	41.1			1.00
5				0.841
6	34.6	1.64	0.00101	0.788
8	32.4			0.756
10	31.1	1.24	0.00083	0.735
11-1/2	30.2			0.682
14	28.0	1.06	0.00078	0.629
17-1/2	25.8			0.575
21-1/2	23.6	0.82	0.00070	0.522
26	21.5	0.67	0.00071	0.47
32	19.3			
36		0.56	0.00082	

Run 23 Whiting and Acetone

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Laboratory balance and indicating potentiometer used.
Net dry weight 242.7 gms.
Total face area 89 sq.cm.

Time, Minutes	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0	0			
2	4			17.1
3.5	6			17.4
5		34.0		17.6
8	10			17.6
12.5	12	33.8	2.8	17.0
17.5	15			16.9
27	20	34.1		16.2
31	22			
42	28	34.3		15.1
57	35	34.0	3.0	15.4
77				12.6
80				11.3
87				8.9
95	41			7.8
110				6.3
125				5.2
140				4.1
155				3.0
170				1.6
185	43.5			0.8
200				0.4
215				0.2
230				0.1
∞	44.6			

Run 23 Whiting and Acetone

Calculations

Time, Minutes	% acetone, dry basis	Gms./hr. /sq.cm.	H	E′	θ′ minutes
0	18.35				
2	16.7				
3.5	15.9				
5		0.612	0.001180		
8	14.2	0.460	0.000900		
12.5	13.4				
17.5	12.2	0.376	0.000782		
27	10.1				
31	9.3	0.360	0.000807		
42	6.8	0.360	0.000809	1.00	0
57	3.95			0.58	15
67		0.133	0.000384		
77					
80		0.103	0.000696		
87					
95	1.5			0.22	53
110		0.058	0.000489		
125					
140					
155					
170					
185	0.5				

Run 24 Whiting and Xylene

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 217.3 gms.
Total face area 89nsq.cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0		32.5		4.7
0.5	4.1	33.4	25.5	4.2
1.0	9.3			3.8
1.5	13.5			4.0
2.0	20.0			3.8
3.0	26.9	34.4		3.2
3.5	29.9			2.7
4.0	31.8			2.0
4.5	33.3			1.6
5.0	34.5			1.4
6.0	36.6	35.3		1.0
∞	43.8			

Run 24 Whiting and Xylene

Calculations

Time, Hours	% xylene, dry basis	Gms./hr. /sq.cm.	H	E'
0	20.2			
0.5	18.3			
1.0	15.9	0.108	0.00072	
1.5	14.0			1.00
2.0	11.0	0.113	0.00078	0.785
3.0	7.8	0.073	0.00069	0.556
3.5	6.4			0.459
4.0	5.5	0.042	0.00080	0.396
4.5	4.8			0.346
5.0	4.3	0.028	0.00069	0.307
6.0	3.3			0.237

Run 25 Whiting and Acetone

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 240.8 grms.
Total face area 89 sq. cm.

Time, Minutes	Loss, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0	0			
10		35.0	5.0	15.9
27	12.2			13.1
40	17.2			12.6
53	22.2			12.4
70	27.2			12.0
92	32.2			9.9
122	36.0			6.5
152	38.5			4.0
182	39.0			1.3
212	39.1			0.4
∞	39.2			

Run 25 Whiting and Acetone

Calculations

Time, Minutes	% acetone, dry basis	Gms/hr. /sq.cm.	H	E'	Θ'
0	16.3				
10					
27	11.2	0.249	0.00080		
40	9.1	0.249	0.00069		
53	7.05	0.249	0.00070	1.00	0
70	5.0	0.192	0.00061	0.706	17
92	2.9	0.111	0.00056	0.412	39
122	1.3	0.070	0.00060	0.188	69
152	0.3	0.028	0.00054		
182	0.1				
212					

Run 26 Whiting and Water

Rough sphere 7.6 cm. diam. on wire core.
Recording balance and recording pyrometer used.
Net dry weight 315.2 gms.
Total face area about 180 sq. cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Dry bulb -wet bulb, °C.	Δt ° C.
0	0			0
0.5	0.8	33.5		9.1
1.0	2.3	34.8	10.5	9.9
1.5	4.2			10.3
2.0	6.5	36.0	10.8	10.4
2.5	8.5			10.4
3.0	11.3	36.8	10.9	10.4
3.5	13.5			10.4
4.0	15.6	37.5	10.9	10.4
4.5	18.6			10.3
5.0	21.0	37.5	10.7	10.2
5.5	23.3			10.2
6.0	25.5	37.3	10.7	10.1
7.0	29.8	37.2	10.6	9.9
8.0	34.4	37.2	10.4	9.7
9.0	38.8	36.5	10.4	9.4
10.0	43.3	36.2	10.4	9.2
11.0	47.3	36.0	10.4	8.7
12.0	51.8	35.5	10.4	7.6
13.0	54.8	35.5	10.3	5.2
14.0	56.5	35.5	10.3	3.4
15.0	57.5	35.5	10.4	2.5
16.0	58.1	35.8	10.5	2.0
17.0	58.6	36.0	10.5	1.7
18.0	58.8	36.5	10.6	1.7
19.0	58.9			
∞	60.4			

Run 26

Calculations

Time, Hours	% water, dry basis	Gms./hr. /sq.cm.	H	E'
0	19.2	0.0128		
0.5		0.0194	0.000302	
1	18.5	0.0233	0.000367	
1.5	17.8	0.0250	0.000378	
2	17.1	0.0267	0.000392	
3.0	15.6	0.0261	0.000384	
3.5	14.9	0.0261	0.000381	
4	14.2	0.0261	0.000381	
5	12.5	0.0261	0.000378	
5.5	11.8	0.0261	0.000382	
6	11.1	0.0261	0.000393	
7	9.7	0.0261	0.000399	
8	8.3	0.0261	0.000410	
9	5.9	0.0255	0.000413	1.00
10	5.5	0.0244	0.000426	0.76
11	4.1	0.0200	0.000420	0.50
12	2.7	0.0117	0.000401	0.33
13	1.8	0.0067	0.000344	0.23
14	1.25	0.0044	0.000322	0.17
15	0.9	0.0033	0.000291	
16		0.0222	0.000248	
17		0.0011		
18				

Run 27 Whiting and Benzol

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame
Recording balance and recording pyrometer used.
Net dry weight 232.2 gms.
Total face area 89 sq. cm.

Time, Minutes	Loss gms.	Dry bulb ° C.	Wet bulb ° C	△t ° C
0				
8	6.5	39.0	12.4	18.5
15	11.7			21.0
23	17.3			21.4
30	21.0			21.0
42	29.3			18.7
57	33.3			14.4
76	37.0			10.4
88	38.7			8.3
119	42.0			6.5
150	45.5			5.0
181	47.5			4.0
212	48.5			2.4
∞	49.0			

Run 27 Whiting and Benzol

Calculations

Time, Minutes	% benzol, dry basis	Gms./hr. /sq.cm.	H	E
0	21.1			1.00
8	18.3	0.483		0.867
15	16.1	0.458	0.00050	0.761
23	13.7	0.393	0.00050	0.647
30	12.0			0.571
42	8.5	0.230	0.00052	0.402
57	6.7	0.168	0.00062	0.32
76	5.2			0.245
88	4.4	0.103	0.00041	0.21
119	3.0			0.143
150	1.5	0.055	0.00040	0.071
181	0.6			
212	0.2			

Run 28 Whiting and Ethyl Acetate

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording pyrometer and recording balance used.
Net dry weight 215.6 gms.
Total face area 89 sq. cm.

Time Minutes	Loss gms.	Dry bulb ° C	Dry bulb -wet bulb, °C.	Δt ° C
0	0	33.5		
7.5	5.7			15.0
15	11.1	35.	22.5	16.2
22.5	15.0			15.6
30	17.2	36.3		14.5
37.5	19.0			13.2
45	20.6	37.2		11.5
60	23.3	38.2		8.4
75	25.0		23.9	7.0
90	26.6	39.0		6.1
105	28.0			5.4
120	29.4	40.5		5.0
135	30.5			4.5
150	31.1			3.9
165	31.6	41.8		3.0
∞	32.4			

Run 28 Whiting and Ethyl Acetate

Calculations

Time, Minutes	% Et.Acet. dry basis	Gms./hr. /sq.cm.	H	E
0	15.0			1.00
7.5	12.4	0.528		0.824
15	9.9	0.449	0.000773	0.657
22.5	8.1	0.269	0.000596	0.537
30	7.1	0.168	0.000515	0.47
37.5	6.2	0.146	0.000584	0.413
45	5.5	0.129	0.000679	0.365
60	4.2	0.099	0.000596	0.28
75	3.4	0.079	0.000489	0.229
90	2.7	0.067	0.000556	0.179
105	2.0	0.063	0.000489	0.135
120	1.4	0.056	0.000393	0.091
135	0.9	0.038	0.000325	0.059
150	0.6	0.025	0.000339	0.04
165	0.4			0.025

Run 29 Whiting and Alcohol

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 238.2 gms.
Total face area 89 sq. cm.
Small cracks appeared on surface from the first.

Time, Hours	Loss gms.	Dry bulb ° C	Dry bulb -wet bulb, °C	△t ° C
0	0	38.2		
0.25				13.9
0.50	7.6			13.7
0.75				13.6
1.00	13.1	41.0		13.6
1.5	18.6		17.9	13.6
2.0	23.4	42.7	17.6	13.2
2.5	27.0		17.7	10.0
3.0	29.4	44.0	17.6	7.7
3.5	30.9			6.0
4.0	32.1	44.5		5.1
4.5	32.9			4.5
5.0	33.5	45.5		4.0
5.5	34.1			3.6
6	34.9	45.5		3.2
7	35.6			1.9
∞	36.5			

Run 29 Whiting and Alcohol

Calculations

Time, Hours	% alcohol, dry basis	Gms./hr. /sq.cm.	H
0			
0.5	12.1	0.1320	0.000615
1.0	9.8	0.1312	0.000584
1.5	7.5	0.1157	0.000509
2.0	5.5	0.0932	0.000465
2.5	4.0	0.0618	0.000532
3.0	3.0	0.0427	0.000507
3.5	2.3	0.0337	0.000441
4.0	1.8	0.0225	0.000367
4.5	1.5	0.0157	0.000306
5.0	1.2	0.0135	0.000217
5.5		0.0157	0.000313
6.0		0.0112	0.000292

Run 30 Whiting and Water

Thickness 3.18 cm.
Dimensions 6.7 x 6.7 cm. Formed in wood frame.
Recording balance and recording pyrometer used
Net dry weight 220.3 gms.
Total face area 89 sq. cm.

Time, Hours	Loss gms.	Dry bulb ° C	Dry bulb -wet bulb, °C	Δ t ° C
0	0	36.3	13.4	9.1
0.5	2.4	38.1	14.2	11.8
1.0	5.0	39.0	14.5	12.1
1.5	7.1	41.0	14.8	12.3
2.0	9.5	41.4	15.0	12.5
3.0	13.9	42.5	15.1	12.7
4.0	18.6	42.7	15.2	12.7
5.0	23.0	43.5	15.2	12.4
6.0	27.0	43.5	15.2	11.6
6.5	29.0	43.5	15.2	10.5
7.0	30.7	43.7	15.2	8.5
7.5	31.8		15.0	6.9
8.0	32.6	43.5	14.8	5.7
8.5	33.4		14.7	4.9
9.0	34.1	43.0	14.3	4.3
10.0	35.0	42	13.8	3.6
11.0	35.9	42	13.4	3.0
12.0	36.6	42	13.3	2.8
13.0	37.2	41.5	13.1	2.4
14.0	37.6	41	13.0	2.2
15.0	38.1	40	12.8	2.0
16.0	38.4	40.5	12.5	1.8
17.0	38.9		12.2	1.1
18.0	39.0	40	12.1	0.9
∞	39.1			

Run 30 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./hr. /sq.cm.	H	Θ'	E'
0	17.7				
0.5	16.6	0.0561	0.000706		
1.0	15.4	0.0516	0.000675		
1.5	14.5	0.0516	0.000661		
2	13.4	0.0516	0.000631		
3	11.4	0.0516	0.000619		
4	9.3	0.0516	0.000616		
5	7.3	0.0505	0.000625		
6	5.5	0.0438	0.000595	0.5	0.86
6.5	4.6	0.0393	0.000630	1.0	.72
7.0	3.8	0.0314	0.000650	1.5	.60
7.5	3.3	0.0247	0.000635	2.0	.52
8	2.9	0.0180	0.000551	2.5	.46
8.5	2.6	0.0168	0.000565	3.0	.40
9	2.3	0.0135	0.000476	3.5	.35
10	1.86	0.0101	0.000435	4.5	.23
11	1.43	0.0090	0.000471	5.5	.18
12	1.13	0.0073	0.000407		
13	0.87	0.0056	0.000309		
14		0.0051			
15		0.0045			
16		0.0045			
17		0.0034			

Run 31 Whiting and Water

Thickness 1.59 cm.
Dimensions 9.5 x 9.5 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 241.0 gms.
Total face area 179 sq. cm.

Time, Hours	Loss gms.	Dry bulb ° C	Dry bulb -wet bulb, °C	Δt ° C
0	0	29.0	8.6	7.6
0.5	2.1		9.3	8.3
1.0	4.2	32	9.7	8.5
1.5	6.6		9.9	8.8
2.0	8.8	34.5	10.2	9.1
3.0	13.3	36.0	10.6	9.6
4.0	18.4	36.5	10.8	9.8
5.0	23.7	36.0	10.6	9.6
6.0	28.6	35.8	10.2	9.0
6.5	31.1		10.0	8.8
7.0	33.2	35.0	10.0	8.4
7.5	35.5		10.0	8.3
8.0	37.7	35.5	10.1	7.8
8.5	39.2		10.1	6.0
9.0	40.5	35.5	10.0	4.5
9.5	41.2		10.0	3.6
10.0	41.8	36.0	10.1	3.2
11.0	43.0	36.3	10.3	2.5
12.0	43.9	36.5	10.2	1.9
13.0	44.4	36.5	10.3	0.8
14.0			10.2	0.4
∞	44.6			

Run 31 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E″
0	18.5			
0.5	17.6	0.0263	0.000456	
1.0	16.7	0.0261	0.000480	
1.5	15.8	0.0261	0.000464	
2	14.8	0.0263	0.000459	
3	13.0	0.0285	0.000456	
4	10.9	0.0285	0.000441	
5	8.7	0.0285	0.000446	
6	6.7	0.0285	0.000456	
6.5	5.6	0.0246	0.000426	1.00
7	4.7	0.0246	0.000441	0.844
7.5	3.8	0.0246	0.000469	0.674
8	2.9	0.0201	0.000434	0.51
8.5	2.2	0.0154	0.000446	0.40
9	1.68	0.0120	0.000486	0.30
9.5	1.39	0.0078	0.000384	0.25
10	1.15	0.0072	0.000389	0.21
11	0.64	0.0061	0.000415	0.12
12		0.0039	0.000376	0.05
13				

Run 32 Whiting and Water

Thickness 2.54 cm.
Dimensions 6.9 x 6.8 cm. Formed in wood frame
Recording balance and pyrometer used
Net dry weight 193.8 gms.
Total wetted face area 94 sq. cm.

