

SIMULTANEOUS MEASUREMENTS OF WEIGHT AND VOLUME  
CHANGES OF WHEAT KERNELS STEEPED IN WATER

by

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## LIST OF SYMBOLS

- $A$  = percent moisture lost in air drying  
 $B, B'$  = dimensionless constants in diffusion equations  
 $b$  = sample regression coefficient  
 $c$  = concentration of diffusing substance at a point in a solid, g./cm.<sup>3</sup>  
 $c_0$  = initial, uniform concentration, g./cm.<sup>3</sup>  
 $c_s$  = concentration at the bounding surface, g./cm.<sup>3</sup>  
 $\bar{c}$  = average concentration, g./cm.<sup>3</sup>  
 $D$  = diffusion coefficient, cm.<sup>2</sup>/sec.  
 $D_0$  = diffusion constant in Arrhenius equation, cm.<sup>2</sup>/sec.  
 $D_m$  = diffusion coefficient of mass, cm.<sup>2</sup>/sec.  
 $D_v$  = diffusion coefficient of volume, cm.<sup>2</sup>/sec.  
 $E$  = energy of activation, cal./mole  
 $f$  = function  
 $f, f, "$  = first, second, ....., derivatives of  $f$   
 $H_0$  = hypothesis  
 $J$  = diffusion current (i.e., the specific rate of mass transfer), g./cm.<sup>2</sup>sec.  
 $K_m$  = the slope of the plot,  $\bar{m} - m_0$  vs  $\sqrt{\theta}$   
 $K_v$  = the slope of the plot,  $\bar{v} - v_0$  vs  $\sqrt{\theta}$   
 $m_0$  = initial moisture content, dry basis, g./g.  
 $m_1$  = average initial moisture gain by capillary action, dry basis, gm./gm.  
 $\bar{m}$  = average moisture content, dry basis, g./g.  
 $m_s$  = effective surface moisture content, dry basis, gm./gm.  
 $n$  = an integer  
 $R$  = universal gas constant, cal./mole, °K

$r_v$  = radius of a sphere with the same volume as a given solid, cm.

$S$  = exposed surface area of a wheat kernel, cm.<sup>2</sup>

$S_p$  = sample standard error of regression coefficient

$r, s$  = special coordinates, cm.

$T$  = absolute temperature, °K

$t$  = student "t" distribution

$V$  = volume of a wheat kernel, cm.<sup>3</sup>

$v_0$  = initial volume content, dry basis, cm.<sup>3</sup>/cm.<sup>3</sup>

$\bar{v}$  = average volume content, dry basis, cm.<sup>3</sup>/cm.<sup>3</sup>

$v_s$  = effective surface volume content, dry basis, cm.<sup>3</sup>/cm.<sup>3</sup>

$V_0$  = initial volume of the wheat kernels

$V_f$  = volume of wheat kernels at the end of absorption  
time cm.<sup>3</sup>

$W_f$  = weight of wheat kernels at the end of absorption time, gm.

$Y$  = percent moisture in air-dry sample as determined by oven drying

$x, y, z$  = Cartesian coordinates, cm.

$\theta$  = time, sec. or hours

$\rho$  = density of fluid, g./cm.<sup>3</sup>

$\psi$  = sphericity of shape factor

T. M. = percent total moisture

$\beta$  = slope of regression line

DIMENSIONLESS FACTORS IN THE DIFFUSION EQUATION

$$\bar{C} = \frac{\bar{c} - c_s}{c_o - c_s}$$

$$C = \frac{c - c_s}{c_o - c_s}$$

$$\bar{M} = \frac{\bar{m} - m_s}{m_o - m_s}$$

$$\bar{V} = \frac{\bar{v} - v_s}{v_o - v_s}$$

$$Z = s/2 \sqrt{D\theta}$$

$$X = S/V \sqrt{D\theta}$$

$$X_m = S/V \sqrt{D_m\theta}$$

$$X_v = S/V \sqrt{D_v\theta}$$

## INTRODUCTION

The problem of water penetration into wheat kernels is of much importance to the biochemical engineering and also milling industry. In the past thirty years, several investigations concerning the mode of water penetration into wheat kernels have been made.

The types of investigations that have been conducted may be classified into two groups. One of these has been the study of actual absorption rate in wheat kernels (quantitative study), (2), (4), (7), (8), (10), and (11). The other type of investigation was concerned with the mechanism of water penetration and the change of structure of wheat kernels during the water penetration (qualitative study), (2), (4), (6), (8), (10), and (11).

Jones (8) classified water absorption into three phases:

- (a) A rapid initial uptake period corresponding to the immediate seizure of water by the bran which is much more hygroscopic than the endosperm.
- (b) A period during which moisture pick up decreases rapidly.
- (c) A period during which the moisture absorption is steady but slow. An almost linear relationship between moisture content and time can be shown for this period.

Swanson's work (11) assured Jones' observation on a rapid initial uptake period, but indicated that perhaps, Jones' third stage of water penetration may not be steady.

Fraser and Haley (4) listed a number of factors affecting moisture absorption by the wheat kernel. Increasing temperature

and time raise the absorption rate of water into all wheats. Wheat types are considered to be important. Soft wheats absorb moisture more rapidly than hard wheats. Previous treatments such as scouring, brushing or washing tends to increase the rate of moisture penetration. Kernel size is also found to be important. Large kernels absorb water less rapidly than small kernels.

Becker's investigation (2) was undertaken to obtain data on the absorption of water by wheat kernels fully immersed in liquid water. He tested the validity of the diffusion equation, and described the nature of water diffusion in the wheat kernel at the boundaries of the spectrum of ambient conditions, and thus defined the limits of the behavior to be expected.

Grosh and Milner's studies of water penetration in wheat grains (6) revealed that cracks, radial and transverse to the crease, occur in hard vitreous endosperm in advance of water movement through the kernels. Peripheral absorption of water creates stresses between wet and dry portions which cause radial and transverse cracks that provide pathways for further penetration of water into endosperm. This cracking phenomenon is of no significance in mealy kernels and in long periods of immersion of kernels in water. It is possible that the wheat kernel can expand as a result of the cracks, which provide pathways for the penetration of water. Pence (10) indicated that the wheat kernel can expand due to the increase in moisture content.

Up to this time, no report of work on the volume gain of wheat kernels during the steeping process has been found in the literature. The objects of the experiment were to determine the

relationship between the volume gain and the weight gain, to develop the integral diffusion equation for the volume gain, to test the validities of the diffusion equation,  $1 - \bar{M} = 2/\sqrt{\pi} S/\sqrt{D_m t}$ , derived by Becker (2), and the diffusion equation to be developed for the volume gain, and to study the mechanism of water penetration into wheat kernels.

In order to develop the diffusion equation for the volume gain, the hypothesis was set up, from evidence found by Grosh and Milner (6) as previously mentioned. It would be reasonable to assume that the cracks formed which provide pathways for the penetrations of water are proportional to the volume expansion of the wheat kernel. If this is true, it may be assumed that the volume increase of the wheat kernel corresponds exactly to the volume of water entering the wheat kernel through cracks. Accepting this hypothesis that the volume gain is identical with the weight gain during the steeping process, the diffusion equation for the volume gain can be developed.

It was known that there may be two possible ways of diffusion of water into the wheat kernel. One possible way of diffusion may be that water diffuses into the wheat kernel through cracks. This may correspond to heterogeneous mechanism. The other may be that water uniformly diffuses into the wheat kernel throughout the endosperm. This may correspond to a homogeneous mechanism. This mechanism would almost certainly be pronounced at higher temperatures.

The present study provides information which is the basis of the commercially important practice of tempering of wheat. Further

included is a study of the actual mechanism of water absorption by the wheat kernel.

## THEORY

The object of this section is to formulate a general diffusion equation for the nonstationary state and to examine methods for the subsequent correlation of data.

### A. Derivation of a General Diffusion Equation (1).

Consider the diffusion of a substance through an elemental volume,  $dx:dy:dz$ , arbitrarily located within a solid. Diffusive flow from the surface  $X$  to the surface  $X + dx$  is caused by a difference between the thermodynamic potentials at their surfaces. When this is due to a difference in concentration, the proportionality between the diffusion current and the potential gradient is conventionally expressed by Fick's first law of diffusion:

$$J_x = -D_x \frac{\partial c}{\partial x} \quad (1)$$

where the proportionality factor  $D$ , the Fickian diffusion coefficient, is, in the general case, a function of concentration, position, and direction. In the stationary state the concentration at a given point is invariant; hence the sum  $J_x + J_y + J_z$  is constant and

$$D_x \frac{\partial c}{\partial x} + D_y \frac{\partial c}{\partial y} + D_z \frac{\partial c}{\partial z} = \text{constant} \quad (2)$$

In the nonstationary state, the diffusion current is a function of time. We obtain the nonstationary state differential

diffusion equation in Cartesian coordinates:

$$\frac{\partial}{\partial x} (D_x \frac{\partial c}{\partial x}) + \frac{\partial}{\partial y} (D_y \frac{\partial c}{\partial y}) + \frac{\partial}{\partial z} (D_z \frac{\partial c}{\partial z}) = \frac{\partial c}{\partial \theta} \quad (3)$$

The differential equations for a constant diffusion coefficient are of the general form:

$$D \left( \frac{\partial^2 c}{\partial r^2} + \frac{n}{r} \frac{\partial c}{\partial r} \right) = \frac{\partial c}{\partial \theta} \quad (4)$$

where  $r$  is a coordinate whose axes are everywhere perpendicular to the bounding surface and whose origin is at the center of symmetry, and  $n$  has the value of zero for planar symmetry, unit for axial symmetry, and two for spherical symmetry.

Consider diffusion in a solid of arbitrary shape. The initial and boundary conditions of interest are:

$$\begin{aligned} c &= c_0 & \text{at } \theta &= 0 \\ c &= c_s & \text{at } s &= 0 \quad \text{and } \theta > 0 \end{aligned} \quad (5)$$

where  $s$  is a general coordinate whose origin is at the bounding surface and whose axes are everywhere perpendicular to the surface (in eq. 4,  $s = r_0 - r$ , where  $r_0$  is the distance from the center of symmetry to the surface).

We shall examine the general form of solutions for a constant diffusion coefficient from the neighborhood of  $\theta = 0$  to  $\theta = \infty$ . The solution of eq. 4 for the case takes the form of the Gauss error integral:

$$1 - c = \frac{2}{\sqrt{\pi}} \int_0^z \exp(-z^2) dz \quad (6)$$

which give the concentration as a function of the distance from the surface; where

$$C = \frac{c - c_s}{c_0 - c_s} \quad \text{and} \quad \bar{z} = \frac{s}{2\sqrt{Dt}} \quad (7)$$

To obtain the average concentration in a finite solid as a function of time near  $t = 0$ , we make a material balance about the bounding surface:

$$(c_0 - \bar{C}) V = \int_0^{\theta} JS \, d\theta \quad (8)$$

where, by Fick's first law;

$$J = -D_s \left( \frac{\partial c}{\partial s} \right)_{s=0} \quad (9)$$

(Note that for a constant diffusion coefficient  $J$  approaches constancy over the surface as the time  $t$  approaches zero.)

The concentration gradient at the surface,  $\left( \frac{\partial c}{\partial s} \right)_{s=0}$ , is obtained by differentiating eq. 6. Putting  $\partial C = \frac{\partial c}{(c_0 - c_s)}$  and  $\partial \bar{z} = \frac{\partial s}{2\sqrt{Dt}}$  and noting the  $\exp(-\bar{z}^2)$  approaches unity as  $t$  and  $s$  approach zero, we find that

$$-\left( \frac{\partial c}{\partial s} \right)_{s=0} \longrightarrow \frac{c_0 - c_s}{\sqrt{\pi D t}} \quad \text{as } t \rightarrow 0 \quad (10)$$

on substituting for  $J$  and integrating, we obtain, from eq. 8,

$$\begin{aligned} \bar{C} &\rightarrow 1 - \frac{2}{\sqrt{\pi}} X \text{ as } X \rightarrow 0, \text{ or} \\ \frac{1 - \bar{C}}{X} &= \frac{2}{\sqrt{\pi}} \quad \text{at } X = 0 \end{aligned} \quad (11)$$

where

$$\bar{C} = \frac{\bar{c} - c_s}{c_o - c_s}, \quad X = S/\sqrt{D\theta} \quad (12)$$

This result provides a first approximation to a general solution, valid in the neighborhood of  $\theta = 0$ , of the nonstationary state differential diffusion equation. Note that the prescribed form of the solution for  $\theta = 0$  is

$$\bar{C} = f(X) \quad (13)$$

To obtain a more accurate approximation, we assume that  $f(X)$  can be represented, in the neighborhood of  $X = 0$ , as a power series in  $X$ ; we find, (Maclaurian's series):

$$f(X) = f(0) + f'(0)X + \frac{f''(0)}{2!}X^2 + \dots + \frac{f^{(n)}(0)}{n!}X^n + \dots \quad (14)$$

Equation (11) immediately gives  $f(0) = 1$  and  $f'(0) = -\frac{2}{\sqrt{\pi}}$ . The higher derivatives,  $f''(0)$ , etc., are clearly dependent on solid shape. However, since the series should converge rapidly near  $X = 0$ , terms higher than  $f''(0)$  will be neglected, giving for our final approximation

$$\bar{C} = 1 - \frac{2}{\sqrt{\pi}}X + \frac{f''(0)}{2!}X^2 \quad (15)$$

B. Evaluation of  $\bar{C}$  in the Case of Moisture Gain.

Equation (15) was derived for a solid of constant dimensions. For such a solid,  $\bar{C}$  is exactly equal to  $\bar{M}$ , where

$$\bar{M} = \frac{(\bar{m} - m_s)}{(m_o - m_s)} \quad (16)$$

$\bar{m}$  is the average moisture content at the given absorption time,  $m_s$  is the effective surface moisture content, and  $m_0$  is the initial moisture content.

### C. Evaluation of $\bar{C}$ in the Case of Volume Gain.

In most natural and synthetic polyomers, moisture adds its volume (as liquid water) to the volume of the solid. If the volume change in the wheat kernel during swelling corresponds exactly the volume of water entering the wheat kernel as stated in the hypothesis formulated in the introduction, by analogy, with the case of moisture gain,  $\bar{C}$  should be exactly equal to  $\bar{V}$ , where

$$\bar{V} = \frac{\bar{v} - v_s}{v_0 - v_s} \quad (17)$$

$\bar{v}$  is the average volume content at the given absorption time,  $v_s$  is the effective surface volume content, and  $v_0$  is the initial moisture content.

## MATERIALS

The wheat used in this study was the variety, Ponca. Samples were prepared with initial moisture contents ranging from 15.59 to 52.35 percent dry basis.

Ponca wheat has approximately the following percentage composition:

Carbohydrates, mostly starch	69.0
Carbohydrates, cellulose	2.6
Protein	11.0

Fat	1.0
Ash	1.7
Water	14.5

Steeping water was taken from the Manhattan City system.

The analysis of water was reported as follows:

Total hardness (parts of calcium carbonate per million)	76
Non-carbonate hardness (parts of calcium carbonate per million)	45
Total dissolved solids ( parts per million)	218
pH	7.5 - 8.0

#### METHODS

The initial moisture content and the initial density of the wheat were carefully measured. Initial moisture content was determined by a two-stage air-oven method (14). For samples containing more than 13 percent moisture, loss of moisture incident to grinding is likely to be excessive, hence the following two-stage procedure was used:

The first stage: Exact weight of sample was recorded, and the weighed sample in the container was placed in a warm, well ventilated place protected from dust, so that wheat would dry reasonably fast and reached an approximately air-dry condition in from 14 to 16 hours. The sample was weighed and the percentage moisture lost in air drying was calculated.

The second stage: The air-dry sample was ground, and approximately 3-4 g. of the well-mixed sample was weighed. The sample was

was placed in the oven at 130° C. ( $\pm 3^\circ$ ) for one hour. The sample was weighed soon after room temperature was attained. The flour residue as total solids and the loss in weight as moisture was reported.