Time, Hours	Loss gms.	Dry bulb ° C	Dry bulb -wet bulb, °C.	Δt ° C
0	0	37.2	11.5	10.2
0.5	1.7	38.1	11.8	10.4
1.0	3.8	39.0	12.4	10.8
2	8.0	41.0	12.6	11.1
3	11.6	41.0	13.4	11.5
4	15.7	41.5	13.5	11.8
5	19.5	41.8	13.5	11.7
6	23.8	41.8	13.4	11.5
6.5	25.8	41.5	13.1	11.2
7.0	28.0	41.5	13.0	10.9
7.5	29.9	41.0	12.9	10.3
8.0	31.4	41.0	12.8	9.8
8.5	33.1	40.0	12.8	8.5
9.0	34.3	40.0	12.9	6.4
9.5	35.3	39.8	13.1	5.1
10.0	36.0	39.0	13.4	4.2
11.0	36.9	38.4	13.2	3.2
12.0	37.7	38.0	13.0	2.5
13.0	38.5	38.0	12.9	2.1
∞	40.1			

Run 32 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	θ'	E'
0	20.7	0			
0.5	19.8	0.0383	0.000578		
1	18.7	0.0426	0.000614		
2	16.6	0.0415	0.000572		
3	14.7	0.0415	0.000542		
4	12.6	0.0415	0.000524		
5	10.5	0.0446	0.000571		
6	8.5	0.0446	0.000581		
6.5	7.5	0.0404	0.000542		
7	6.2	0.0404	0.000560		
7.5	5.2	0.0404	0.000591		
8	4.5	0.0356	0.000566	0.4	0.879
8.5	3.5	0.0277	0.000542	0.9	0.707
9	2.9	0.0234	0.000627	1.4	0.586
9.5	2.5	0.0181	0.000583	1.9	0.485
10	2.1	0.0138	0.000529	2.4	0.415
11	1.66	0.0096	0.000443	3.4	0.324
12	1.25	0.0085	0.000510	4.4	0.292
13	0.8			5.4	0.141

Run 33 Whiting and Water

Thickness 0.64 cm.
Dimensions 15.1 x 14.5 cm. Formed in wood frame.
Recording balance and recording pyrometer used
Net dry weight 280.5 gms.
Total wetted face area 437 sq. cm.

Time, Hours	Loss Gms.	Dry bulb ° C	Dry bulb -wet bulb, °C.	Δt ° C
0	0	35.0	12.6	
0.5	6.1	35.2	12.7	11.6
1.0	12.7	35.8	13.0	12.0
1.5	18.9	36.3	13.2	12.3
2.0	26.8	37.2	13.3	12.3
2.25	30.2		13.6	12.5
2.5	34.7	38.0	13.8	12.3
2.75	37.7		14.0	11.7
3.0	40.5	38.6	14.1	9.9
3.25	42.7		14.1	7.8
3.50	44.6	39.0	14.2	5.8
3.75				3.9
4.	45.1	39.0	14.2	2.4
4.5		39.0	14.2	0.7
∞	46.1			

Run 33 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'
0	16.4			
0.5	14.2	0.0311	0.000398	
1.0	11.9	0.0302	0.000374	
1.5	9.7	0.0315	0.000386	
2.0	6.9	0.0327	0.000401	
2.25	5.7	0.0343	0.000415	
2.5	4.0	0.0327	0.000396	1.0
2.75	3.0	0.0274	0.000376	.74
3.0	2.0	0.0225	0.000387	.49
3.25	1.21	0.0183	0.000416	.30
3.5	0.5	0.0126	0.000426	.13
3.75				
4.0	0.34			

Run 34 Whiting and Water

Thickness 3.82 cm.
Dimensions 6.9 x 6.8 cm. Formed in wood frame
Recording balance and recording pyrometer used
Net dry weight 287.4 gms.
Total wetted face area 94 sq. cm.

Time, Hours	Loss gms.	Dry bulb ° C.	Dry bulb -wet bulb, °C.	△t ° C.
0	0	40.0	14.3	
1	3.8	40.0	14.0	
2	10.0	39.1	13.2	
3	15.0	39.1	12.6	
4	19.2	39.1	12.4	
5	22.8	39.1	12.4	10.2
6	26.3	39.1	12.4	9.9
7	29.7	39.1	12.1	9.7
7.5	31.5	39.1	12.1	9.4
8.0	33.2	39.0	12.1	9.1
8.5	34.9	39.0	12.1	9.1
9.0	36.5	39.0	12.0	8.8
9.5	38.4		12.1	8.7
10.0	40.0	38.0	12.1	8.6
10.5	41.6		12.1	8.2
11.0	43.2	38.0	12.1	7.9
11.5	44.8		12.1	7.3
12.0	45.6	38.0	12.1	6.8
12.5	46.7		12.1	6.0
13.0	47.8	38.0	12.1	5.2
13.5	48.6		12.1	4.3
14.0	49.3	38.0	12.0	3.7
14.5	49.9		12.0	3.2
15.0	50.3	38.0	12.0	3.1
16	51.1	38.5	12.4	3.0
17	51.5	40.0	13.1	2.8
18	51.9	41.0	13.8	2.8
20	52.9	42.0	14.2	2.4
22	54.3	42.5	13.5	1.9
24	54.7	42.0	13.4	1.8
30		39.5	12.5	0.8
36		38.0	13.3	0.4
∞	56.7			

Run 34 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'
0	19.8			
1	18.5			
2	16.3	0.0553		
3	14.8	0.0490	0.00069	
4	13.1	0.0490	0.00069	
5	11.8			
6	10.6	0.0340	0.00052	
7	9.4	0.0362	0.00057	
7.5	8.8	0.0351	0.00057	
8	8.2	0.0362	0.00059	
8.5	7.6	0.0362	0.00060	
9	7.1	0.0362	0.00061	
9.5	6.4	0.0340	0.00057	
10	5.9	0.0340	0.00059	1.00
10.5	5.3	0.0330	0.00062	.904
11	4.7	0.0308	0.00060	.808
11.5	4.2	0.0271	0.00060	.712
12	3.9	0.0234	0.00056	.666
12.5	3.5	0.0229	0.00062	.599
13.0	3.2	0.0202	0.00064	.533
13.5	2.8	0.0160	0.00062	.485
14	2.6	0.0138	0.00065	.443
14.5	2.4	0.0106	0.00059	0.406
15	2.2	0.0096	0.00052	0.384
16	1.96	0.0064	0.00038	0.335
17	1.8	0.0043	0.00034	0.311
18	1.68	0.0053	0.00034	0.288
20	1.37	0.0064	0.00046	0.229
22		0.0032	0.00028	0.143

Run 35 Whiting and Water

Thickness 0.64 cm.
Dimensions 15.1 x 14.5 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 284.0 grams
Total wetted face area 437 sq.cm.

Time, Hours	Loss, gms.	Dry bulb, ° C.	Dry bulb -wet bulb ° C.	Δt ° C.
0	0	32.5	10.4	9.1
0.5	5.3	35.6	10.6	9.7
1.0	10.7	36.5	11.3	10.3
1.5	17.2	37.7	11.6	10.7
2.0	22.5	38.2	11.6	10.7
3	33.4	38.8	11.4	10.3
3.25	36.0		11.4	9.8
3.5	38/3	39.2	11.4	9.0
3.75	40.5		11.4	7.8
4.0	41.8	39.2	11.4	6.1
4.25	42.9		11.4	4.6
4.50	43.5	39.2	11.4	3.6
4.75	44.2		11.4	2.4
∞	44.4			

Run 35 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'
0	15.6			
0.5	13.7	0.0256	0.000406	
1.0	11.8	0.0272	0.000400	
1.5	9.5	0.0272	0.000397	
2.0	7.7	0.0254	0.000355	
3.0	3.9	0.0246	0.000373	1.00
3.25	2.95	0.0215	0.000342	.76
3.5	2.2	0.0197	0.000348	.56
3.75	1.39	0.0163	0.000348	.35
4.0	.92	0.0135	0.000323	.24
4.25	.53	0.0073	0.000293	.14
4.5	.31	0.0059	0.000302	.08
4.75		0.0046	0.000367	.02

Run 36 Pressed Pulp and Water

Dry thickness 1.12 cm.
Dimensions 15.0 x 15.0 cm. Edges covered with paraffin.
Recording balance and recording pyrometer used.
Net dry weight 132.0 gms. Soaked under water 30 min.
Total wetted face area 449 sq.cm.
Thermocouples 0.5 cm. from surface.

Time, Hours	Loss, gms.	Dry bulb ° C.	Dry bulb -wet bulb ° C.	Δt ° C.
0		34.5	11.0	
0.5		36.7	12.0	10.2
1.0		38.2	12.4	10.7
2.0	25.2	39.5	13.1	11.8
2.45	31.0			
3.0	41.4	40.0	13.4	12.1
4.0		40.0	13.6	12.3
5.0		40.0	14.0	12.6
5.35	73.2			
6.0	83.2	40.0	13.8	12.3
7.0	98.4	39.5	13.7	12.2
8.0	111.3	39.0	13.5	10.0
9.0	122.0	38.6	13.2	7.8
10.0	128.8	38.2	13.0	6.2
11	134.8	37.3	12.4	5.1
12	139.7	36.7	12.2	4.6
13	144.6	36.3	12.0	4.2
14	147.2	35.8	11.8	3.8
15	150.6	35.4	11.6	3.5
16	153.4	34.4	11.4	3.3
17	156.4	34.0	11.2	3.1
18	159.0	33.5	11.0	2.8
19	161.3	33.0	10.9	2.6
20	163.7	33.8	10.9	2.5
21	165.8	33.5	10.9	2.4
22	168.5	33.5	10.9	2.4
24	172.2	35.8	11.8	2.5
26	175.5	37.2	12.3	2.3
28	178.0	37.5	12.5	1.8
30	180.1	37.5	12.5	1.4
36	182.0	36.3	12.3	0.5
48	183.5	34.4	12.3	0
∞	184.0			

Run 36 Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'
0	13.92			
0.5				
1.0				
2.0	120.1	0.0269	0.000340	
2.45	115.8			
3	107.9	0.0392	0.000480	
4	97.5	0.0411	0.000495	
5				
5.35	84.0			
6	76.4	0.0372	0.000450	
7	63.9	0.0318	0.000387	1.00
8	55.0	0.0262	0.000403	.85
9	47.1	0.0172	0.000336	.73
10	41.8	0.0138	0.000338	.65
11	37.5	0.0109	0.000315	.58
12	33.6	0.0091	0.000294	.52
13	30.0	0.0080	0.000284	.46
14	27.9	0.0078	0.000305	.43
15	25.2	0.0078	0.000297	.39
16	23.2	0.0064	0.000286	.36
17	20.9	0.0060	0.000289	.32
18	19.0	0.0057	0.000301	.29
19	17.1	0.0051	0.000292	.26
20	15.5	0.0049	0.000290	.24
21	13.9	0.0047	0.000290	.22
22	11.7	0.0042	0.000262	.18
24	8.9	0.0039	0.000239	.14
26	6.4	0.0032	0.000214	.10
28	4.6	0.0026	0.000212	.07
30	2.9			
36	1.5			
48				

Run 37 Pressed Pulp and Paper

Dry thickness 0.75 cm.
Dimensions 9.7 x 19.8 cm. Edges covered with paraffin.
Recording balance and recording pyrometer used.
Net dry weight 74.5 gms.
Total wetted face area 382 sq.cm.

Time, Hours	Loss, gms.	Dry bulb ° C.	Dry bulb - wet bulb ° C.	Δt ° C.
0	0	30.6		
1	11.9	32.6	9.9	9.7
2	22.4	32.5	9.5	9.2
3	32.6	32.0	9.1	8.8
4	42.5	31.1	8.8	8.3
5	52.3	31.0	8.6	8.3
6	61.6	31.5	8.6	8.3
7	71.5	30.5	8.2	7.8
8,	81.7	31.1	8.5	8.2
9	91.6	32.0	8.9	8.4
10		31.8	9.0	7.7
11	109.0	32.2	9.1	6.2
12	114.2	32.5	9.3	5.4
13	118.5	31.1	9.3	4.7
14	122.0	30.6	9.1	4.2
15	125.1	30.5	8.9	3.7
16	127.5	30.5	8.8	3.2
17	130.2	30.0	8.5	2.6
18	132.0	29.7	8.4	2.1
19	133.4	29.5	8.3	1.6
20	134.8	29.5	8.2	1.8
21	135.6	29.0	8.0	0.6
22	136.3	29.0	7.8	0.2
23	136.6	29.0	8.0	0.2
24	136.7	29.0	8.0	0
∞	138.0			

Run 37 Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E
0	185.2			
1	169.2	0.0293	0.000460	
2	155.2	0.0272	0.000450	
3	141.6	0.0264	0.000457	
4	128.2	0.0259	0.000476	
5	115.2	0.0251	0.000461	
6	102.3	0.0251	0.000461	
7	96.1	0.0262	0.000511	
8	75.6	0.0262	0.000486	
9	62.1	0.0272	0.000491	1.00
10				.78
11	38.9	0.0157	0.000394	.63
12	32.0	0.0131	0.000388	.52
13	26.2	0.0099	0.000323	.42
14	21.5	0.0092	0.000332	.35
15	17.2	0.0076	0.000312	.28
16	14.1	0.0068	0.000323	.23
17	10.4	0.0051	0.000297	.17
18	8.2	0.0042	0.000304	.13
19	6.3	0.0037	0.00348	.10
20	4.4	0.0029	0.000243	.07
21		0.0020	0.000499	
22		0.0013		
23		0.0005	0.0004	
24				

Run 38 Whiting and Water

Thickness 3.18 cm.
Dimensions 6.6 x 6.6 cm. Formed in wood frame.
Laboratory balance and indicating potentiometer used.
Net dry weight 238.5 gms.
Total wetted face area 87 sq.cm.