The percentage of total moisture in the original sample was calculated as follows:

$$T. M. = A + \frac{(100 - A) Y}{100} \quad (18)$$

where

T. M. = percent total moisture

A = percent moisture lost in air drying

Y = percent moisture in air-dry sample as determined by oven drying

The pycnometer was used to measure the initial density of the wheat. In the study of water penetration into the wheat kernel, sphericity of the wheat kernel should be evaluated in order to apply diffusion equations for weight gains and volume gains. Evaluating sphericity of the wheat kernel, porosity of samples should be known. For the measurement porosity, the weighed sample was charged into a 2" - diameter glass column after the water tank was heated to the desired temperature by the automatic control heater (see Figure 1.). At the end of each given absorption time, the bed height and the volume of the sample were measured in order to calculate the porosity.

The initial moisture pick-up by capillary action was studied at several temperature levels.

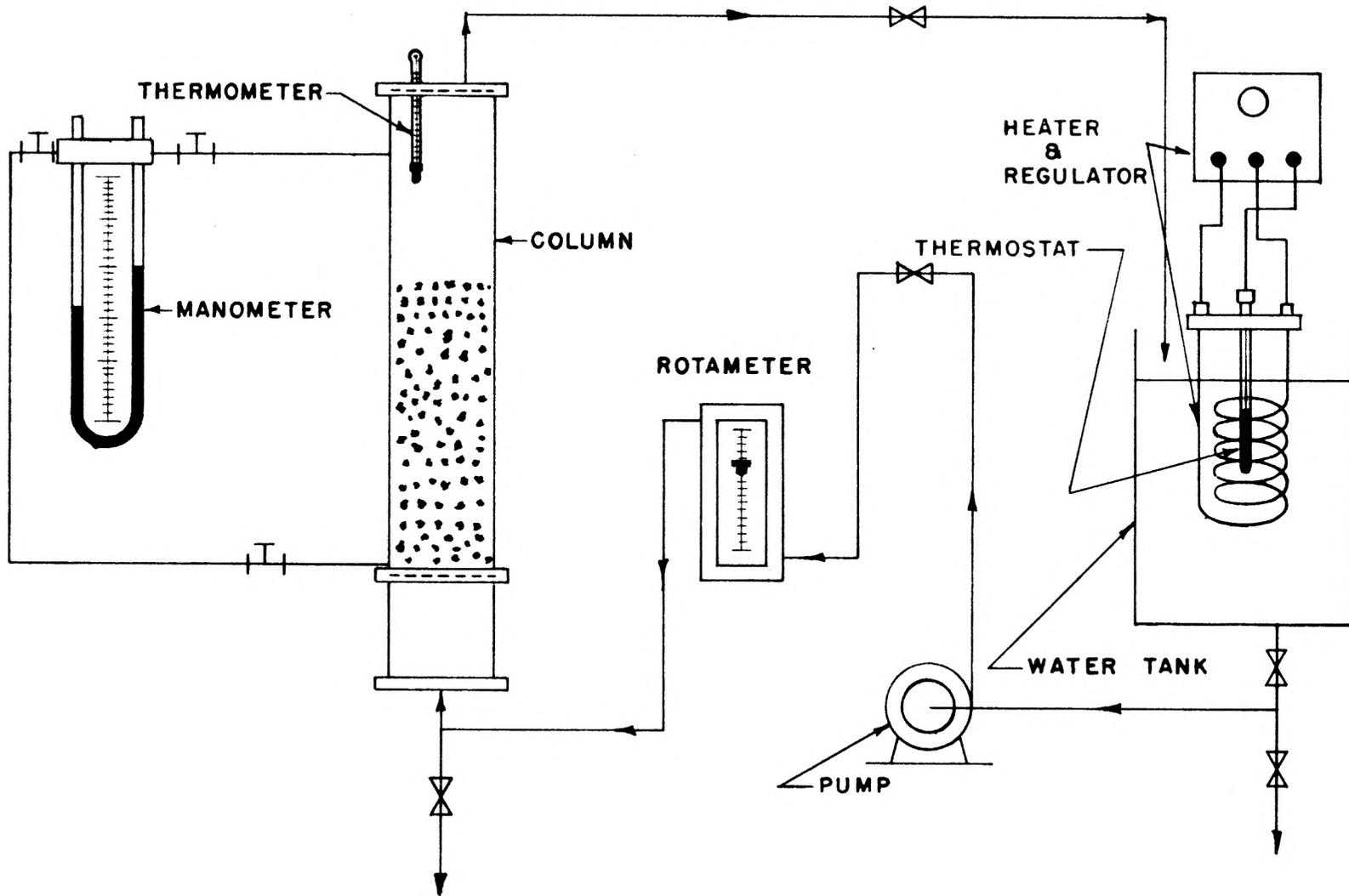


Fig. I. Schematic Diagram of Equipment

The absorption of water and the volume increase were simultaneously studied as a function of time, temperature, and initial moisture content, in order to find the relation between the volume gain and the weight gain, then to develop the diffusion equation for the volume gain, and to test the validities of the diffusion equations for the mass and the volume.

Twenty gram-samples were placed in wire gauze baskets and immersed in a stirred water bath controlled within  $0.5^{\circ}$  F of the set temperature. At the end of the absorption period the samples were quickly removed from the water bath and superficially dried on a large filter paper (2). After surface water on the wheat kernels was removed, the weight of the samples was determined, and the moisture gain was calculated from the gain in weight of the sample.

For the measurement of volume of wheat kernels, the liquid displacement method was used. In order to find a suitable liquid which is not absorbed by wheat kernels, several organic solvents such as toluene, benzene, and carbon tetra-chloride were tested. It was found that toluene was the most suitable solvent which was not absorbed by wheat kernels within 15 minutes, hence toluene has been used to measure the volume of the sample by liquid displacement method throughout experiments.

After the weight of the sample was measured at the end of each absorption time, the sample was charged into a burette which was already filled with exact known amount of toluene. The volumetric displacement of the toluence was taken as the volume of the sample.

Experiments were carried over a wide range of temperature from  $80^{\circ}$  F to  $179^{\circ}$  F ( $26.67^{\circ}$  C to  $81.67^{\circ}$  C), and absorption periods ranged from several minutes to seven hours.

## RESULTS

All the pertinent data, both experimentally obtained and calculated, are assembled in Table 1 to Table 8 in the Appendix. They are also graphically presented in Figure 2 through Figure 17 in the Appendix.

Experimental data on the weight increase by surface capillary action at various temperature levels are tabulated in Table 1 and are also graphically presented in Figure 2, showing that the weight increase by surface capillary action is practically independent of the temperature variation. All the experimental data on weight and volume gains at each given absorption time are assembled in Table 2 and also are graphically presented in Figure 2 and Figure 3. In order to find out the relationship between moisture gains and volume gains, the product of density of fluid and volume gain as a function of moisture gain, and the product of density of fluid and volume gain as a function of moisture gain from which the initial moisture gain by capillary action was subtracted, are plotted in Figures 4 and 5 which showing that exact linear relationship between the volume gain and the moisture gain.

In order to test the applicabilities of diffusion equations for the moisture gain and for the volume gain as a function of the square root of absorption time are plotted in Figure 7 and Figure 8,

showing the linear relationships between the moisture gain and the square root of absorption time and between the volume gain and the square root of absorption time. Slopes of linear regression lines at each temperature level in Figures 7 and 8 were statistically evaluated and are listed in Table 3.

Results on measurements of volume and surface area of a wheat kernel are assembled in Table 4. The moisture gain as a function of initial moisture content at 158° F and 86° F, and the volume gain as a function of initial volume content at 158° F and 86° F are plotted in Figures 9 and 10. These two figures indicate that the linear regressions on an effective surface moisture content of 0.765 gm./gm., and on an effective surface volume content of 1.05 cm.<sup>3</sup>/cm.<sup>3</sup> respectively.

Generalized correlations of data for the cases of moisture gain and volume gain are tabulated in Table 5 and they are also graphically presented in Figures 12 and 13, showing the high validity of diffusion equations for the mass and the volume.