Time, Hours	Free water left, gms.	Dry bulb ° C.	Wet bulb ° C.	Δt ° C.
0	42.2			
0.42	40.5	29.3	21.1	7.8
0.92	38.0	29.7	21.3	7.8
1.51	34.9	29.9	21.4	7.8
2.17	32.3	30.1	21.6	7.7
2.5	31.4	30.1	21.6	7.7
3.0	29.5	30.2	21.7	7.7
7.53	12.4	30.4	21.8	6.5
7.83				
8.58	8.9	30.5	21.8	5.2
8.83	8.4			5.0
9.33	7.2	30.4	21.7	3.7
10.33	6.2	30.3	21.8	2.8
11.17	5.8	30.6	21.9	2.3
13.17	4.2	30.4	21.6	1.6
14.33	3.2			
15.5	2.6	30.9	22.0	1.3
16.33	2.1	31.0	22.0	1.2
26		31.4	22.8	0.4

Run 38 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'	θ'
0	17.7				
0.42	17.0	0.051	0.00097		
0.92	15.9	0.055	0.00106		
1.51	14.6	0.054	0.00103		
2.17	13.6	0.044	0.00085		
2.5	13.2	0.041	0.00080		
3.0	12.4	0.046	0.00089		
7.53	5.2	0.044	0,00100	1.00	0
8.58	3.76	0.033	0.00096	0.72	1.05
8.83	3.54	0.028	0.00082	0.68	1.30
9.33	3.04	0.020	0.00079	0.59	1.80
10.33	2.60	0.010	0.00055	0.50	2.80
11.17	2.46			0.47	3.64
13.17	1.77			0.34	5.64
14.33	1.35			0.26	6.80
15.5	1.08			0.21	7.97

Runs 38a, 38b, 38c, and 38d

Moisture Gradients in Whiting

Samples made up similar to, and dried at the same time as Run 38, but without thermocouples. Square chunks 3.3 x 3.3 cm. cut from the center of each and sliced parallel to the drying face. Weighed quickly on a watch glass, dried in an oven, and weighed. Slices number from face (No. 1) in towards center.

	38a	38b	38c	38d
Net wt., gms.	291.5	274.8	291.5	290.1
Net wt. when sampled, gms.	258.2	243.3	252.0	251.1
Time of drying, hours	8.0	10.5	13.5	15.75

Slice No.	1	2	3	4	5
Sample No. 38a					
Water, gms.	0.121	0.129	0.133	0.114	0.177
Dry wt., gms.	4.688	4.157	4.109	3.507	4.842
Thickness, m.m.	2.28	1.90	1.90	1.90	1.90
% water, dry basis	2.58	3.10	3.24	3.25	3.65

Slice No.	6	7	8	9
Sample No. 38a(Cont.)				
Water, gms.	0.125	0.140	0.123	0.120
Dry wt., gms.	3.495	4.137	3.499	3.504
Thickness, m.m.	1.90	1.90	1.90	1.90
% water, dry basis	3.58	3.38	3.51	3.42

Slice No.					
Sample No. 38b					
Water, gms.	0.109	0.161	0.161	0.158	0.190
Dry wt., gms.	3.726	4.607	4.223	4.049	4.808
Thickness, m.m.	1.14	1.90	1.90	1.90	1.90
% water, dry basis	2.92	3.49	3.81	3.95	3.95

Slice No.				
Sample No. 38b(Cont.)				
Water, gms.	0.180	0.164	0.170	0.198
Dry wt., gms.	4.453	3.963	3.598	4.594
Thickness, m.m.	1.90	1.90	1.80	1.90
% water, dry basis	4.04	4.14	4.72	4.31

Slice No.					
Sample No. 39c	0.				
Water, gms.	0.003	0.017	0.033	0.047	0.047
Dry weight, gms.	4.115	2.934	3.187	3.732	3.394
Thickness, m.m.	2.58	1.90	1.90	1.90	1.90
% water, dry basis	0.07	0.58	1.03	1.26	1.38

Slice No.

Slice No.				
Sample No. 39c(Cont)				
Water,gms.	0.051	0.64	0.068	0.053
Dry weight,gms.	3.257	2.669	5.546	3.407
Thickness,m.m.	1.90	1.90	1.90	1.90
% water,dry basis	1.56	2.39	1.22	1.55

Runs 38a, 38b, 38c, and 38d (Continued)

Sample No. 39d						
Water, gms.	0.003	0.004	0.027	0.047	0.051	0.059
Dry weight, gms.	2.602	3.511	3.752	4.047	3.765	3.955
Thickness, m.m.	1.01	1.90	1.90	1.90	1.90	1.90
% water, dry basis	0.11	0.11	0.74	1.16	1.35	1.49
	0.071	0.075	0.072			
	4.209	4.388	4.246			
	1.90	1.90	1.90			
	1.69	1.71	1.70			

Run 39 Whiting and Water

Thickness 3.18 cm.
Dimensions 6.6 x 6.6 cm. Formed in wood frame.
Recording balance and recording pyrometer used.
Net dry weight 225.2 gms.
Total wetted face area 87 sq.cm.

Time, Hours	Free water left, gms.	Dry bulb ° C.	Dry bulb - wet bulb ° C.	Δ t ° C.
0	34.1	38.2		
0.5		38.5		
1	32.4	38.6	15.4	12.0
2	29.6	39.6	16.3	12.8
3	24.7	39.8	16.5	13.2
4	20.1		16.4	13.1
5	15.9		16.3	12.4
5-1/2		40.2	16.3	12.1
6	11.9		16.2	11.3
6-1/2			16.0	9.9
7	8.4		15.8	8.4
7-1/2		39.9	16.2	7.1
8	6.2	40.0	16.3	5.9
8-1/2			16.2	5.3
9	4.9		16.1	4.5
10	4.2		15.6	3.5
11			15.5	3.1
12			15.4	2.6
13			15.3	2.3
32		39.8		

Run 39 Whiting and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'
0				
1	14.1			
2	13.1	0.0529	0.000612	
3	10.9	0.0529	0.000595	
4	8.8	0.0529	0.000612	
5	7.1	0.0482	0.000599	
5.5	6.2	0.0460	0.000589	
6.0	5.3	0.0425	0.000605	1.00
6.5	4.5	0.0402	0.000679	0.85
7.0	3.7	0.0345	0.000766	0.706
7.5	3.22	0.0264	0.000636	0.61
8.0	2.73			0.52
8.5	2.43	0.0161	0.000517	0.46
9	2.16	0.0126	0.000489	0.41
10	1.86		0.000481	0.35
11				
12				
13				

Runs 39a, 39b, 39c, and 39d

Moisture Gradients in Whiting

Samples made up similar to, and dried at the same time as Run 39, but without thermocouples. Square chunk 3.3 x 3.3 cm. cut from the center of each and sliced parallel to drying face. Weighed quickly on watch glasses, dried in an oven, and re-weighed. Slices number from face (No. 1) in towards center,

TABLE I

	39a	39b	39c	39d
Net wet wt., gms.	269.2	253.3	270.3	278.8
Net when sampled,gms.	260.9		239.4	244.1
Time of drying,hours.	1.5	4.0	5.33	7.08

Runs 39a, 39b, 39c and 39d (Cont.)

Table II

Slice No.	1	2	3	4	5	6	7	8	9
Sample No. 39a									
Water,gms.	0.365	0.467	0.494	0.480	0.486	0.405	0.440	0.439	0.425
Dry wt., gms.	3.050	3.845	4.094	3.896	3.978	3.281	3.615	3.573	3.452
Thickness,m.m.	1.27	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
% water,dry basis	12.0	12.1	12.1	12.3	12.2	12.3	12.2	12.3	12.3
Sample No. 39b									
Water,gms.	0.116	0.198	0.202	0.212	0.237	0.212	0.210	0.235	0.233
Dry wt., gms.	2.353	3.754	3.704	3.825	4.132	3.684	3.741	4.035	3.991
Thickness,m.m.	1.01	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
% water,dry basis	4.94	5.44	5.44	5.54	5.74	5.75	5.61	5.82	5.84
Sample No. 39c									
Water,gms.	0.079	0.100	0.131	0.119	0.142	0.137	0.144	0.146	0.147
Dry wt., gms.	4.335	4.330	4.862	4.036	4.540	4.286	4.312	4.229	4.234
Thickness,m.m.	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
% water,dry basis	1.82	2.31	2.69	2.95	3.12	3.20	3.33	3.45	3.47
Sample No. 39d									
Water,gms.	0.002	0.002	0.030	0.051	0.070	0.070	0.069	0.084	0.083
Dry wt., gms.	2.686	3.911	4.078	4.091	4.428	4.013	4.126	4.282	4.130
Thickness.m.m.	1.01	1.90	1.90	1.90	1.90	1.90	1.90	1.90	1.90
% water, dry basis	0.1	0.1	0.74	1.25	1.58	1.74	1.67	1.96	2.0

Run 40 Pressed Pulp and Water

Dry thickness 1.8 cm.
Dimensions 8.9 x 15.0 cm. Edged covered with paraffin.
Recording balance and recording pyrometer used.
Net dry weight 115.0 gms.
Total wetted face area 266 sq.cm.

Time, Hours	Loss, Gms.	Dry Bulb ° C.	Dry Bulb - Wet Bulb ° C.	Δt ° C.
0	0	34.3	14.1	10.9
0.5	5.8		14.1	12.2
1.0	11.9		14.2	12.1
1.5	18.0		14.2	12.1
2.0	24.1		14.1	12.1

Run 40 Pressed Pulp and Water

Calculations

Time, Hours	Gms./Hr. /sq.cm.	H
0		
0.5	0.0459	0.000561
1.0	0.0459	0.000566
1.5	0.0459	0.000566
2.0	0.0459	0.000566

Run 41 Pressed Pulp and Water

Dry thickness 1.8 cm.
Dimensions 8.9 x 15.0 cm. Edges covered with paraffi
Recording balance and recording pyrometer used.
Net dry weight 115.0 gms.
Total wetted face area 266 sq.cm.
Soaked under water 20 minutes.

Time, Hours	Free water left, gms.	Dry Bulb ° C.	Dry Bulb -wet bulb ° C.	Δ t ° C.
1	160.5	33.7	14.6	12.3
2	148.6	33.9	14.6	12.3
3	137.1		13.6	11.3
4	126.9		13.9	11.0
5	115.9		12.9	10.6
6	105.5		13.4	10.7
7	93.9		13.0	10.3
8	83.6		12.9	10.0
9	73.5		12.8	9.7
10	64.8		12.7	8.9
11			12.6	7.0
12		34.8	12.3	5.5
13	47.6		14.1	5.8
14	43.2		14.5	5.4
15	39.1		14.6	5.0
16	35.6		14.7	4.8
17	32.8		14.7	4.7
18	30.1		14.7	4.5
19	27.6		14.6	4.3
20	25.7		14.6	4.3
21	23.6		14.6	4.2
22	21.7		14.8	4.3
23	19.7		15.8	4.9
24	17.9		16.4	5.6
25	15.9	40.0	16.2	5.2
26	14.2		15.8	4.6
27	13.1		15.5	4.3
28	11.9		15.3	3.8
29	10.3		15.2	3.5
30	9.1		15.0	3.3
31	7.6		14.6	3.0
32	6.7		14.3	2.7
33	5.6		14.1	2.4
34	4.5		14.0	2.2
35	3.9		13.9	2.0
36	3.2	39.0	13.8	1.8
37	2.6		13.7	1.6

Run 41 Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H
0			
1	140	0.0410	0.000496
2	129	0.0410	0.000510
3	119	0.0410	0.000555
4	110	0.0406	0.000557
5	101	0.0406	0.000570
6			
7	82	0.0410	0.000598
8	73	0.0410	0.000610
9	64	0.0380	0.000591
10	56.3	0.0297	0.000506
11		0.0244	0.000534
12			
13	41.5	0.0175	0.000449
14	37.6	0.0162	0.000446
15	34.0	0.0143	0.000431
16	31.0	0.0117	0.000369
17	28.5	0.0101	0.000328
18	26.2	0.0101	0.000341
19	24.0	0.0083	0.000286
20	22.4	0.0075	0.000259
21	20.5	0.0075	0.000266
22	18.9	0.0071	0.000242
23	17.1	0.0071	0.000209
24	15.6	0.0071	0.000190
25	13.8	0.0068	0.000198
26	12.3	0.0053	0.000175
27	11.4	0.0041	0.000148
28	10.3	0.0053	0.000212
29		0.0053	0.000229
30	7.9	0.0049	0.000228
31	6.6	0.0045	0.000225
32	5.8	0.0037	0.000212
33	4.9	0.0041	0.000260
34	3.9	0.0034	0.000232
35	3.4	0.0041	0.00031
36	2.8	0.0026	0.000225
37	2.3	0.0023	0.000214

Run 42 Sheet Pulp and Water

Sulphite pulp lap as received from the Eastern Mfg. Co. Dried in balance case without removal from hook of chemical balance. Wetted with water at air temperature.
Dimensions 5.09 cm. x 1.27 cm. x 0.094 cm.
Total face area 129 sq.cm.
Equilibrium weight plus tare before wetting 4.023
Tare weight 0.776

Time, Minutes, Seconds	Total wt.gms.	Dry Bulb ° C.	Wet Bulb ° C.
0	8.580		
1:35	8:560		
3:05	8.540	27.6	25.8
4:50	8.520	28.0	26.0
6:40	8.500		
12:15	8.430		
14:45	8.400		
18:50	8.350		
27:25	8.250	28.1	25.9
31:15	8.200	28.1	25.5
39:20	8.100		
43:30	8.050		
47:25	8.000		
50:45	7.950		
54:30	7.900	28.0	25.0
58:20	7.850		
61:40	7.800	27.8	24.7
64:45	7.750		
67:50	7.700	27.5	24.5
71:10	7.650		
74:30	7.600		
77:40	7.550		
84:10	7.450	27.3	24.2
87:20	7.400		
93:55	7.300		
129:30	6.770 →	26.8 →	23.8
130:50	6.750		
137:35	6.650		
141:10	6.600		
147:45	6.500		
161:25	6.300		
168:15	6.200		
182:00	6.000		
188:50	5.900	27.0	23.6
195:30	5.800	27.0	23.6
202:25	5.700		
208:35	5.600		

Run 42 Sheet Pulp and Water (Continued)

Time, Minutes, Seconds	Total wt., gms.	Dry Bulb ° C.	Wet Bulb ° C.
215:30	5.500	27.3	23.6
222:15	5.400		
229:30	5.300	27.3	23.7
233:15	5.250		
236:45	5.200		
240:20	5.150		
244:05	5.100		
251:45	5.000	27.4	23.9
255:35	4.950		
259:45	4.900		
263:45	4.850		
267:50	4.800		
272:15	4.750		
276:40	4.700	27.5	24.0
281:20	4.650		
286:15	4.600		
291:20	4.550		
296:30	4.500	27.6	24.1
302:00	4.450		
308:05	4.400		
314:30	4.350		
318:45	4.320		
323:10	4.290		
328:00	4.260		
333:25	4.230		
339:20	4.200	27.9	24.3
343:45	4.180		
348:50	4.160	28.0	24.3
354:35	4.140		
362:00	4.120		
371:20	4.100	28.1	24.3
377:30	4.090		
385:30	4.080	28.0	24.4
397:25	4.070		
414:05	4.060	28.0	24.4
442:45	4.050		
2000	3.964	25.3	19.4

Run 42 Sulphite Pulp and Water

Calculations

Time Minutes, Seconds	% water, dry basis	Gms./Hr. /sq.cm.	R' = gms./hr./sq.cm. /°C.wet bulb depression
0	140.2		
1:35		0.0061	0.00340
3:05		0.0058	0.00306
4:50	138.2	0.0052	0.00260
6:40	137.9	0.0054	0.00270
12:15	135.9	0.0057	0.00286
14:45	134.9	0.0057	0.00271
18:50	133.2	0.0056	0.00262
27:25	130.1	0.0057	0.00259
31:15	128.7	0.0059	0.00226
39:20	125.6	0.0057	0.00219
43:30	124.0	0.0057	0.00211
47:25	122.2	0.0064	0.00228
50:45	120.9	0.0066	0,00228
54:30	119.2	0.0061	0.00203
58:20	117.9	0.0065	0.00213
61:40	116.2	0.0072	0.00232
64:45	114.8	0.0075	0.00246
67:50	113.1	0.0072	0.00239
71:10	111.7	0.0070	0.00231
74;30	110.1	0.0072	0.00236
77:40	108.5	0.0072	0.00234
84:10	105.7		
87:20	103.9		
93:55	100.8		
129:30	84.6		
130:50	84.0	0.0069	0.00225
137:35	80.9	0.0067	0.00217
141:10	79.1	0.0068	0.00216
147:45	76.1	0.0069	0.00216
161:25	70.0	0.0068	0.00213
168:15	66.9	0.0068	0.00206
182:00	60.8	0.0069	0.00209
188:50	57.7	0.0069	0.00203
195:30	54.6	0.0069	0.00203
202:25	51.6	0.0071	0.00203
208:35	48.5	0.0071	0.00197

Run 42 Calculations (Cont'd.)