Diffusion coefficients of mass and volume were calculated from the slopes obtained from Figures 7 and 8. The calculated diffusion coefficients of mass and volume are assembled in Table 6. They are also graphically illustrated as a function of the reciprocal of absolute temperature in Figure 14 through Figure 17. The diffusion constants, and the energies of activation in the Arrhenius relation for mass and volume obtained from Figure 14 through Figure 17 are assembled in Table 7. Statistical analyses of data on this study are summarized in Table 8.

## DISCUSSION AND CONCLUSION

## The Relation Between the Moisture Gain and the Volume Gain.

As mentioned in the introduction, one of the objects of this experiment was to find out whether there is a definite relation between the moisture gain and the volume gain. Grosh and Milner (6) indicated that cracks are initiated in wheat by the tempering process. The X-ray studies done by Grosh and Milner (6) confirmed the presence of transverse and radial primary cracks. Observations of the concentration of moisture at the cracks in the early stages of wetting and the section wetting of endosperm portions bounded by these cracks provide additional evidence that these cracks are formed in the kernel as a result of tempering. Also their observations showed that water moves into the endosperm through cracks, and after long period of wetting or in mealy kernels, cracking phenomenon is of no significance. Cracks provide pathways for the penetration of water. Pence (10) stated that the wheat kernel can expand due to the increase in moisture content. If this evidence is true, there should be a definite relation between the moisture gain and the volume gain and also it might be reasonable to assume that the volume gain was completely accounted for the mass of water entering the wheat kernel.

By comparison of the two sets of curves in Figures 2 and 3, it appears that qualitatively the curves for weight and for volume are identical. This indicates that there is a definite linear relationship between weight changes and volume changes.

The product of fluid density and volume change at the end of each absorption time as a function of weight change, for all temperature levels, is plotted in Figure 4. It has been known that a very rapid initial moisture gain is due to another phenomenon rather than slow diffusion into the interior of the kernel. Initial moisture gain by capillary action, 3.0 percent (wet basis), has been subtracted from the average weight gain, and then the product of fluid density and volume change as a function of weight change for all temperature levels is shown in Figure 5. Except for a few points, most of the data are in close agreement with the 45 degree-line which represents that the volume change is exactly equal to the weight change. The few deviations from 45 degree-line might have resulted from the fact that the cracking phenomenon, which would increase the volume of kernels, became of no significance at the higher temperatures and the longer periods of immersion.

In order to confirm that the product of volume change and water density is identical with the weight change, all the data were statistically analyzed by using the IBM 650, automatic computing machine (13). First, the sample correlation coefficients,  $r_b$ , of the line on Figures 4 and 5 were evaluated. The sample correlation coefficients  $r_b$  of the lines of Figures 4 and 5 were found to be 0.9995 and 0.994 respectively. These values highly signified a perfect linear correlation between the volume change and the weight change. Next, the hypothesis that  $\beta = 1$ , where  $\beta$  is the slope of the regression line, was tested against  $b$  where  $b$  is the sample regression coefficient (slope) by using formula,  $t = \frac{b - \beta}{S_b}$  (13). "t" is the deviation of the estimated slope from

that of the population measured in terms of  $S_p$  as the unit, and  $S_p$  is the sample standard error of regression coefficient. The sample regression coefficients for lines in Figures 4 and 5 were found to be 0.9990 and 0.9980 respectively. By using the table of "t" - distribution in Snedecor (13), the hypothesis,  $\beta = 1$  was accepted at 0.05 level and also 0.01 level. This test definitely indicates that the product of water density and volume change is identical with the weight change. The results of the statistical analyses are summarized in Table 8.

This relation between the weight change and the volume change will be useful in developing the integral diffusion equation for volume.

#### Correlations of Data on the Weight and Volume Gains

As described in the section of theory, mathematical analysis (1) of the non-stationary state of diffusion in solids of arbitrary shape shows that at times in the neighborhood of  $\theta = 0$  and under the conditions

$$m = m_0 \quad \text{at } \theta = 0 \quad (19)$$

$$m = m_s \quad \text{at the bounding surface} \quad \text{at } \theta > 0$$

$$D_m = \text{constant}$$

the integral diffusion equation is of the general form (2) where

$$\bar{M} = 1 - 2/\sqrt{\pi} X_m + BX_m^2 \quad (20)$$

$$\bar{M} = \frac{m_s - \bar{m}}{m_s - m_0}, \quad X_m = S/V \sqrt{D_m \theta}$$

and

$M_0$  = initial moisture content, dry basis-----gm./gm.

$\bar{m}$  = average moisture content at a given  
absorption time, dry basis-----gm./gm.

$m_s$  = effective moisture content at bounding  
surface at times greater than zero,  
dry basis-----gm./gm.

$\theta$  = absorption time-----sec.

$S$  = area of bounding surface-----cm.<sup>2</sup>

$V$  = volume of a wheat kernel-----cm.<sup>3</sup>

$D_m$  = diffusion coefficient of mass-----cm.<sup>2</sup>/sec.

$B$  = dimensionless constant.

Since it has been shown that the volume increase of the wheat kernel during a steeping process corresponds exactly to the volume of moisture entering the wheat kernel, the non-stationary-state diffusion equation of solids for arbitrary shape, equation 15, may be applied in the case of volume change.

At the vicinity of  $\theta = 0$  and under the conditions that

$$V = v_0 \text{ at } \theta = 0$$

$$v = v_s \text{ at the bounding surface, at } \theta = 0$$

$$D_v = \text{constant.}$$

The integral diffusion equation for the case of volume should be, by analogy, of the general form:

$$\bar{V} = 1 - 2/\pi \times X_v + B'X_v^2 \quad (22)$$

where

$$\bar{V} = \frac{v_s - \bar{V}}{v_s - v_0} \quad X_v = S/V \sqrt{D_v \theta}$$

and

$v_0$  = initial volume content, dry basis-----cm<sup>3</sup>/cm<sup>3</sup>

$\bar{v}$  = average volume content at a given absorption time, dry basis-----cm<sup>3</sup>/cm<sup>3</sup>

$v_s$  = effective volume content at the bounding surface at times greater than zero, dry basis-----cm<sup>3</sup>/cm<sup>3</sup>

$D_v$  = diffusion coefficient of volume-----cm<sup>2</sup>/sec.

$B'$  = dimensionless constant

at small values of  $X_m$  and  $X_v$  equations 20 and 22 approximate to:

$$1 - \bar{m} = 2/\sqrt{\pi} X_m \quad (23)$$

and

$$1 - \bar{v} = \frac{2}{\sqrt{\pi}} X_v \quad (24)$$

or, in terms of the experimental variables,

$$\bar{m} - m_0 = K_m \sqrt{\theta} \quad (25)$$

and

$$\bar{v} - v_0 = K_v \sqrt{\theta} \quad (26)$$

where

$$K_m = 2/\sqrt{\pi} (m_s - m_0) S/V \sqrt{D_m}$$

and

$$K_v = 2/\sqrt{\pi} (v_s - v_0) S/V \sqrt{D_v}$$

Therefore, if diffusion equations are applicable, at small values of  $X_m$  and  $X_v$  the moisture gain and volume gain of a wheat kernel

during a steeping process should be approximately proportional to the square root of the absorption time. Figures 7 and 8 show that such a relation was indeed obeyed. The curves for the volume gain in Figure 8 extrapolate to zero volume gain at time zero. However, the curves for the moisture gain (Fig. 7) did not extrapolate to zero moisture gain at time zero, but to an intercept,  $\bar{m}_1$ , initial moisture gain by capillary action. The experimental data were analyzed statistically to obtain the slopes,  $K_m$ ,  $K_v$ , and the intercepts  $\bar{m}_1$  of the linear regression of the moisture gain and the volume gain on the square root of the absorption time. The results of slopes,  $K_m$  and  $K_v$  of linear regression of the moisture gain and the volume gain on the square root of the absorption time are presented in Table 3.