Time Minutes, Seconds	% water, dry basis	Gms./Hr. /sq.cm.	R' = gms./hr./sq.cm. /°C.wet bulb depression
215:30	45.5	0.0068	0.00184
222:15	42.3	0.0067	0.00184
229:30	39.3	0.0063	0.00175
233:15	37.7	0.0064	0.00178
236:45	36.2	0.0066	0.00183
240:20	34.6	0.0064	0.00183
244:05	33.1	0.0061	0.00174
251:45	30.1	0.0061	0.00174
255:35	28.5	0.0058	0.00166
259:45	27.0	0.0057	0.00163
263:45	25.5	0.0057	0.00163
267:50	24.0	0.0055	0.00157
272:15	22.4	0.0053	0.00151
276:40	20.9	0.0051	0.00146
281:20	19.3	0.0049	0.00140
286:15	17.8	0.0047	0.00134
291:20	16.2	0.0045	0.00129
296:30	14.7	0.0044	0.00126
302:00	13.2	0.0040	0.00114
308:05	11.6	0.0037	0.00106
314:30	10.1	0.0035	0.00100
318:45	9.1	0.0032	0.00089
323:10	8.2	0.0030	0.00084
328:00	7.3	0.0027	0.00075
333:25	6.4	0.0024	0.00067
339:20	5.45	0.0022	0.00060
343:45	4.73	0.0020	0.00054
348:50	4.21	0.0017	0.00046
354:35	3.6	0.0014	0.00038
362:00	2.98	0.0011	0.00029
371:20	2.37	0.0009	0.00023
377:30	2.06	0.0007	0.00019
385:30	1.75		
397:25	1.45	0.0003	
414:05	1.14	0.0002	
442:45	0.83		

Run 43 Sheet Pulp and Water

Two thickness sulphite pulp lap basted together with cotton thread. Each piece 5.09 x 12.7 x 0.094 cm. and similar to No. 42.
Total face area 129 sq. cm.
Equilibrium weight plus tare before wetting 7.021 gms.
Tare 0.764 gms.

Time Minutes, seconds	Total Weight gms.	Dry Bulb °C	Wet Bulb °C
0.	16.050	26.2	21.1
7.50	15.900		
13.20	15.800		
19.25	15.700		
24.20	15.600	25.5	20.6
30.00	15.500	25.4	20.4
35.20	15.400	25.3	20.2
40.50	15.300		
46.15	15.200		
51.55	15.100		
57.15	15.000		
62.35	14.900		
67.50	14.800	25.3	20.1
73.20	14.700		
78.45	14.600		
84.10	14.500		
122.35	13.800	25.7	19.9
128.15	13.700		
133.50	13.600		
139.35	13.500		
156.40	13.200		
162.20	13.100		
167.55	13.000	25.5	19.5
173.20	12.900		
178.55	12.800		
184.45	12.700		
190.25	12.600		
196.20	12.500		
202.05	12.400		
227.05	12.000		

Run 43 Continued

Time Minutes, seconds	Total Weight gms.	Dry Bulb °C	Wet Bulb °C
232.05	11.900		
238.20	11.800		
244.40	11.700		
257.20	11.500		
263.40	11.400	24.7	19.5
290.15	11.000		
296.45	10.900		
303.20	10.800		
317.00	10.600	24.7	19.6
334.20	10.350		
344.35	10.200		
351.20	10.100		
358.25	10.000		
368.55	9.850		
372.30	9.800		
382.55	9.650		
386.20	9.600		
393.30	9.500	24.4	19.0
400.25	9.400		
407.40	9.300		
415.35	9.200		
423.40	9.100		
432.15	9.000	25.0	19.4
440.50	8.890		
447.50	8.880		
452.00	8.750		
456.10	8.700		
1700	6.957	24.8	15.9

Run 43 Sulphite Pulp and Water

Calculations

Time Minutes, Seconds	% water, dry basis	Gms./Hr. /sq.cm.	R' = gms./hr./sq.cm. /°C.wet bulb depression
0	144		
7:50	141.7	0.0088	0.00176
13:20	140	0.0081	0.00162
19:25	139	0.0085	0.00170
24:20	137	0.0088	0.00176
30:00	135	0.0085	0.00170
35:20	134	0.0086	0.00169
40:50	132	0.0085	0.00167
46:15	130.6	0.0084	0.00165
51:55	129	0.0085	0.00167
57:15	127.3	0.0087	0.00167
62:35	125.8	0.0088	0.00169
67:50	124	0.0087	0.00168
73:20	122.7	0.0085	0.00161
78:45	121	0.0085	0.00158
84:10	119.4	0.0085	0.00152
122:35	108.2	0.0083	0.00146
128:15	106.8	0.0083	0.00143
133:50	105.0	0.0082	0.00141
139:35	103.3	0.0081	0.00140
156:40	98.7	0.0082	0.00139
162:20	97.1	0.0082	0.00136
167:55	95.5	0.0084	0.00140
173:20	94.0	0.0084	0.00140
178:55	92.3	0.0081	0.00137
184:45	90.8	0.0081	0.00140
190:25	89.1	0.0081	0.00140
196:20	87.5	0.0080	0.00140
202:05	86	0.0076	0.00136
227:05	79.6	0.0084	0.00154
232:05	78	0.0084	0.00155
238:20	76.4	0.0074	0.00140
244:40	74.8	0.0073	0.00137
257:20	71.6	0.0074	0.00139
263:40	70.0	0.0072	0.00139

Run 43 Calculations (Cont'd.)

Time Minutes, Seconds	% water, dry basis	Gms./Hr. /sq.cm.	R' = gms./hr./sq.cm. /°C.wet bulb depression
290:15	63.5	0.0071	0.00137
296:45	61.9	0.0071	0.00137
303:20	60.4	0.0069	0.00135
317:00	57.1	0.0067	0.00131
334:20	53.1	0.0067	0.00131
344:35	50.8	0.0068	0.00133
351:20	48.1	0.0067	0.00129
358:25	47.5	0.0066	0.00127
368:55	45.2	0.0066	0.00125
372:30	44.4	0.0066	0.00125
382:55	42.0	0.0067	0.00126
386:20	41.1	0.0067	0.00124
393:30	39.6	0.0067	0.00124
400:25	38.0	0.0065	0.00120
407:40	36.4	0.0061	0.00111
415:35	34.8	0.0057	0.00104
423:40	33.2	0.0056	0.00100
432:15	31.6	0.0057	0.00102
440:50	29.8	0.0059	0.00105
447:50	28.4	0.0057	0.00103
452:00		0.0056	0.00100
456:10			

Run 44 Sheet Pulp and Water

Single thickness sulphite pulp lap
as in Run 42.
Dimensions 5.09 x 12.7 x 0.094 cm.
Total face area 129 sq. cm.
Equilibrium weight plus tare before
wetting 3.907
Tare 0.773

Time Minutes, seconds	Total Weight gms.	Dry Bulb °C	Wet Bulb °C
0	8.050	26.2	21.1
5.10	7.959		
7.50	7.900		
17.10	7.800	25.5	20.6
23.45	7.600	25.4	20.4
29.05	7.500		
34.20	7.400		
39.35	7.300		
45.00	7.200		
50.20	7.100		
55.40	7.000		
60.50	6.900		
66.15	6.800		
71.40	6.700	25.3	20.1
77.05	6.600		
82.30	6.500		
126.15	5.700	25.7	19.9
132.00	5.600		
137.35	5.500		
143.10	5.400		
160.10	5.100		
166.05	5.000		
172.05	4.900	25.5	19.5
178.20	4.800		
184.40	4.700		
191.30	4.600		
198.50	4.500		
206.50	4.400		
232.10	4.150		
239.35	4.100		
248.40	4.050		

Run 44 Continued

Time Minutes, seconds	Total Weight gms.	Dry Bulb °C	Wet Bulb °C
255.45	4.02o		
262.05	4.000		
272.10	3.980	24.7	19.5
290.30	3.960		
313.30	3.950	24.7	19.6
341.30	3.945		
361.30	3.940	24.4	19.0
436.		25.0	19.4
460.	3.933	25.1	19.5
1700	3.895	24.8	15.9

Run 44. Sulphite Pulp and Water.

Calculations

Time, Minutes, Seconds	% Water Dry Basis	Gms./hr. /sq. cm.	R^1 = gms./hr./sq. cm. /1°C. wet bulb depression.
0	132.0		
5:10	129	0.0088	0.00176
7:50	127	0.0087	0.00174
17:10	124	0.0087	0.00174
23:45	117.8	0.0087	0.00174
29:05	114.6	0.0087	0.00174
34:20	111.3	0.0088	0.00176
39:35	108.3	0.0087	0.00171
45:00	105	0.0086	0.00169
50:20	102	0.0087	0.00171
55:40	99	0.0088	0.00173
60:50	95.6	0.0088	0.00170
66:15	92.4	0.0085	0.00164
71:40	89.2	0.0085	0.00164
77:05	85.9	0.0085	0.00161
82:30	82.6	0.0085	0.00158
126:15	57.3	0.0083	0.00148
132:00	54.1	0.0082	0.00141
137:35	50.9	0.0084	0.00145
143:10	47.6	0.0083	0.00143
160:10	38.1	0.0082	0.00139
166:05	34.9	0.0078	0.00130
172:05	31.7	0.0076	0.00127
178:20	28.5	0.0074	0.00123
184:40	25.3	0.0071	0.00121
191:30	22.1	0.0066	0.00114
198:50	18.9	0.0061	0.00107
206:50	15.7	0.0052	0.00091
232:10	7.76	0.0039	0.00070
239:35	6.16	0.0028	0.00051
248:40	4.56	0.0023	0.00043
255:45	3.61	0.0017	0.00032
262:05	2.97	0.0012	0.00023
272:10	2.33	0.0007	0.00013
290:30	1.69	0.0004	0.00008
313:30	1.37		

Run 45 Sheet Pulp and Water

Dried in still air in ventilated chemical balance. Two thicknesses sulphite pulp lap basted together with cotton thread.
Each piece 5.09 x 12.7 x 0.094 cm.
Same sample as #43. Edges dipped in Collodion. Equilibrium weight plus tare before wetting 7.007 gms.
Tare 0.764 gms.
Total face area 129 sq. cm.

Time Minutes, seconds	Total Weight gms.	Dry bulb °C	Wet bulb °C
0	15.620		
6.55	15.470		
14.55	15.300		
24.25	15.100	23.8	16.8
34.50	14.900		
43.20	14.700		
52.50	14.500		
62.10	14.300		
71.30	14.100	23.5	16.4
85.30	13.800		
94.55	13.600		
141.50	12.600	24.1	16.7
155.50	12.300		
170.00	12.000		
183.50	11.700		
193.25	11.500	23.7	16.5
240.10	10.560		
285.55	9.650		
292.35	9.530		
299.50	9.400		
307.10	9.270		
313.15	9.170		
320.10	9.050	22.8	16.3
328.00	8.920		
334.15	8.820		
340.20	8.720	22.5	15.8
351.30	8.550		
359.45	8.430		
369.10	8.300		
377.05	8.200	22.4	16.1

Run 45 Continued

Time Minutes, seconds	Total Weight gms.	Dry bulb °C	Wet bulb °C
388.45	8.06o		
394.00	8.000		
403.50	7.900		
414.50	7.800	22.1	16.0
427.40	7.700		
44o.00	7.600		
455.30	7.500		
374.40	7.400	22.0	16.0
500.00	7.300		
516.55	7.250	22.9	16.6
540.10	7.200		
552.10	7.180	22.9	16.5
568.10	7.160		

Run 45. Sulphite Pulp and Water.

Calculations

Time, Minutes, Seconds	% Water dry basis	Gms./hr. /sq. cm.	R^1 = gms./hr./sq. cm. /°C. wet bulb depression
0	138.0		
6:55	135.8	0.0100	0.00143
14:55	132.8	0.0099	0.00141
24:25	129.4	0.0098	0.00140
34:50	126.3	0.0098	0.00140
43:20	123.1	0.0099	0.00141
52:50	120.0	0.0099	0.00141
62:10	116.7	0.0099	0.00142
71:30	113.5	0.0099	0.00142
85:30	108.8	0.0099	0.00140
94:55	105.4	0.0099	0.00137
141:50	95.0	0.0099	0.00135
155:50	84.8	0.0099	0.00134
170:00	80.0	0.0100	0.00137
183:50	75.1	0.0099	0.00138
193:25	72.0	0.0096	0.00133
240:10	57.0	0.0093	0.00130
285:55	42.5	0.0089	0.00126
292:35	40.5	0.0085	0.00123
299:50	38.3	0.0084	0.00124
307:10	36.3	0.0079	0.00119
313:15	34.6	0.0078	0.00118
320:10	32.7	0.0078	0.00120
328:00	30.6	0.0076	0.00116
334:15	29	0.0075	0.00112
340:20	27.4	0.0073	0.00116
351:30	24.7	0.0069	0.00112
359:45	22.8	0.0066	0.00101
369:10	20.7	0.0061	0.00097
377:05	19.1	0.0057	0.00091
388:45	16.9	0.0054	0.00087
394:00	15.9	0.0049	0.00080
403:50	14.3	0.0045	0.00073
414:50	12.7	0.0041	0.00066
427:50	11.1	0.0037	0.00061
440:00	9.5	0.0033	0.00054
455:30	7.9	0.0027	0.00045
474:40	6.3	0.0021	0.00035
500:00	4.7	0.0016	0.00026
516:55	3.9	0.0012	0.00019
540:10	3.1	0.0009	0.00014
552:10	2.8	0.0007	0.00010
568:10	2.5		

Run 46 Sheet Pulp and Water

Single thickness sulphite pulp lap as in Run 42
Edges coated with collodion.
Dimensions 5.09 x 12.7 x 0.094 cm.
Total face area 129 sq.cm.
Equilibrium weight plus tare before wetting 3.912
Tare 0.777

Time, Minutes, seconds	Total wt. gms.	Dry bulb ° C.	Wet bulb ° C.
0	7.950		
7:20	7.800		
17:10	7.600	23.8	16.8
27:15	7.400		
36:55	7.200		
45:40	7.000		
55:20	6.800		
65:15	6.600	23.5	16.4
75:05	6.400		
84:45	6.200		
94:25	6.000		
146:00	5.000		
150:40	4.900		
156:05	4.800		
161:40	4.700		
170:35	4.550		
173:45	4.500		
180:30	4.400		
188:00	4.300	23.7	16.5
196:55	4.200		
238:00	3.970	23.5	16.6
282:30	3.938		
310:30	3.933	22.8	16.3
370:30	3.933	22.5	15.8
438	3.939	22.0	16.0
523	3.942	22.9	16.6

Run 46. Sulphite Pulp and Water.

Calculations

Time, Minutes, Seconds	% Water, dry basis	gms/hr. /sq. cm.	R^1 = gms./hr./sq. cm. /1° C wet bulb depression
0	129		
7:20	124	0.0095	0.00135
17:10	117.7	0.0094	0.00134
27:15	111.3	0.0095	0.00135
36:55	105	0.0101	0.00145
45:40	98.5	0.0101	0.00145
55:20	92	0.0095	0.00136
65:15	85.8	0.0095	0.00135
75:05	79.4	0.0095	0.00136
84:45	73	0.0096	0.00138
94:25	66.6	0.0093	0.00133
146:00	36.7	0.0095	0.00135
150:40	31.5	0.0093	0.00131
156:05	28.3	0.0085	0.00117
161:40	25.1	0.0081	0.00112
170:35	20.3	0.0076	0.00105
173:45	18.8	0.0071	0.00098
180:30	15.6	0.0065	0.00090
188:00	12.4	0.0057	0.00079
196:55	6.00	0.0040	0.00055
238:00	1.85	0.0030	0.00021

Run 47 Nitrocellulose

Containing alcohol and ether as received from
Picatinny Arsenal. Material pressed into brass
rings 3.5 cm. dia.
Dried in tunnel drier. Removed from weighings
on chemical balance.

Time, Hours	47(a)			47(b)			Dry Bulb ° C.
	Total wt. gms.	Dia. m.m.	Thickness m.m.	Total wt. gms.	Dia. m.m.	Thick. m.m.	
0	17.300	3.5	9.5	43.080	3.5	2.5	
1.17	16.230			41.380			36
2.67	15.77	3.3		40.16	3.3		37
26	14.38	3.1	7.1	36.48	3.12	2.3	37
50	14.08	2.9	7.1	34.87	2.92	2.2	
76	13.95			34.04			
127	13.81			33.51		2.16	
146	13.78	2.84	7.1	33.43	2.84		
169	13.76			33.36			34
217	13.72			33.26			
313	13.665			33.09			37
364	13.655			33.07			37.5
412	13.645			33.04			32
504	13.61			32.95			32
647	13.57			32.87			
745	13.56			32.83			33
817	13.56			32.81			34
1033	13.54	2.8		32.75	2.8		
1920	13.503			32.662			
Tave	7.104			15.986			

Runs 48, 49, 50, 51. White (Poplar) Wood

Dried in tunnel drier using laboratory balance
Edges of samples covered with M.J.B. Cement
Samples soaked under water over night.

Sample	Dimensions	Net bone dry weight
48	15.2x16.2x0.41 cm.	31.9 gms.
49	15.6x20.3x1.27 cm.	182.6
50	15.9x30.5x0.69 cm.	109.8
51	15.2x15.2x1.91 cm.	211.0

Time,	Loss in weight, gms.				Dry Bulb	Wet Bulb
Minutes	48	49	50	51	° C.	° C.
0						
12	4.4					
16		6.1	9.8			
19				7.0		
23				6.4		
24	8.4					
25		10.0		6.4		
27			16.2		30.3	18.7
32	10.9					
33		12.0				
34				7.5		
35			20.2		29.4	18.3
40		12.5				
41	13.1					
42				7.7		
45			24.2		29.1	18.1
55	16.6	14.5				
56				8.9		
58			29.8		28.8	17.9
69		15.7				
70	18.8					
71				10.1		
72			34.6			
96		16.9				
98				11.9		
100	22.7					
102			42.0			

Runs 48, 49, 50, 51 (Continued)

Time, Minutes	Loss in weight, gms. 48	49	50	51	Dry Bulb ° C.	Wet Bulb ° C.
132		19.0				
134				13.4		
136	23.6				28.9	17.8
138			47.6			
240		22.8				
242				16.4		
244	24.9					
246			55.9			
300		23.8				
302				17.6	28.9	17.9
304	25.3					
306			57.8			
480		26.3				
482				19.5		19.9
484	25.5					
486			61.3			
1430		34.2				
1432				24.3	32.0	20.4
1434	25.8					
1436			65.3			
∞	26.5	41.4	67.6	33.4		
Bone dry	27.5	46.8	71.0	39.0		

Run 52. White Wood and Water.

Dry thickness 1.27 cm.
Dimensions 15.5 x 20.3 cm. Edges lacquered. Recording balance used.
Net Dry weight 182.6 gms.
Equilibrium weight 192.9 gms.
Total wetted face area 629 sq. cm.
Sample soaked 3 days.

Time, Hours	Free Water Left, Gms.	Dry Bulb °C.	Wet Bulb °C.
0	62.2	34.5	18.3
0.5	50.4		
1.0	42.1	36.8	19.3
1.5			
2.0	32.9		
3.0	27.0		
4.0	23.6		
5.0	20.7		
6.0	18.4		
7.0	16.6		
8.0	14.8		
9.0	13.2		
10.0	11.7		
21.0		32.3	16.3
	0	34.2	15.6

Run 52. White Wood and Water.

Calculations

Time, Hours	% Water, dry basis	gms./hr. /sq. cm.	E
0	39.7		1.00
0.5	33.2	0.0392	0.81
1.0	28.7	0.0221	0.676
2.0	23.7	0.0116	0.529
3	20.4	0.0067	0.434
4	18.6	0.0050	0.38
5	17.0	0.0040	0.333
6	15.7	0.0032	0.296
7	14.7	0.0029	0.267
8	13.7	0.0027	0.238
9	12.9	0.0025	0.212
10	12.0	0.0024	0.188
21	5.6		

Run 53. White Wood and Water.

Dry thickness 0.41 cm.
Dimensions 15.2 x 16.2 cm. Edges lacquered. Recording balance and recording pyrometer used.
Net dry weight 31.9 gms.
Equilibrium weight 32.9 gms.
Air temperature 31 - 36°C.
Total wetted face area 493 sq. cm.
Sample soaked under water 5 days.

Time, Hours	Free Water Left, gms.	Dry Bulb-Wet Bulb, °C.
0	45.9	16.9
0.12		
0.25	40.6	
0.5	36.0	
1.0	26.1	16.9
1.5	17.6	
2.0	9.9	16.4
2.5	5.0	
3.0	3.1	15.3
3.5	2.1	
4.0		14.5

Run 53 White Wood and Water

Calculations

Time, Hours	% water dry basis	gms./hr. /sq.cm.	E
0	147		1.00
0.12		0.043	
0.25	130.7		0.885
0.5	116.0	0.0385	0.784
1.0	85.0	0.0385	0.569
1.5	58.2	0.0320	0.383
2.0	34.2	0.0250	0.216
2.5	18.8	0.0111	0.109
3.0	12.9	0.0055	0.067
3.5	9.7	0.0026	0.046
4.0			
∞	3.1		

Run 54. White Wood and Water.

Dry thickness 0.69 cm.
Dimensions 30.5 x 15.9 cm. Edges lacquered. Recording balance and recording pyrometer used.
Net dry weight 109.8 gms.
Equilibrium weight 114.1 gms.
Air temperature 31-36°C.
Total wetted face area 970 sq. cm.
Sample soaked under water 6 days.

Time, Hours	Free Water Left, gms.	Dry Bulb -Wet Bulb, °C.
0	127.0	18.1
0.37	119.4	17.3
0.62	107.7	16.8
1.12	93.5	16.2
2.0	68.5	15.5
3.0	46.0	14.9
4.0	30.2	14.6
5.0	18.9	17.3
6.0	12.3	17.9
7.0	8.5	

Run 54 White Wood and Water

Calculations

Time, Hours	% water dry basis	Gms./hr. /sq.cm.	E
0	119.8		1.00
0.37	112.8	0.0378	0.94
0.62	102.0	0.0342	0.848
1.12	88.1	0.0303	0.736
2	66.4	0.0254	0.540
3	45.9	0.0220	0.362
4	31.4	0.0136	0.238
5	21.2	0.0089	0.149
6	15.1	0.0053	0.097
7	11.7	0.0031	0.067
∞	3.9		

Run 55. White Wood and Water.

Dry thickness 1.8 cm.
Dimensions 15.2 x 15.2 cm. Edges lacquered. Recording balance and recording pyrometer used.
Net dry weight 211.0 gms.
Equilibrium weight 215.3 gms.
Air temperature 31-35°C.
Total wetted face area 463 sq. cm.
Sample soaked under water 10 days--would float in water.

Time, Hours	Free Water Left, Gms.	Dry Bulb -Wet Bulb, °C.
0	100.0	17.3
0.5	90.1	
1.0	81.0	17.0
1.5	74.7	
2.0	69.5	17.1
2.5		
3.0	62.6	17.2
3.5	58.9	
4.0	55.9	16.7
5.0	50.8	16.7
6.0	46.3	16.6
7.0	42.3	16.9
8.0	39.4	16.7
9.0	36.9	16.6
10.0	34.5	16.3

Run 55 White Wood and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. /sq.cm.	E
0	49.4		1.00
0.5	44.7	0.0406	0.901
1.0	40.4	0.0325	0.910
1.5	37.4	0.0244	0.747
2.0	35.0		0.695
3.0	31.5	0.0166	0.626
3.5	29.9	0.0140	0.589
4.0	28.5		0.559
5	26.1	0.0110	0.508
6	24.0	0.0086	0.463
7	22.0	0.0073	0.423
8	20.6	0.0060	0.394
9	19.5	0.0052	0.369
10	18.3	0.0045	0.345
∞	2.0		

Run 56.

Moisture Gradients in Pulp.

Small blocks of pressed pulp coated with M. J. B. cement on edges and one face. Soaked under water one hour and put in drier with uncoated face up. Air velocity 0.8-1.0 m./sec. After different drying periods each block was removed and cut in slices parallel to the drying face. The wet slices were weighed quickly on watch glasses, dried in an oven, and weighed again. Slices number from face in towards center, i.e. the outer side of slice 1 of each block was in contact with the drying air.

Dimensions:

56 a	3.5 x 3.3 x 0.8 cm.
56 b	3.8 x 3.8 x 1.35 cm.
56 c	3.4 x 3.4 x 1.37 cm.

Table I.

Time Hours	Weight, gms. a	b	c	Dry Bulb °C	Wet Bulb °C
Dry	7.56	13.07			
0	15.09	27.51	21.06		
1.0	13.94	26.05	19.88	33.0	15.3
2.1	12.80	24.49	18.50	33.6	
2.6	12.19				
4.4		21.44	16.00	31.0	14.0
6.0		19.60	15.07		
6.5			14.79		

Slices cut and weighed quickly after last weighing recorded above.

Run 56. (cont.)

Table II:

Slice No.	1	2	3	4	5	6	7
Sample 56 a.							
Water, gms.	0.442	0.565	0.830	0.832	0.737		
Dry weight, gms.	0.669	0.881	1.322	1.346	1.233		
Thickness, m.m.	0.81	1.07	1.60	1.63	1.50		
% Water, dry basis	64.6	64.0	62.8	61.8	60.2		
Sample 56 b.							
Water, gms.	0.335	0.802	0.698	0.634	0.694	0.634	0.514
Dry weight, gms.	0.922	1.563	1.337	1.231	1.321	1.200	0.968
Thickness, m.m.	1.27	2.13	1.83	1.67	1.80	1.65	1.32
% Water, dry basis	36.3	51.2	52.1	51.4	52.5	52.8	53.0
Sample 56 c.							
Water, gms.	0.222	0.620	0.612	0.702	0.612	0.519	0.541
Dry weight, gms.	1.093	1.436	1.323	1.482	1.294	1.114	1.172
Thickness, m.m.	1.50	1.96	1.81	2.04	1.78	1.53	1.58
% Water, dry basis	20.3	43.1	46.2	47.4	47.3	46.5	46.1

Run 57 Moisture Gradients in Pulp

Procedure similar to that of Run 56, but soaked under water 2.5 hours. Drying of 57d and 57e started together.

Sample 57d. 3.5 x 3.6 x 1.34 cm.
Dry weight 11.50 gms. Weight at start of drying 24.10 gms. Sliced after 18 hours drying - weight 14.06 gms.

Sample 57e. 3.8 x 3.8 x 1.37 cm.
Dry weight 13.46 gms. Weight at start of drying 29.20 gms. Sliced after 20 hours drying - weight 15.77 gms.

Slice No.	1	2	3	4	5	6	7
Sample 57d							
Water, gms.	0.042	0.105	0.205	0.324		0.488	0.392
Dry wt., gms.	1.139	1.341	1.386	1.424		1.499	1.277
Thick., m.m.	1.32	1.58	1.60	1.65		1.75	1.50
% water, dry basis	3.7	7.8	14.8	22.7		32.6	30.7
Sample 57e							
Water, gms.	0.002	0.040	0.150	0.306	0.374	0.382	0.288
Dry wt., gms.	0.860	1.359	1.635	1.630	1.338	1.317	1.248
Thick., m.m.	1.07	1.70	2.03	2.03	1.68	1.65	1.53
% water, dry basis	0.2	2.9	9.2	18.8	27.9	29.0	23.1

Run 58 Brick, Clay and Water

Wet thickness 3.18 cm.
Dimensions 6.9 x 6.9 cm. Formed in wood frame.
Recording balance and indicating potentiometer used.
Net dry weight 224.3 gms.
Total wetted face area 89.0 sq.cm.