#### The Initial Moisture Gain, $\bar{m}_1$

If the linear relation between the moisture gain and the square root of the absorption time indeed signifies obedience to Fick's law with a constant diffusion coefficient, then the occurrence of the non-zero intercept  $\bar{m}_1$  would mean that there was a very rapid initial absorption of water which was due to another phenomenon rather than slow diffusion into the interior of the wheat kernel. The nature of the phenomenon may be explained from the structure of the wheat kernel, for the outer most layer, the pericarp, is highly porous and should quickly become saturated by capillary action (2). Jones (8) was the first to distinguish this aspect of liquid water absorption by wheat. Therefore, it appears that the intercept,  $\bar{m}_1$  was the amount of water required for

saturation of the pericap. The value of the average initial moisture gain by capillary action in these experiments was 0.0358 gm./gm. (dry basis) for Ponca wheat whose initial moisture content was 0.1559 gm./gm. (dry basis) as shown in Table 1 and Figure 6. It was found through experiments that the initial moisture gain by capillary action was independent of temperature variation. Pence and Swanson's observations (11) confirmed that the initial stages of penetration of water are not affected by temperature change. (See Figure 6)

The Effective Surface Moisture Content,  $M_s$ , and The Effective  
Surface Volume Content,  $V_s$

Equations 23 and 25 show that if the diffusion coefficient of the mass is independent of moisture content in the range studied, the product of the slope,  $k_m$ , in Figure 7 and the kernel volume-to-surface ratio  $V/S$  should be a linear function of the initial moisture content and should extrapolate to an intercept,  $m_0 = m_s$  at  $K_m V/S = 0$ , where  $m_s$  is the effective moisture gain,  $\bar{m} - m_0$  should be a linear function of the initial moisture content and should extrapolate to an intercept  $m_0 = m_s$  at  $\bar{m} - m_0 = 0$ .

The moisture gains at 86° F and 158° F for fifteen minutes of absorption time were determined at a large number of initial moisture contents. Figure 9 shows that the data fulfilled the above expectation reasonably well, and indicated that the effective moisture content at the surface of a wheat kernel immersed in liquid water was approximately 0.765 gm./gm.. Becker (2) found

$m_s$  to be approximately 0.75 gm./gm. at 22° C (72° F) for a constant absorption time of fifteen minutes.

In the case of the volume study, equations 24 and 26 also show that if the diffusion coefficient of volume is independent of volume content in the range studied,  $K_v V/S$  should be a linear function of the initial volume content and should extrapolate to an intercept  $v_o = v_s$  at  $K_v V/S = 0$ , where  $V_s$  is the volume gain,  $\bar{v} - v_o$ , should be a linear function of the initial volume content and should extrapolate to an intercept  $v_o = v_s$  at  $\bar{v} - v_o = 0$ .

The volume gain at 86° F and 158° F for a constant absorption time of fifteen minutes was also determined at a large number of initial volume contents. The initial volume content was expressed as the volume of water in the initial wheat per unit volume of dry wheat ( $\text{cm}^3/\text{cm}^3$ ). Figure 10 shows that the data well agreed above expectation, and indicates that the effective surface volume content of a wheat kernel immersed in liquid water was approximately  $1.05 \text{ cm}^3/\text{cm}^3$ . It may be worthwhile to point out that the ratio of the effective surface volume content to the effective surface moisture content,  $v_s/m_s$ , should be identical with the ratio of the density of wheat to the density of water,  $\frac{\rho_{\text{wheat}}}{\rho_{\text{H}_2\text{O}}}$ . Experimental values of  $v_s/m_s$ , and  $\frac{\rho_{\text{wheat}}}{\rho_{\text{H}_2\text{O}}}$  were 1.373 and 1.375 respectively. These two values are practically identical.

#### The Volume to the Surface Area Ratio, $V/S$

The volume to surface area ratio was evaluated by using the formula (1),  $V/S = \psi r_v/3$ , where  $\psi/5$  is the ratio of the surface area of a sphere of equal volume to the surface area of the solid,

(  $\psi = \frac{4\pi r_v^2}{S}$  ), and is a shape factor commonly known as the sphericity, and  $r_v$  is the radius of a sphere with volume equal to that of the wheat kernel. It can be assumed that the sphericity of a swelling solid is constant, unless swelling is unusually anisotropic. Since the porosity is closely related to the sphericity, the porosity could be used as the sole determining factor of sphericity.

Experiments were carried out at several temperature levels in order to determine the porosity by using the packed bed column (See Figure 1). The porosity of the bed for purpose of calculation was defined as the void space between the particles, (not including any void spaces within the particles) divided by the total volume of the bed. The experimental values of porosity were in the range 0.38 to 0.482. Since there are several variables such as particle diameter, column diameter, particle size distribution, particle shape, and method of charging believed to influence the porosity in the bed, in no case could the results of porosity measurement be duplicated exactly. The study of porosity showed that porosity was practically independent of time and also temperature variation, but at temperatures above 140° F there was a slight tendency for the porosity to increase with increasing absorption time. The average value of the porosity, 0.45, was used to estimate particle sphericity from Figure 11 (3), assuming that the type of packing in the bed was "loose" packing. The estimated sphericity at a porosity of 0.45 was approximately 0.91 from Figure 11. This value of the sphericity is exactly identical with that estimated

by Becker (1). Using this sphericity, 0.91 and  $r_v$  estimated from known data for volume at the end of each absorption time, the volume to surface area ratio was evaluated. The volume to the surface area ratio increased slightly with increasing absorption time. Rigorously speaking, therefore, the treatment of  $V/S$  as a constant would not be permitted. But the volume to the surface area ratio was treated as a constant in order to satisfy one of the assumptions made in deriving the diffusion equations. Two different values of the constant  $V/S$ , the initial  $V/S$  and the average  $V/S$ , were used in evaluating diffusion coefficients of mass and volume for the Arrhenius relation for the sake of checking the effect of  $V/S$  variation. The estimated initial  $V/S$  was 0.0547 cm. The values of the average  $V/S$  at each temperature level are presented in Table 4.

#### General Correlations of Data on the Weight and Volume Gains

Figures 12 and 13 show general correlation of all the data on the moisture gain and the volume gain for temperatures in the range 80° F to 179° F, initial moisture content of 0.1559 gm./gm., dry basis, and initial volume content of 0.2242 cm<sup>3</sup>/cm<sup>3</sup>. The correlating parameters in the case of moisture gain were calculated from  $1 - \bar{M} = \frac{\bar{m} - m_0 - \bar{M}_1}{m_s - m_0}$  and  $X_m = S/V \sqrt{D_m \theta}$ . Equation 23 can therefore, be used for practical prediction of the moisture gain as a function of the independent variables. The correlating parameters in the case of volume gain were also calculated from  $1 - \bar{V} = \frac{\bar{v} - v_0}{v - v_0}$  and  $X_v = S/V \sqrt{D_v \theta}$ . Similarly, equation 24 can be,

therefore, used for practical prediction of the volume gain as a function of the independent variables. Figures 12 and 13 give a definite indication of the accuracy with which such predictions can be made.

In order to test the validity of equation 23 for the moisture gain and equation 24 for the volume gain, all the data were also statistically analyzed using the IBM 650, automatic digital computer (13). First, the sample correlation coefficient,  $r_b$  between dimensionless factors,  $1 - \bar{M}$  and  $X_m$ , and the sample correlation coefficient,  $r_b$  between dimensionless factors,  $1 - \bar{V}$  and  $X_v$  were evaluated. The sample correlation coefficients between  $1 - \bar{M}$  and  $X_m$ , and between  $1 - \bar{V}$  and  $X_v$  were 0.997 respectively. Both values of the sample correlation coefficient signified almost perfect linear correlation between them. Next, the hypothesis,  $\beta = 2/\sqrt{\pi}$ , (slope of equations 23 and 24) was tested against  $b$ , where  $b$  is the sample regression coefficient of Figure 12 or that of Figure 13, by using formula,  $t = \frac{b - \beta}{S_b}$  (13). The sample regression coefficients evaluated for Figures 12 and 13 were 1.1127 and 1.1225 respectively. By using the table of "t" distribution in Snedecor (13), the hypothesis,  $\beta = 2/\sqrt{\pi}$  or 1.1283 was accepted at 0.05 level and also 0.01 level for both Figures 12 and 13. The tests of the hypothesis indicated high validity of equation 23 for the moisture gain and equation 24 for the volume gain.