Time, Hours	Free water left, gms.	Wet Bulb ° C.	Dry Bulb ° C.	Δt ° C.
0	61.5		39.0	13.8
0.25			37.0	14.7
1.00	56.9	17.4	35.8	13.1
1.25			35.4	12.8
1.50			35.0	13.1
1.83		17.1	34.8	13.0
2.00	51.6			
2.17		16.0	33.8	12.4
2.5				13.0
2.67				13.4
3.0	46.8			
3.25			35.2	13.4
3.92		16.2	33.8	13.1
4.5			35.0	13.7
4.92		17.5	36.0	14.4
5.0	39.0			
5.75		17.1	35.0	13.3
6.0	34.7			
6.42		17.7	36.3	14.4
6.84				14.4
7.0				
8.0	26.2			
9.0	21.9			
10.0	18.3			
11.0	15.6			
12.0	13.6			
12.5		17.1	35.8	6.2
15	9.3			

Run 58 Brick Clay and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. /sq.cm.	H	E
0	27.4			
1	25.3	0.0561	0.000636	
2	23.0	0.0561	0.000660	
3	20.8	0.0501	0.000555	
4	19.1	0.0445	0.000501	
5	17.4	0.0456	0.000476	
6	15.5	0.0408	0.000444	
7				
8	11.7	0.0495		
9	9.75	0.0304		
10	8.15	0.0332		
11	6.95	0.0279		
12	6.05	0.0253		
12.5		0.0236	0.000566	
15	4.13	0.013		

Run 59 Brick Clay and Water

Wet thicknes 1.59 cm.
Dimensions 9.5 x 9.5 cm. Formed in wood frame. Recording balance and indicating potentiometer used.
Net dry weight 229.6 gms.
Total wetted face area 178 sq. cm.

Time Hours	Free water left, gms.	Dry Bulb °C	Wet Bulb °C	Δt °C
0	61.6	32.3		
0.08		32.3	16.7	9.3
0.67				12.0
1.0	54.9			
1.17		32.3	16.7	12.2
2.0	48.3			
2.5		32.4	16.6	12.8
2.93		32.6		13.2
3.0	41.6			
3.33				13.1
3.53				13.5
4.0	33.9	33.0		13.5
5.0	27.8			
6.0	22.1			
7.0	17.1			
7.17		38.0		12.3
7.33				12.1
7.5		38.2	19.8	11.4
8.0	12.7			
9.0	9.5			
10.0	7.2			
11.0	6.0			

Run 59 Brick Clay and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. /sq.cm.	E'	H
0	26.9			
1	23.9	0.0349		0.000430
2	21.1	0.0347		0.000414
3	18.1	0.0354		0.000396
4	14.8	0.0354		0.000388
4.5			1.00	0.000381
5	12.1	0.0336	0.898	0.000351
6	9.6	0.0301	0.715	0.000320
7	7.45	0.0265	0.552	
8	5.52	0.0192	0.41	
9	4.14	0.0124	0.308	
10	3.14		0.233	
11	2.61		0.194	

Run 60 Brick Clay and Water

Wet thickness 0.64 cm.
Dimensions 14.5 x 15.1 cm. Formed in wood frame.
Recording balance and indicating potentiometer used.
Net dry weight 287.6 gms.
Total wetted face area 436 sq. cm.

Time Hours	Free water left, gms.	Dry Bulb	Wet Bulb	Δt °C
0	74.0	37.0		
0.25		35.4	16.3	14.4
0.5		35.0		15.4
0.75		36.4	17.7	15.8
1.0		36.7	17.7	16.0
1.25		36.8	17.7	16.3
1.50		37.1	17.9	16.5
1.75		37.2	18.0	16.7
2.0	42.4	37.2	18.0	16.5
2.17		37.0	17.7	16.3
2.5	33.0	37.2	18.0	16.3
2.75		37.1	18.0	15.8
3.00	25.3	37.0	17.9	15.3
3.25		36.6	17.8	14.1
3.50	18.5			
3.67		34.1	16.7	11.5
3.92		33.5	16.8	10.1
4.00	13.2			
4.17		33.0		8.7
4.42		32.9	16.2	7.3
4.5	9.9			
5.0	7.0			
5.5	5.1			

Run 60 Brick Clay and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E''
0	25.8			
1				
2	14.8	0.0412	0.000376	
2.5	11.5	0.0405	0.000376	1.00
3	8.8	0.037	0.000372	0.766
3.5	6.44	0.027	0.000350	0.56
4	4.59	0.020	0.000347	0.40
4.5	3.46	0.0137	0.000344	0.30
5	2.44	0.0094	0.000334	0.212
5.5	1.78	0.0066	0.000367	0.155

Run 61 Hand Pressed Pulp and Water

Dry thickness 0.69 cm.
Dimensions 14.7 x 14.7 cm. Edges covered with Collodion.
Recording balance and indicating potentiometer used.
Net dry weight 69.2 gms.
Total wetted face area 432 sq. cm.

Time Hours	Free water left, gms.	Dry Bulb °C	Wet Bulb °C	Δt °C
0	160.9			
0.35		35.0	16.7	14.3
0.85		33.0	15.6	14.2
1.0	144.3			
1.77		31.8		14.2
2.0	127.6			
2.6		32.7	15.7	13.9
3.0	110.5	36.7	18.0	15.4
3.5		37.6		15.7
4.0	91.8	38.0	18.7	15.7
4.5		38.1	18.7	15.7
5.0	73.9	38.1	18.7	15.7
5.5		38.0	18.4	15.6
6.0	55.9	37.6	18.3	15.3
6.5		37.5	18.3	14.7
7.0	38.2	37.3	18.3	13.6
7.25		37.0	17.9	12.2
7.5	31.3	37.0	17.9	11.4
7.75		36.8	17.8	10.6
8.0	25.7	36.7		10.2
8.25		36.6	17.7	9.6
8.5	21.4	36.5	17.6	9.0
8.75		36.5	17.5	8.7
9.0		37.0	17.9	8.7
9.5	13.7			
10.0	12.1			
11	7.7			
12	4.9			

Run 62 Hand Pressed Pulp and Water

Dry thickness 0.69 cm.
Dimensions 14.7 x 14.7 cm. Edges covered with Collodion.
Recording balance used.
Net dry weight 69.2 gms.
Total wetted face area432 sq. cm.

Time, Hours	Free Water Left, Gms.
0	136.2
1	119.3
2	101.0
3	81.8
4	63.3
5	44.5
6	30.0
7	20.3
8	13.3
9	7.3
10	3.4
11	1.3
12	0.7
13	0.3

Run 61. Hand Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	H	E'	θ'
0	232.4				
1	208.5	0.0380	0.000398		
2	184.2	0.0393	0.000416		
3	159.7	0.0398	0.000377		
4	132.7	0.0402	0.000382		
5	106.8	0.0402	0.000382		
6	80.8	0.0410	0.000400		
7	55.1	0.0375	0.000417	0.83	0.5
7.5	45.1	0.0268	0.000358	0.68	1.0
8	37.1	0.0220	0.000324	0.56	1.5
8.5	30.9	0.0178	0.000298	0.465	2.0
9					
9.5	19.8	0.0123		0.30	3.0
10	17.5	0.0102		0.26	3.5
11	11.1	0.0074		0.167	4.5
12	7.1	0.0051		0.106	5.5

Run 62. Hand Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.
0	197	
1	172.2	0.0448
2	146	0.0404
3	118.1	0.0455
4	91.5	0.0420
5	64.3	0.0388
6	43.3	0.0251
7	29.3	0.0180
8	19.2	0.0153
9	10.5	0.0121
10	4.9	0.0067
11	1.9	

Run 63 Hand Pressed Pulp and Water

Dry thickness 0.69 cm.
Dimensions 14.7 x 14.7 cm. Edges covered with Collodion.
Recording balance used.
Net dry weight 69.2 gms.
Total wetted face area 432 sq. cm.
Dry bulb - wet bulb about 17°C.

Time, Hours	Free Water, Left, gms.
0	142.8
1	127.5
2	111.0
3	93.4
4	73.2
5	52.0
6	33.0
7	20.7
8	12.5
9	6.8
10	3.3
11	1.4
12	0.6
13	0.3

Run 63. Hand Pressued Pulp and Water

Calculations

Time, Hours	% water, dry basis	Gms./Hr. /sq.cm.	E'
0	206		
1	184	0.0389	
2	160.2	0.0392	
3	134.9	0.043	
4	105.8	0.0524	
5	75.0	0.0455	1.00
6	47.6	0.0382	0.635
7	29.9	0.0213	0.398
8	18.0	0.0164	0.240
9	9.8	0.0112	0.131
10	4.8	0.0065	0.063
11	2.0		0.027

Run 64 Hand Pressed Pulp and Water

Dry thickness 0.69 cm.
Dimensions 14.7 x 14.7 cm. Edges covered with collodion.
Recording balance and indicating potentiometer used.
Net dry weight 69.2 gms.
Total wetted face area 432 sq.cm.

N.B. Sample soaked and left to dry in unheated drier overnight before start of readings.

Time, Minutes	Free water left, gms.	Dry Bulb ° C.	Wet Bulb ° C.	Δt ° C.
0	28.6			
17	26.5	26.8		6.5
26	25.6	26.8	18.4	6.3
44	23.0	26.4		6.0
60	21.3	25.9	18.3	5.5
79	19.8	25.3		5.2
114	16.8	25.3	17.6	4.7
150	14.5	25.1	17.7	4.2
189	12.2	25.0	16.2	3.7
250	8.3	24.5	16.9	2.8
294	7.2	25.3	15.1	2.3
375	4.5	25.4	15.6	1.2
390	3.8	25.5		1.1
422	3.0	25.5	15.8	0.8
444	2.5			0.6
459		25.2	15.2	0.4

Run 64. Hand Pressed Pulp and Water

Calculations

Time, Minutes	% water, dry basis	Gms./Hr. /sq.cm.	H
0	41.2		
17	38.2	0.0157	0.00036
26	36.9	0.0159	0.00038
44	33.2	0.0138	0.00034
60	30.7	0.0123	0.00033
79	28.6	0.0113	0.00032
114	24.2	0.0104	0.00033
150	20.9	0.0090	0.00032
189	17.6	0.0071	0.00029
250	12.0	0.0063	0.00034
294	10.4	0.0058	0.00038
375	6.5	0.0042	0.00052
390	5.5		
422	4.3		
444	3.6		
459			

Run 65 Calcium Chloride Solution

10 c.c. strong $CaCL_2$ solution in Petri dish dried in Collins' drying chamber over strong sulphuric acid.
Air temperature 32.0° C.
Tare 36.267 gms.

Time, Minutes	Total weight
0	47.670
18	47.485
67.5	46.510
74.0	46.460
80	46.410
85.5	46.370
90.5	46.260
100.3	46.110
111	45.940
119	45.850
127	45.790
132.5	45.690
135.5	45.650
141.5	45.590
147.5	45.510
154.5	45.410
163.5	45.285
180	45.060
191	44.920
202.5	44.780
216	44.620
230	44.450

Run 66 Hand Pressed Pulp and Water

Dry thickness 0.69 cm.
Dimensions 14.7 x 14.7 cm. Edges covered with collodion.
Recording pyrometer and recording balance used.
Dry weight (net) 69.2 gms.
Total wetted face area 432 sq.cm.

Time, Hours	Free water left, gms.	Dry Bulb ° C.	Δt ° C.	Dry Bulb - Wet Bulb ° C.
0	137.1			
0.5				
1.0	120.0	38.2	15.4	19.2
1.5		38.1		
2.0	101.7		15.7	19.3
2.25		38.2		
3.0	84.2		15.7	19.5
4.0	65.5		15.9	19.8
4.75		38.5		
5.0	47.4		15.4	19.6
6.0	31.1		11.9	19.2
6.5	25.4		10.5	19.0
7.0	21.1		9.0	18.9
7.25		37.2		
7.75		37.2		
8.0	14.4		8.9	21.4
9	8.5		6.3	22.2
10	4.4		3.6	22.3
11	1.9		2.2	22.6
12	0.6			
∞	0			

Run 66 Hand Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. sq.cm.	H	E'
0	198			
0.5				
1.0	173.1	0.0431	0.000416	
1.5				
2.0	146.9	0.0449	0.000426	
2.25				
3.0	121.7	0.0439	0.000416	
4.0	94.6	0.0439	0.00041	
4.75				
5.0	68.5	0.0425	0.000416	1.00
6.0	44.9	0.0280	0.00036	0.655
6.5	36.7	0.0227	0.000328	0.535
7.0	30.4	0.0183	0.000309	0.445
7.25				
7.75				
8.0	20.8	0.0141	0.000236	0.304
9.0	12.3	0.0109	0.000263	0.179
10.0	6.35	0.0079	0.000333	0.093
11.0	2.74	0.0035	0.000246	0.040
12.0	0.87			

Run 67 Calcium Chloride Solution

Strong $CaCL_2$ solution in 8.6 cm. dia. x 1.0 cm. deep glass Petri dish suspended on recording balance.
Face area 58.1 sq.cm.

Time, Hours	Free water left, gms.	Dry Bulb ° C.	Wet Bulb ° C.
0	23.4		
1	20.4	37.0	26.6
2	17.4		
3	15.1	38.0	22.6
4	12.3		
5	9.6	38.0	23.0
6	8.1		
7	7.0	37.6	21.8
8	5.6		
9	4.2		
10	3.1		
11	2.1		
12	1.5		
13	1.0		
14	0.5		

Run 68 Calcium Chloride Solution

Strong $CaCL_2$ solution placed in 9.6 cm. dia. x 1.0 cm. deep glass dish on drier floor. Eight cold junctions immersed in solution, with hot junctions in air over dish. Weights not taken.