Finally, it should be noted that the applicability of equations 23 and 24 over the entire range of experimentation is partly due to the prior assumption of their validity made to

define the basis for treatment of the data. Therefore, because the analyses were prejudiced in their favor, equations 23 and 24 should be regarded as imperfect, though highly expedient, approximations to general solutions.

The Diffusion Coefficient of Mass,  $D_m$  and the Diffusion Coefficient of Volume,  $D_v$

The diffusion coefficient of mass,  $D_m$ , is given directly by equations 23 and 25, once the effective surface moisture content is known ( $D_m = \left( \frac{\sqrt{\pi}}{2} \frac{V/S}{m_s - m_0} \right)^2$ ). The diffusion coefficient of volume  $D_v$  can be evaluated by equations 24 and 25, after the effective surface volume content is known ( $D_v = \left( \frac{\sqrt{\pi}}{2} \frac{V/S}{\frac{V}{V_s} - \frac{V}{V_0}} \right)^2$ ). The diffusion coefficient of mass  $D_m$  and the diffusion coefficient of volume  $D_v$  were calculated by using the initial  $V/S$  and the average  $V/S$  as mentioned in a previous section. Figures 14, 15, 16, and 17 show diffusion coefficients calculated from the present data as a function of the reciprocal of the absolute temperature. The values of diffusion coefficient, which covered a wide range of temperature, gave for the energy of activation in the Arrhenius relation  $D = D_0 e^{-\frac{E}{RT}}$ , where  $E$  is the energy of activation,  $R$  is the universal gas constant, and  $T$  is the absolute temperature. The constants  $D_0$ , and the slopes ( $E/R$ ) of the linear regression lines of the Arrhenius relation for mass and volume were estimated by the method of least squares. The values of the energy of activation found were 13.012 K. cal./mole for  $D_m$  based on the initial  $V/S$ , on 14.216 K. Cal./mole for  $D_m$  based on the average  $V/S$ . 11.813 K. cal./mole for  $D_v$  based on the average  $V/S$ .

It can be seen that the linear regression lines in Figure 14

and Figure 16 give poor correlations by the Arrhenius relation.  $D_m$  and  $D_v$  at higher temperature deviate remarkably from the linear regression lines obtained by the method of least squares. Careful inspections of Figures 16 and 14 indicate that the plots of the Arrhenius relation show the definite curvature. However, the data from these non-linear relationships in Figures 14 and 16 were divided into two parts, and each of these parts was treated separately using the method of least squares. The results obtained were two straight lines on each plot which were in close agreement with the Arrhenius relation.

As mentioned previously in discussion the  $V/S$  ratio, two different values of the constant  $V/S$ , the initial  $V/S$  and the average  $V/S$ , were used in evaluating diffusion coefficients of mass and volume for the Arrhenius relation, for the sake of checking the effect of  $V/S$  variation. Each of Figures 14 through 17 gives two distinct plots, one based on the initial  $V/S$ , and the other based on the average  $V/S$ . It is difficult to determine which plot gives the better Arrhenius relation since statistically the slopes are very nearly the same for each plot, and by careful inspection the scatter of points for each plot appears to be nearly identical.

The values of the activation energies for the diffusion coefficients of the mass and volume based on the initial  $V/S$  and the average  $V/S$  are presented in Table 6. The activation energy at temperatures above  $150^\circ F$  was almost twice as much as the activation energy at temperatures below  $150^\circ F$  for both the volume and mass diffusion. It may be worthwhile to point out that two linear regression lines of the Arrhenius relation in Figure 13 and Figure

15 intercept each other at the temperature of  $150^{\circ}$  F.

Frost and Pearson (5) stated that the occurrence of two linear regression lines of the Arrhenius relation can result if there are two competing mechanisms or reactions with different activation energies and is often observed where the same reaction may occur both homogeneously and heterogeneously. The homogeneous mechanism usually has a higher activation energy and so it is favored at high temperatures, whereas the heterogeneous mechanism predominates at lower temperatures.

It has been known that the gelatinization of starch occurs at the vicinity of  $150^{\circ}$  F. Exact gelatinization temperature is a characteristic of the variety of starch, and also depends on the pH of water (9). Due to the gelatinization, the wheat kernel became softer, the water penetration might be more uniform throughout the wheat kernel. At temperatures above  $150^{\circ}$  F water might directly penetrate into the wheat kernel through endosperm rather than through cracks. Therefore, it is quite possible that at temperatures above  $150^{\circ}$  F the homogeneous mechanism would follow after the heterogeneous mechanism would proceed in steeping of the wheat kernel. It may be noteworthy that two linear lines of the Arrhenius relation will be very useful to evaluate the gelatinization temperature.

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## BIBLIOGRAPHY

1. Becker, H. A.  
A study of diffusion in solids of arbitrary shape, with application to the drying of the wheat kernel. J. Applied polymer Science. 1: 212-226 (1959).
2. Becker H. A.  
On the absorption of liquid water by the wheat kernel. National Research Council, Saskatoon: Issued as N. R. C. No. 0000.
3. Brown, G. G.  
Unit operations. New York: John Wiley and Sons, Inc., 1951.
4. Fraser, C. W.  
Factors that influence the rate of absorption of water by wheat. Cereal Chemistry 9: 45-49 (1932).
5. Frost, A. A. and R. G. Pearson  
Kinetics and mechanism. New York: John Wiley and Sons, Inc., 1958.
6. Grosh, G. M. and M. Milner  
Water penetration and internal cracking in tempered wheat grains. Cereal Chemistry .36: 260-273 (1959).
7. Grosh, G. M. and M. Milner  
The penetration of moisture into the wheat kernel. Milling Production, October 1955.
8. Jones, C. R.  
Observations on the rate of penetration of water into the wheat grain. Milling 113, 4: 80-86 (1949).
9. Kerr, R. W.  
Chemistry and industry of starch. Second edition, New York: Academic Press, 1950.
10. Pence, R. O.  
Physical changes in wheat during tempering. Assoc. Operative Millers Bulletin, 2: 129-134 (1937).
11. Pence, R. O. and C. O. Swanson  
Rate of water penetration in wheat during tempering. Assoc. Operative Millers Bulletin, 316 (1930).

12. Perry, J. H.  
Chemical engineer's handbook. Third edition, New York:  
McGraw - Hill, 1950.
13. Snedecor, G. W.  
Statistical methods. Fifth edition, Ames: The Iowa  
State College Press, 1956.
14. Swanson, E. C.  
Cereal laboratory Methods, Sixth edition, St. Paul:  
American Association of Cereal Chemists, Inc., 1957.

**APPENDIX**

## TABLES

Table 1. Weight increase by surface capillary action.

Temp. ° F.	W <sub>0</sub> gm.	W <sub>f</sub> gm.	% increase (wet basis)	% increase (dry basis)
80	20.00	20.57	2.8	3.294
	20.00	20.53	2.6	3.063
85	20.00	20.57	2.80	3.294
	20.00	20.57	2.80	3.294
90	20.00	20.65	3.14	3.756
	20.00	20.65	3.14	3.756
100	20.00	20.57	2.80	3.294
	20.00	20.65	3.14	3.756
110	20.00	20.57	2.80	3.294
	20.00	20.70	3.38	4.045
119	20.00	20.65	3.14	3.756
	20.00	20.75	3.61	4.334
Average		20.62	3.00	3.583

Table 2. Experimental data on weight and volume gains.

Run No.	Temp. °F.	Time min.	$W_f$ grams	$m$ gm. gm.	$V_f$ cm. <sup>3</sup>	$v$ cm. <sup>3</sup> /cm. <sup>3</sup>
1	80	0	20.00	0.1559	14.76	0.2242
		5	20.89	0.2074	15.71	0.3054
		10	21.47	0.2409	16.30	0.3518
		20	21.65	0.2513	16.50	0.3684
		30	21.87	0.2640	16.70	0.3850
		45	22.30	0.2888	17.15	0.4223
		60	22.38	0.2935	16.80	0.3933
		120	24.37	0.4084	19.0	0.5757
		240	24.99	0.4443	19.5	0.6172
		300	25.18	0.4553	19.7	0.6338
		420	26.05	0.5055	20.6	0.7084
2	80	0	20.00	0.1559	14.76	0.2242
		5	20.89	0.2074	15.71	0.3054
		10	21.47	0.2409	16.30	0.3518
		20	21.65	0.2513	16.25	0.3684
		30	21.87	0.2640	16.70	0.3850
		45	22.30	0.2888	17.15	0.4223
		60	22.38	0.2935	16.50	0.3682
		180	25.46	0.4715	19.10	0.5840
		240	25.94	0.4992	19.60	0.6255
		300	26.30	0.5200	19.90	0.6504
		420	27.28	0.5766	20.90	0.7333

Table 2. (cont'd)

Run No.	Temp. °F.	Time min.	$W_f$ grams	$M$ gm. gm.	$V_{f_3}$ cm. <sup>3</sup>	$v$ cm. <sup>3</sup> /cm. <sup>3</sup>
9	85	0	20.00	0.1559	14.76	0.2242
		5	21.10	0.2195	15.88	0.3170
		10	21.60	0.2484	16.40	0.3601
		20	21.80	0.2599	16.60	0.3767
		30	22.00	0.2715	16.80	0.3933
		45	22.40	0.2946	17.20	0.4265
		60	22.90	0.3232	17.70	0.4679
		120	23.55	0.3611	18.30	0.5173
		180	25.55	0.4766	20.40	0.6918
		240	26.25	0.5171	21.20	0.7582
8	90	0	20.00	0.1559	14.76	0.2242
		5	21.29	0.2304	16.08	0.3336
		10	21.57	0.2466	16.35	0.3560
		20	21.80	0.2599	16.60	0.3767
		30	22.07	0.2755	16.88	0.3999
		45	22.57	0.3044	17.35	0.4389
		60	23.07	0.3333	17.80	0.4762
		120	24.43	0.4119	19.10	0.5840
		180	25.70	0.4853	20.40	0.6918
		240	26.26	0.5177	20.90	0.7330
360	27.50	0.5893	22.20	0.8411		

Table 2. (cont'd)

Run No.	Temp. °F.	Time min.	$W_f$ grams	$\bar{m}$ gm.gm.	$V_{f_3}$ cm. <sup>3</sup>	$\bar{v}$ cm. <sup>3</sup> /cm. <sup>3</sup>
4	100	0	20.00	0.1559	14.76	0.2242
		15	21.90	0.2657	16.70	0.3850
		30	22.40	0.2946	17.20	0.4596
		60	23.30	0.3466	18.20	0.5094
		90	24.20	0.3986	19.00	0.5757
		120	25.53	0.4755	20.00	0.6587
		180	26.50	0.5316	29.00	0.7333
		240	27.23	0.5737	21.00	0.7914
		360	28.16	0.6275	22.60	0.8743
6	116	0	20.00	0.1559	14.76	0.2242
		5	21.60	0.2484	16.37	0.3576
		10	22.20	0.2831	17.00	0.4100
		20	22.95	0.3264	17.75	0.4721
		30	23.20	0.3408	18.00	0.4928
		45	23.90	0.3819	18.70	0.5509
		60	25.17	0.4547	19.80	0.6421
		120	27.47	0.5876	21.70	0.7997
		180	28.31	0.6362	22.60	0.8743
		240	28.80	0.6645	23.10	0.9158
		360	30.20	0.7454	24.90	1.0650

Table 2. (cont'd)

Run No.	Temp. °F.	Time min.	$W_f$ grams	$M$ gm./gm.	$V_f$ cm. <sup>3</sup>	$\bar{v}$ cm. <sup>3</sup> /cm. <sup>3</sup>
12	120	0	20.00	0.1559	14.76	0.2242
		15	22.70	0.3119	17.50	0.4513
		30	23.40	0.3524	18.20	0.5094
		45	24.10	0.3929	18.90	0.5674
		60	24.80	0.4333	19.60	0.6255
		120	26.30	0.5200	21.10	0.7499
		180	28.26	0.6333	22.50	0.8660
		240	28.71	0.6593	23.00	0.9075
		360	29.90	0.7280	24.20	0.0070
15	130	0	20.00	0.1559	14.76	0.2242
		5	21.95	0.2686	16.78	0.3916
		10	22.40	0.2946	17.27	0.4323
		20	23.23	0.3426	18.10	0.5011
		30	23.90	0.3818	18.75	0.5550
		45	24.68	0.4264	19.55	0.6213
		60	25.60	0.4795	20.45	0.6960
		120	27.80	0.6067	22.50	0.8660
		180	29.05	0.6789	23.70	0.9655
		240	30.00	0.7338	24.60	0.0401
		300	31.00	0.7916	25.60	1.1231
		360	31.80	0.8378	26.50	1.1977
		420	32.65	0.8869	27.30	1.2641

Table 2. (cont'd)

Run No.	Temp. °F.	Time min	$W_f$ grams	$\bar{m}$ gm./gm.	$V_f$ cm. <sup>3</sup>	$\bar{v}$ cm. <sup>3</sup> /cm. <sup>3</sup>
13	140	0	20.00	0.1559	14.76	0.2242
		5	21.90	0.2659	16.80	0.3933
		10	22.48	0.2992	17.40	0.4431
		20	23.40	0.3524	18.32	0.5193
		30	24.27	0.4027	19.25	0.5965
		45	25.17	0.4547	20.15	0.6711
		60	26.15	0.5113	21.00	0.7416
		120	28.45	0.6634	23.28	0.9307
		180	30.05	0.7367	24.80	1.0567
		240	31.50	0.8205	26.20	1.1728
	360	33.93	0.9609	28.60	1.3719	
19	140	0	20.00	0.1559	14.76	0.2242
		5	21.90	0.2659	16.80	0.3933
		10	22.48	0.2992	17.40	0.4431
		20	23.40	0.3524	18.32	0.5193
		30	24.27	0.4027	19.25	0.5965
		45	25.17	0.4547	20.15	0.6711
		60	27.10	0.5662	21.75	0.8038
		120	29.90	0.7280	24.35	1.0194
		180	31.80	0.8378	26.00	1.1563
		240	33.10	0.9130	27.20	1.2558
	360	33.80	0.9534	28.20	1.3387	

Table 2. (cont'd)

Run No.	Temp. : °F.	Time : min.	W <sub>f</sub> : grams	$\bar{m}$ : gm.gm.	V <sub>f</sub> : cm. <sup>3</sup>	$\bar{v}$ : cm. <sup>3</sup> /cm. <sup>3</sup>
16	150	0	20.00	0.1559	14.76	0.2242
		5	22.38	0.2935	17.20	0.4265
		10	23.23	0.3425	18.10	0.5011
		20	24.20	0.3986	19.05	0.5799
		30	25.58	0.4784	20.45	0.6960
		45	26.71	0.5437	21.52	0.7847
		60	27.80	0.6067	22.45	0.8619
		120	30.20	0.7454	24.85	1.0609
		180	31.90	0.8436	26.50	1.1977
		240	34.10	0.9707	28.60	1.3718
		300	35.77	1.0673	30.35	1.5170
		360	36.63	1.1170	30.90	1.5626
420	37.30	1.1557	31.50	1.6124		
14	158	0	20.00	0.1559	14.76	0.2242
		5	22.60	0.3062	17.40	0.4431
		10	23.60	0.3640	18.43	0.5285
		20	24.85	0.4362	19.70	0.6338
		30	26.35	0.5229	21.20	0.7582
		45	27.30	0.5778	22.15	0.8370
		60	28.70	0.6587	23.25	0.9282
		120	32.35	0.8688	26.85	1.2267

Table 2. (cont'd)