Time, Hours	Dry Bulb - wet bulb ° C.	Δt ° C.
0	17.4	13.4
1	17.6	12.5
2	17.8	12.4
3	17.9	12.2
4	17.7	11.2
5	17.4	10.2
6.0	17.2	9.0
6.5	20.4	11.0
7.0	21.0	10.5
7.5	21.3	10.0
8.0	21.4	9.2
8.5	21.5	8.5
9.0	21.7	8.0
9.5	21.7	7.3
10.0	21.9	6.8
10.5	21.9	6.3
11.0	21.8	5.6
11.5	21.7	5.1
12.0	21.7	4.6
12.5	21.8	4.0
13.0	21.8	2.7
13.5	21.7	1.9
14.0	21.6	1.8
15.0	21.4	1.6

Run 69 Pressed Pulp and Water

Dry thickness 1.7 cm. Soaked under water 5 hours.
Dimensions 6.0 x 14.9 cm. Edges covered with collodion.
Recording pyrometer and recording balance used.
Net dry weight 82.0 gms.
Total wetted face area 179 sq.cm.
Air temperature 37-43°

Time, Hours	Free water left, gms.	Dry bulb - wet bulb ° C.	Δt ° C.
0	118.5		
1	108.3	19.0	15.8
2	100.5	18.9	15.7
3	89.3	18.6	15.5
4	80.0	22.0	18.4
5	70.0	22.2	18.2
6	59.0	22.9	18.1
7	49.0	23.0	17.0
8	40.6	23.0	14.0
9	33.4	23.0	
10	28.7	22.8	Pyrometer out of commission.
11	24.5	22.7	
12	20.4	22.5	
13	17.4	22.4	
14	14.4	22.2	
15	12.2	22.1	
16	10.4	22.0	
17	8.9	21.9	
18	7.4	21.8	
19	5.9	18.7	
20	4.9	18.0	
21	4.0	17.1	
22	3.1	16.8	
23	2.4	16.2	

Run 69 Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. /sq.cm.	H	E'
0	144.6			
1	132.1	0.0574	0.00054	
2	122.5	0.055	0.00052	
3		0.0524	0.00050	
4	97.6	0.055	0.00045	
5	85.4	0.058	0.00048	
6	72.0	0.056	0.00046	
7	59.8	0.0535	0.00047	1.00
8	49.5	0.044	0.00047	.829
9	40.7	0.028		.681
10	35.0	0.024		.586
11	29.9	0.024		.500
12	24.9	0.020		.416
13	21.2	0.016		.355
14	17.6	0.012		.296
15	14.9	0.011		.249
16	12.7	0.0092		.212
17				.182
18	9.0	0.0084		.151
19	7.2	0.007		.120
20	6.0			.100
21	4.9	0.005		.082
22	3.8			.063
23	2.9			.049

Run 70 Pressed Pulp and Water

Dry thickness 1.70 cm. Soaked in water 19 hrs.
Dimensions 6.0 x 14.9 cm. Edges covered with collodion.
Recording pyrometer and recording balance used.
Net dry weight 82.0 gms.
Air temperature 36-42° C.
Total wetted face area 179 sq.cm.

Time, Hours	Free water left, gms.	Δt ° C.	Dry Bulb - Wet Bulb ° C.
0	124.7		
1.0	115.2	13.6	17.9
2.0	104.9		17.9
3.0	95.2		18.4
4.0	85.1	14.5	18.8
5.0	74.2	16.7	21.2
6.0	62.9	16.6	21.4
7.0		16.7	21.8
7.5	(46)	16.9	21.9
8.0	41.7	15.8	22.1
9.0	34.3	12.3	22.1
10.0	28.7	10.3	22.0
11.0	25.2	8.9	21.8
12.0	21.8	7.9	21.4
13.0	19.0	7.6	21.3
14.0	16.8	7.3	21.3
15.0	14.6	6.9	21.3
16.0	12.9	6.7	21.2
17.0	11.4	6.5	21.0
18.0	9.9	6.2	20.9
19.0	8.6	6.0	20.7
20.0	7.2		
21.0	6.4		
22.0	5.3		
23.0	4.8		
24.0	4.1		
25.0	3.5		
26.0	3.0		
27.0	2.5		
28.0	2.1		
29.0	1.5		
30.0	1.4		
∞	0		

Run 70 Pressed Pulp and Water

Calculations

Time, Hours	% water, dry basis	gms./hr. /sq.cm.	overall coef. of ht. flow,H	E'
0	151.8			
1	140.3	0.0564	0.000616	
2	127.8	0.0536	0.000580	
3	116.1	0.0548	0.000575	
4	104.0	0.0564	0.000579	
5	90.5	0.0615	0.000549	
6	76.6	0.0615	0.000551	
7				
7.5				1.00
8	50.9	0.0447	0.000427	0.907
9	41.8	0.0341	0.000429	0.745
10	35.0	0.0251	0.000376	0.0624
11	30.7	0.0196	0.000340	0.548
12	26.6	0.0173	0.000332	0.474
13	23.2	0.0140	0.000277	0.412
14	20.5	0.0123	0.000254	0.365
15	17.8	0.0109	0.000237	0.317
16	15.7	0.0100	0.000224	0.280
17	13.9	0.0084	0.000192	0.248
18	12.1	0.0078	0.000190	0.218
19	10.5	0.0078	0.000192	0.187
20	8.8	0.0061	0.000157	0.157
21	7.8	0.0056		0.139
22	6.5			0.115
23	5.8			0.104
24	5.0			0.089
25	4.3			
26	3.65			
27	3.04			
28	2.56			
29	1.82			
30	1.7			

Run 71 Pressed Pulp and Paper

Block of pressed pulp about 5x5 cm. dried without forced convection in room air, with thickness measurements.

Time, Minutes	Net weight, grams	Thickness, m.m.
0	17.84	12.8
14	17.67	12.7
37	17.43	12.6
65	17.14	
88	16.91	
97	16.78	12.6
167	16.04	12.6
212	15.73	12.6
247	15.37	12.6
377	14.19	12.6
412	13.90	12.6
587	12.31	12.6
∞	8.30	11.7
Oven dry	8.176	

Run 72 Brick Clay and Water

Dimensions 7.0 x 7.0 x 2.54 cm.
Edges covered with tin foil.
Total face area 98 sq.cm. Net dry wt. 196.2 gms.
Placed at end of flue through which air was forced by a blower.
Air velocity 10.6 m. per second.
Laboratory platform balance used.

Time, Minutes	Total water left.gms.	Dry bulb ° C.	Wet bulb ° C.
0	51.5		
10	48.1		
24	44.8		
41	40.4		
55	36.9		
90	29.9		
103	27.1		
115	26.2		
125	25.1		
135	23.8		
145	22.4		
155	22.2	25.3	16.9
170	20.9		
180	20.0	25.7	16.9
190	19.8	22.9	15.5
200	19.1		
210	18.7	24.2	16.2
220	18.0		
Oven dry	0		

Run 72 Brick Clay and Water

Calculations

Time, Minutes	% total water, dry basis	gms./hr. /sq.cm.
0	26.3	
10	24.5	
24	22.8	0.157
41	20.6	0.157
55	18.8	0.157
90	15.2	0.107
103	13.8	
115	13.3	0.071
125	12.8	
135	12.1	
145	11.4	0.051
155	11.3	
170	10.6	
180	10.2	0.038
190	10.1	
200	9.7	
210	9.5	0.032
220	9.2	

Run 73 Brick Clay and Water

Dimensions 7.0 x 7.0 x 2.54 cm.
Edges covered with tin foil.
Total face area 98 sq.cm. Net dry weight 193.9 gms.
Placed at end of flue through which air
was forced by a blower.
Air velocity 15.2 m. per second.
Laboratory platform balance used.

Time, Minutes	Total water left, gms.	Dry Bulb ° C.	Wet Bulb ° C.
0	52.8	24.6	16.9
41	39.5	25.7	16.4
51	36.4		
67	32.0		
87	27.8		
102	25.9	24.1	15.8
119	24.0	25.4	17.4
138	22.2	26.1	18.1
162	20.6		
183	19.1	26.3	17.9
205	18.4	23.2	16.4
216	17.4		

Run 73 Brick Clay and Water

Calculations

Time, Minutes	% total water, dry basis	gms./hr. /sq.cm.
0	27.3	
41	20.4	0.174
51	18.8	0.174
67	16.5	
87	14.4	0.107
102	13.4	0.074
119	12.4	0.064
138	11.5	0.051
162	10.6	0.039
183	9.9	0.034
205	9.5	
216	9.0	

Run 74 Brick Clay and Water

Dimensions 7.0 x 7.0 x 2.54 cm.
Edges covered with tin foil.
Total face area 98 sq.cm.
Dried resting on laboratory balance without forced convection.

Time, Minutes	Free water left, gms.	Dry bulb ° C.	Wet bulb ° C.
0	48.3	26.7	17.7
30	46.7	27.0	17.3
54	46.2	27.3	17.4
70	45.0	27.5	
130	43.8	27.7	17.6
165	42.6	27.4	
222	40.4	25.7	15.5
328	35.9	25.9	
370	34.3		
414	32.4	24.9	
435	31.5		
∞	200.6		

Run 75 Brick Clay and Water

Dimensions 7.0 x 7.0 x 2.54 cm.
Edges covered with tin foil. Total face area 98 sq.cm.
Recording balance used.
Drier used without forced convection of air.
Equilibrium weight 202.8 gms. Dry weight 200.0

Time, Hours	Free water left.gms.	Dry Bulb ° C.	Wet Bulb ° C.
0	44.5	26.2	19.0
2			
4	40.2		
6	38.7		
8	36.9		
10	34.6		
12	32.0		
14	29.9		
16	27.5		
18	25.3		
20	23.4		
22	21.5	25.8	17.7
24	19.4		
26	17.2		
28	15.4		
30	13.6		
32	11.9		
34	10.3		
36	8.5		
38	7.2		
40	6.0		
42	4.9		
44	3.9		
46	3.1		

Run 75 Brick Clay and Water

Calculations

Time, Hours	% total water, dry basis	gms./hr. /sq.cm.
0	22.2	
2		0.011
4	20.1	0.010
6	19.3	0.009
8	18.4	0.011
10	17.3	0.012
12	16.0	0.012
14	14.9	0.012
16	13.7	0.012
18	12.6	0.0105
20	11.7	0.0097
22	10.7	0.0102
24	9.7	0.011
26	8.6	0.0102
28	7.7	0.0092
30	6.8	0.0092
32	5.9	0.0085
34	5.1	0.0087
36	4.2	0.0077
38	3.6	0.0064
40	3.0	0.0059
42	2.9	0.0054
44	1.9	0.0047
46	1.5	0.0039
∞	1.4	

Run 76 Whiting and Water

Dimensions 6.9 x 6.8 x 2.54 cm.
Total face area 94 sq.cm. Net dry weight 200.8 grams.
Placed in vertical position at end of a flue through which air was forced by a blower.
Air velocity 9-11 m./sec.
Laboratory platform balance used.
Formed in wood frame lined with tin foil.
Dry bulb 26.4 ° C. (ave.). Wet bulb 18.2° C.(ave.).

Time, Minutes	Free water left, gms.
0	38.6
13	34.5
24	31.2
35	28.6
50	25.5
65	22.4
84	18.2
97	16.2
122	12.4
136	10.9
152	8.8
166	8.1
183	6.6
201	5.4
228	4.6
240	3.8
265	3.6
301	2.9

Run 76 Whiting and Water

Calculations

Time, Minutes	% water, dry basis	grms./hr. /sq.cm.
0	19.2	
13	17.2	0.189
24	15.5	0.167
35	14.2	0.148
50	12.7	0.134
65	11.1	0.130
84	9.05	0.117
97	8.05	0.098
122	6.16	0.084
136	5.31	0.074
152	4.4	0.061
166	4.03	0.052
183	3.3	0.040
201	2.7	0.033
228	2.3	0.022
240	1.9	0.016
265	1.8	
301	1.44	

Run 77 Whiting and Water

Dimensions 8.9 x 9.4 x 1.6 cm.
Total face area 167 sq.cm. Net dry weight 239.7 gms.
Place in vertical position at end of flue thru
which air was forced by a blower.
Air velocity 9-11 m./sec.
Laboratory platform balance used.
Formed in wood frame lined with tin foil.
Ave. dry bulb 26.4° C. Ave. wet bulb 18.2° C.

Time, Minutes	Free water left, gms.
0	45.8
7	41.4
14	39.1
25	35.2
37	30.3
53	24.9
74	18.2
86	14.7
111	9.1
125	7.5
141	5.7
155	5.4
190	4.5
217	2.7
229	2.4
254	1.9
290	1.2

Run 77 Whiting and Water

Calculations

Time, Minutes	% water dry basis	gms./hr. /sq.cm.
0	19.1	
7	17.3	
14	16.3	0.141
25	14.7	0.141
37	12.7	0.141
53	10.4	0.120
74	7.6	0.113
86	6.14	0.099
111	3.8	0.055
125	3.13	0.036
141	2.38	0.026
155	2.26	0.020
190	1.88	0.013
217	1.13	0.010
229	1.00	0.009
254	0.79	0.008
290	0.5	

Run 78 White Wood and Water

Dimensions 15.2 x 16.2 x 0.41 cm. (as in Run 48)
Wood soaked under water 4 months.
Recording balance used.
Net dry weight 31.9 gms.
Total face area 492 sq.cm.

Time, Hours	Free water left, gms.	Dry Bulb ° C.	Wet Bulb ° C.
0	84.5	37.0	
1	67.5		
2	50.4		
2.5	40.9		
3.0	32.7		
3.5	23.5		
4.0	16.9	39.7	22.0
4.5	9.6		
5.0	4.9		
5.5	3.1		
6.0	2.3		
7.0	1.5		

Run 78 White Wood and Water

Calculations

Time, Hours	% water dry basis	gms./hr. /sq.cm.
0	265	
1.0	243	0.035
2.0	158	0.035
2.5	128.3	0.035
3.0	102.6	0.035
3.5	73.6	0.032
4.0	53.0	0.027
4.5	30.1	0.022
5.0	15.4	0.011
5.5	9.7	0.0053
6.0	7.2	0.0026
7.0	4.7	

Run 79 White Wood and Water

Dimensions 15.9 x 30.5 x 0.69 cm. (as Run 50)
Wood soaked under water 4 months.
Recording balance used.
Net dry weight 109.8 gms.
Total face area 970 sq.cm.

Time, Hours	Free water left, gms.	Dry bulb °C.	Wet bulb °C.
0	252.0	38.3	
1	222.0		
2	192.4		
3	163.9	41.0	22.7
4	134.5		
5	105.2		
6	77.4		
6.5		42.0	
7	52.1		
7.5	41.8		
8.0	32.7	42.3	
8.5	25.2		
9.0	19.5		
9.5	15.3		
10	11.9		
11	7.3		
12	5.2		
13	3.9		
14	3.1		
15	2.5		
16	1.9		
17	1.6		

Run 79 White Wood and Water

Calculations

Time, Hours	% water dry basis	gms./hr. /sq.cm.
0	229.6	
1.0	202.1	0.0307
2.0	175.3	0.0303
2.5		0.03
3.0	147.3	0.03
3.5		0.03
4.0	122.5	0.03
4.5		0.03
5.0		0.0294
5.5		0.0286
6.0	70.5	0.0273
7.0	47.5	0.023
8.0	29.8	0.017
8.5	23.0	0.0136
9.0	17.8	0.0103
9.5	13.9	0.0078
10	10.8	0.0062
11	6.7	0.0033
12	4.7	0.0016
13	3.6	0.0010
14	2.8	0.0007
15	2.3	0.0005
16	1.7	0.0004

Run 80 White Wood and Water

Dimensions 15.6 x 20.3 x 1.27 cm.
Wood soaked under water 4 months.
Recording balance used.
Net dry weight 182.6 gms.
Total face area 634 sq.cm.

Time, Hours	Free water left, gms.	Dry bulb ° C.	Wet bulb ° C.
0	164.9	41.5	23.6
1	144.2		
2	125.2		
3	110.6		
4	100.5	42.2	
5	91.7	42.6	25.7
6	84.0		
7	77.0		
8	71.0		
9	65.7	42.8	
10	61.0		
11	56.5		
12	52.4		
13	47.8	41.7	
14	44.8		
15	41.7		
16	39.0		
17	36.8		
18	35.0		
19	31.8		
20	29.6		
21	27.5		
22	26.0		
23	24.5		
24	23.2		
26	19.9		
28	16.2	42.6	
30	13.7		
32	11.2		
36	7.3		

Run 80 White Wood and Water

Calculations

Time, Hours	% water dry basis	gms./hr. /sq.cm.	E
0	90.2		
1	79.0	0.0316	0.875
2	68.5	0.0276	0.76
2.5		0.023	
3	60.5	0.020	0.671
3.5		0.0175	
4	55.0	0.0157	0.61
4.5		0.0139	
5	50.2	0.0129	0.556
5.5		0.0122	
6	46.0	0.0144	0.51
7	42.1	0.0102	0.466
8	38.9	0.0088	0.431
8.5		0.0084	
9	36.0	0.0079	0.399
9.5		0.0076	
10	33.4	0.0074	0.37
11	31.0	0.0068	0.343
12	28.7	0.0063	0.318
13	26.2	0.0057	0.29
14	24.5	0.0050	0.272
15	22.9	0.0047	0.253
16	21.4	0.0039	0.236
17	20.2	0.0038	0.223
18	19.2	0.0035	0.212
19	17.4	0.0032	0.193
20	16.2	0.0028	0.18
21	15.1		0.167
22	14.2		0.158
23	13.4		0.149
24	12.7		0.141
26	10.9		0.121

Run E-1 Humidity Equilibrium Data

Sulfite pulp as received in tap form from Eastern Mfg. Company

Drier position	1	2	3	2	4	5	3
Original weight, gms.	53.289	53.255	53.358	53.414	53.365	53.502	53.603
Equilibrium weight	53.255	53.358	53.414	53.365	53.502	53.603	53.427
Tare	50.050	50.050	50.050	50.050	50.050	50.050	50.050
Net dry weight	3.205						
Equil. water gms.	0	0.103	.159	.110	.247	.348	.172
Days to equil. wt.	3	13	12	22	22	27	62
% water, dry basis	0	3.21	4.96	3.42	7.70	10.86	5.36
% H_2SO_4 in bubbler at finish	98.8	49.9	39.3	49.7	28.4	20.6	42.5
Temperature °C.		21.5		23.0	21.2	22.0	25.0
% relative humidity	0	36.2	57.8	36.7	77.7	88.0	51.5

Run E-2. Humidity Equilibrium Data

Shavings of white wood (poplar) - same wood as used in drying runs 48-55 inclusive and 78-81 inclusive.

Drier position	4	5	4	3	2	1
Original weight, gms.	54.456	54.493	54.610	54.536	54.460	54.419
Equilibrium weight	54.493	54.610	54.536	54.460	54.419	54.354
Tare	52.705	52.705	52.705	52.705	52.705	52.705
Net dry weight						1.649
Equil. water, gms.	0.139	0.256	0.182	0.106	0.065	0
Days to equil. wt.	4	24	22	22	27	62
% water, dry basis	8.4	15.2	11.0	6.4	3.9	0
% H_2SO_4 in bubbler at finish	28.1	16.2	27.6	40.3	49.7	92.9
Temperature, °C.	23.0	21.5	23.0	21.2	22.0	25.0
% relative humidity	78.8	91.8	78.9	56.0	36.5	0

Run E-3. Humidity Equilibrium Data

Whiting Powder (for rubber trade) as used in drying experiments.

Drier position	2	3	4
Original weight, gms.	43.732	43.731	43.732
Equilibrium weight, gms.	43.731	43.733	43.737
Tare	37.294	37.294	37.294
Net dry weight			
Equilibrium water, gms.			
Days to equil. weight	3	9	19
% water, dry basis			
% H_2SO_4 in bubbler at finish	51.0	39.4	28.6
Temperature, °C.	22.0	22.0	22.2
% relative, humidity	34.5	58.0	78.0

Run E-4. Humditiy Equilibrium Data

"Celotex" as dried by Sanford at W.P.I., broken up into very small pieces.

Drier position	1	2	3	4	5
Original weight, gms.	52.714	52.697	52.807	52.778	52.870
Equilibrium wt., gms.	52.697	52.807	52.778	52.870	52.881
Tare	50.855				
Net dry weight	1.842				
Equilibrium water, gms.	0	0.110	0.081	0.173	0.184
Days to equil. wt.	23	22	22	27	62
% water, dry basis	0	5.97	4.40	9.40	10.0
% H_2SO_4 in bubbler at finish	92.0	39.0	49.6	29.4	32.2
Temperature, °C.	22.0	23.0	21.2	22.0	25.0
% relative humidity	0	58.1	37.2	76.6	72.0

V - Series. Pressed Pulp and Water

Run V-1

Dimensions 7.05 x 8.95 x 1.80 cm.

Time, Minutes	Weight, gms.	Dry bulb, °C.	Wet bulb, °C.	Air Velocity m./sec.
0	138.2	25.3	14.0	4.89
15	134.7	25.3	14.0	4.84
30	131.4	24.5	13.6	5.00
45	128.4	24.2	13.5	4.85
60	125.5	24.1	13.6	4.65
75	122.6	23.7	13.3	4.57
90	119.9	24.5	14.3	
105	117.2	25.1	14.3	4.84
Dry	57.4			

Run V-2

Dimensions 7.05 x 8.95 x 1.80 cm.

Time, Minutes	Weight gms.	Dry bulb, °C.	Wet bulb, °C.	Air Velocity m./sec.
0	133.6	24.4	13.9	6.21
15	129.8	24.8	13.8	6.65
30	126.3	24.7	13.8	6.36
45	122.95	24.6	14.1	6.44
60	119.5	24.7	13.8	6.31
Dry	57.4			

V - Series. Pressed Pulp and Water

Runs V-3 to V-19 inclusive made with block of dimensions 5.03 x 5.24 x 1.52 cm. Total face area 52.6 sq.cm.

Run	Time, Minutes	Weight Gms.	Dry Bulb, °C.	Wet Bulb, °C.	Air Velocity in./sec.
V-3	0	47.33	22.7	12.2	8.39
	15	45.02	22.8	12.0	8.20
	30	42.68	22.7b	12.0	8.21
	45	40.43	22.9	12.3	8.16
	60	38.33	23.0	12.6	8.06
	75	-	23.4	13.4	
	Dry	22.82			
V-4	0	47.74	24.1	12.2	9.04
	15	44.96	24.0	12.6	9.46
	30	42.32	23.9	12.4	8.56
	45	39.73	23.8	12.1	8.55
	60	37.41	23.9	12.5	8.49
	Dry	22.82			
V-5	0	49.60	26.0	16.4	1.96
	15	48.13	26.4	16.8	2.01
	30	46.52	26.7	16.9	1.85
	45	45.12	26.3	16.6	1.76
	60	43.66	26.2	17.6	2.08
	Dry	22.82			
V-6	0	49.72	25.5	16.1	0.60
	15	48.20	25.5	16.1	0.57
	30	46.79	25.2	15.9	0.53
	45	45.38	25.2	15.9	0.50
	60	44.06	25.3	16.0	0.47
	Dry	22.82			
V-7	0	49.09	24.6	13.1	4.82
	15	47.13	24.6	12.6	4.81
	30	45.20	24.9	13.0	4.85
	45	43.33	24.5	12.4	4.80
	60	41.52	24.9	12.9	4.75
	Dry	22.82			

V - Series (Cont'd.)

Run	Time, Minutes	Weight Gms.	Dry Bulb, °C.	Wet Bulb, °C.	Air Velocity in/sec.
V-8	0	46.33	25.5	12.7	5.89
	15	44.15	25.5	12.8	6.09
	30	41.93	25.3	12.5	5.66
	45	39.64	25.4	12.5	5.81
	60	37.54	25.5	12.6	5.81
	Dry	22.82			
V-9	0	47.65	27.3	14.2	7.11
	15	44.97	27.3	14.2	7.56
	30	42.45	27.5	14.3	7.14
	45	40.00	27.6	14.4	6.62
	60	47.57	27.8	14.6	7.00
	Dry	22.82			
V-10	0	48.30	23.9	11.2	Free
	34.5	47.21	23.8	11.1	
	60	46.45	23.8	11.1	Convection
	120	44.46	24.6	11.7	
	Dry	22.8			
V-11	0	50.76	23.7	11.6	4.01
	15	49.01	23.5	11.6	3.73
	30	47.38	24.2	12.1	3.35
	45	45.81	24.3	12.1	3.82
	60	44.25	24.5	12.3	3.88
	Dry	22.82			
V-12	0	49.74	23.5	11.6	6.70
	15	47.44	23.2	11.5	6.70
	30	45.28	23.5	11.7	6.76
	45	43.15	23.5	11.8	6.89
	Dry	22.82			
V-13	0	49.88	22.8	11.8	3.20
	15	48.40	22.6	11.7	3.22
	30	47.00	22.8	11.9	3.26
	46	45.53	22.6	11.9	3.25
	Dry	22.82			

V - Series (Cont'd.)

Run	Time, Minutes	Weight gms.	Dry Bulb, °C.	Wet Bulb, °C.	Air Velocity m./sec.
V-14	0	48.45	22.5	11.9	3.20
	15	47.02	22.3	11.8	
	30	45.74	22.1	11.7	3.22
	45	44.41	22.1	11.7	3.19
	Dry				
V-15	0	48.33	21.4	11.3	2.49
	15	47.18	21.7	11.4	2.49
	37	45.39	22.3	11.7	2.53
	52	44.19	22.4	11.8	2.58
	Dry	22.82			
V-16	0	49.18	22.3	11.8	2.08
	30	46.84	22.6	12.1	2.11
	60	44.60	21.8	11.7	2.11
	Dry	22.82			
V-17	0	49.57	22.6	9.9	2.07
	30	47.04	22.8	9.7	1.80
	60	44.64	22.8	9.7	1.77
	90	42.12	23.3	10.0	2.08
	Dry	22.82			
V-18	0	48.30	21.0	8.9	13.35
	10	45.52	21.7	8.5	
	20	43.13	20.6	8.5	13.35
	Dry	22.82			
V-19	0	52.02	25.6	11.9	12.40
	10	48.87	25.9	12.1	
	20	46.22	25.9	12.1	
	30	43.72	25.9	12.1	12.30
	Dry	22.82			

Run V-1 to V-19 inclusive.

Pressed pulp and water.

Calculations of Results of Air Velocity.

Runs for conditions at 100% water, dry basis.

Run	R' = gms./hr./sq.cm./°C difference between wet bulb and dry bulb temp.	Corrected Air Velocity, m./sec.
V 1	0.053	4.63
V 2	0.063	6.00
V 3	0.106	7.60
V 4	0.114	8.60
V 5	0.074	2.06
V 6	0.074	4.01
V 7	0.079	4.69
V 8	0.084	5.70
V 9	0.097	6.90
V 10	0.0186	free air
V 11	0.063	3.41
V 12	0.091	6.33
V 13	0.0625	3.26
V 14	0.062	3.21
V 15	0.056	2.62
V 16	0.053	2.21
V 17	0.045	1.91
V 18	0.150	12.03
V 19	0.140	11.20

cal unit

APPENDIX V

TABLE OF NOMENCLATURE

A = surface area

c = black body radiation coefficient, = 0.000137 cal./(sec.)(sq.cm.)((°C. abs./100)^4

E = ratio of free liquid content to initial free liquid content = $\frac{T - T_E}{T_o - T_E}$

E' = free liquid content of solid divided by the free liquid content at the critical point.

G = rate of evaporation as gm.mols/(hr.)(sq.cm.)(m.m. Δp.)

h_c = surface coefficient of heat flow, air to solid, as gm.cal./(sec.)(sq.cm.)(°C.)

H = overall coefficient of heat transfer from air to evaporation zone, cal./(sec.)(sq.cm.)(°C.) = 0.000136 x B.t.u./(hr.)(sq.ft.)(°F.)

H_a = absolute humidity of air under drying conditions prevailing, weight per unit weight dry air.

H_s = absolute humidity of saturated air at temperature of the solid or liquid being dried, weight per unit weight dry air.

k_D = diffusion constant, vapor through solid, gms./(sec.)(sq.cm.)(cm.)(m.m. Δp.)

k_h = thermal conductivity, cal./(sec.)(sq.cm.)(cm.)(°C.)

K = diffusion constant, water through solid, gms./(sec.)(sq.cm.)(cm.)(unit difference in v, = K'/ρ.

K' = diffusion constant, water through solid, gms./(sec.)(sq.cm.)(cm)(unit difference in T, = $K\rho$.

K_s = surface coefficient of vapor diffusion. gms./(sec.)(sq.cm.)(unit Δp.

M = molecular weight

p = partial vapor pressure.

p_a = partial vapor pressure of the vapor in the main body of the carrier gas.

p_e = black body coefficient.

p_s = partial vapor pressure of vapor over liquid at the point where evaporation is taking place.

r = latent heat of vaporization, cal./gm.

R = half thickness of slab.

R' = evaporation coefficient, gms./(hr.)(sq.cm.)(°C.) difference between wet bulb and dry bulb temperature.

R'' = evaporation coefficient, gms./(hr.)(sq.cm.)(unit absolute humidity difference)

t_a = temperature of drying air.

t_s = temperature of the liquid or solid being dried at the point where evaporation occurs.

T = water content on dry weight basis = gms. water per gm. bone dry solid.

T_E = equilibrium water content on dry weight basis = water content after infinite time under constant drying conditions, = gms. water per gm. dry solid.

T_o = initial water content on dry weight basis, = gms. water per gm. dry solid.

u = air velocity, m./sec.

v = water content on volume basis, gms./c.c. = T .

W = weight of water or other liquid.

Δ = ratio of free water concentration at any point to initial free water concentration at that point.

θ = time

θ' = time after start of falling rate period.

ρ = density.

APPENDIX VI

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