Run No.	Temp. : °F.	Time : min.	$W_f$ : grams	$\bar{m}$ : gm.gm.:	$V_f$ : cm. <sup>3</sup>	$\bar{v}$ : cm. <sup>3</sup> /cm. <sup>3</sup>
14	158	180	35.50	1.0516	30.00	1.4880
		240	36.80	1.1268	31.32	1.5974
		300	38.85	1.2453	32.98	1.7351
		360	41.03	1.3712	34.90	1.8943
		420	41.85	1.4186	35.85	1.9731
17	170	0	20.00	0.1559	14.76	0.2242
		5	22.80	0.2877	17.75	0.4721
		15	25.20	0.4564	20.10	0.6587
		30	20.10	0.6240	22.60	0.8743
		45	29.70	0.7165	24.30	1.0153
		60	31.05	0.7945	25.60	1.1231
		120	36.45	1.1065	30.90	1.5626
		180	40.70	1.3520	34.95	1.8985
		240	43.25	1.4990	37.45	2.1058
		300	46.70	1.6990	41.15	2.4126
420	49.90	1.8840	44.50	2.6905		
18	179	0	20.00	0.1559	14.76	0.2242
		5	23.30	0.3466	18.10	0.5011
		15	26.30	0.5200	21.00	0.7416
		30	29.00	0.6760	23.80	0.9738
		45	30.80	0.7800	25.30	1.0982

Table 2. (cont'd)

Run :	Temp. :	Time :	$W_f$ :	$\bar{m}$ :	$V_f$ :	$\bar{v}$
No. :	$^{\circ}\text{F.}$ :	min. :	grams :	gm.gm. :	$\text{cm.}^3$ :	$\text{cm.}^3/\text{cm.}^3$
18	179	60	32.80	0.8956	27.30	1.2641
		120	40.00	1.3117	34.00	1.8197
		180	46.15	1.6671	39.35	2.2634
		240	50.00	1.8896	43.20	2.5826
		300	54.10	2.1265	47.40	2.9309
		360	55.38	2.1959	49.80	3.1300

Table 3. Slopes of linear regression lines for  $\bar{m} - m_0$  vs.  $\sqrt{\theta}$  and  $\bar{v} - v_0$  vs.  $\sqrt{\theta}$

Run No.	Temp. °F.	$k_m \times 10^3$ * g./g.sec. <sup>1/2</sup>	$k_v \times 10^3$ + cm. <sup>3</sup> /cm. <sup>3</sup> sec. <sup>1/2</sup>
1	80	2.050	3.457
2	80	2.269	3.413
9	85	2.411	4.245
8	90	2.626	4.359
4	100	3.086	4.826
6	116	4.160	6.318
12	120	4.027	6.077
15	130	4.664	7.113
13	140	5.367	8.236
19	140	5.829	8.673
16	150	6.596	9.684
14	158	8.054	11.570
17	170	10.920	15.640
18	179	13.690	19.02

\*  $K_m$ , the slope of linear regression line for  $\bar{m} - m_0$  vs.  $\sqrt{\theta}$

+  $K_v$ , the slope of linear regression line for  $\bar{v} - v_0$  vs.  $\sqrt{\theta}$

Table 4. Results on measurements of volume and surface area of a wheat kernel.

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V^2}$	$S$
	$^{\circ}P$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{cm.^2}{cm.}$	cm. <sup>2</sup>
1*	80	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02628	0.1842	0.0559	17.889	0.4701
		10	0.02721	0.1863	0.0565	17.699	0.4816
		20	0.02755	0.1872	0.0568	17.605	0.4850
		30	0.02787	0.1880	0.0570	17.543	0.4889
		45	0.02863	0.1898	0.0576	17.361	0.4970
		60	0.02805	0.1888	0.0572	17.482	0.4904
		120	0.03172	0.1961	0.0595	16.806	0.5331
		240	0.03255	0.1881	0.0601	16.638	0.5416
		360	0.03289	0.1988	0.0603	16.583	0.5454
420	0.03439	0.2018	0.0612	16.339	0.5619		
2 <sup>x</sup>	80	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02628	0.1848	0.0559	17.889	0.4701
		10	0.02721	0.1863	0.0565	17.699	0.4816

\* The average  $\frac{V}{S} = 0.05781$  cm.

x The average  $\frac{V}{S} = 0.0579$  cm.

Table 4. (Cont'd.)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
2 <sup>x</sup>	80	20	0.02755	0.1872	0.0568	17.605	0.4850
		30	0.02788	0.1880	0.0570	17.543	0.4889
		45	0.02863	0.1885	0.0572	17.482	0.4904
		60	0.02755	0.1872	0.0568	17.605	0.4850
		180	0.03189	0.1970	0.0598	16.722	0.5333
		240	0.03272	0.1985	0.0602	16.611	0.5435
		300	0.03322	0.1996	0.0605	16.528	0.5491
		420	0.03489	0.2027	0.0615	16.260	0.5673
9*	85	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02650	0.1851	0.0561	17.825	0.4724
		10	0.02737	0.1870	0.0567	17.636	0.4827
		20	0.02771	0.1878	0.0570	17.543	0.4861
		30	0.02805	0.1885	0.0572	17.482	0.4904

\* The average  $\frac{V}{S} = 0.0579$  cm.

x The average  $\frac{V}{S} = 0.0585$  cm.

+ The average  $\frac{V}{S} = 0.05943$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
9*	85	45	0.02871	0.1899	0.0576	17.361	0.4984
		60	0.02954	0.1917	0.0581	17.211	0.5084
		120	0.03054	0.1939	0.0588	17.006	0.5194
		180	0.03405	0.2012	0.0610	16.393	0.5582
		240	0.03539	0.2051	0.0622	16.077	0.5690
8 <sup>x</sup>	90	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02684	0.1859	0.0564	17.730	0.4759
		10	0.1868	0.1868	0.0567	17.636	0.4813
		20	0.1885	0.1885	0.0572	17.482	0.4844
		30	0.1890	0.1890	0.0573	17.452	0.4918
		45	0.1907	0.1907	0.0578	17.301	0.5010
		60	0.1921	0.1921	0.0583	17.152	0.5098
		120	0.1970	0.1970	0.0598	16.722	0.5326

\* The average  $\frac{V}{S} = 0.0579$  cm. x The average  $\frac{V}{S} = 0.0585$  cm. + The average  $\frac{V}{S} = 0.05943$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_V$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
8 <sup>x</sup>	90	180	0.2011	0.2011	0.0610	16.393	0.5583
		240	0.2027	0.2027	0.0615	16.260	0.5673
		360	0.2070	0.2070	0.0628	15.923	0.5901
4+	100	0	0.02464	0.1803	0.0547	18.282	0.4505
		15	0.02788	0.1881	0.0571	17.513	0.4883
		30	0.02871	0.1900	0.0576	17.361	0.4984
		60	0.03033	0.1934	0.0587	17.035	0.5175
		90	0.03172	0.1961	0.0595	16.806	0.5331
		120	0.03339	0.1998	0.0606	16.501	0.5510
		240	0.03606	0.2049	0.0622	16.077	0.5797
		360	0.03773	0.2049	0.0622	16.077	0.6066
6*	116	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02733	0.1870	0.0567	17.636	0.4820
		10	0.02838	0.1892	0.0574	17.421	0.4944
* The average $\frac{V}{S} = 0.0579$ cm.    x The average $\frac{V}{S} = 0.0585$ cm.    + The average $\frac{V}{S} = 0.05943$ cm.							
* The average $\frac{V}{S} = 0.0599$ cm.    x The average $\frac{V}{S} = 0.06045$ cm.    + The average $\frac{V}{S} = 0.05943$ cm.							

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	$S^2$
	$^{\circ}P$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
6*	116	20	0.02963	0.11919	0.0582	17.094	0.5091
		30	0.03005	0.1929	0.0585	17.094	0.5137
		45	0.03122	0.1952	0.0592	16.891	0.5273
		60	0.03305	0.1991	0.0604	16.556	0.5472
		120	0.03623	0.2053	0.0623	16.051	0.5815
		180	0.03773	0.2082	0.0632	15.822	0.5970
		240	0.03856	0.2097	0.0636	15.723	0.6063
		360	0.04157	0.2150	0.0652	15.337	0.6376
12x	120	0	0.02464	0.1803	0.0547	18.282	0.4505
		15	0.02921	0.1911	0.0580	17.241	0.5036
		30	0.03038	0.1937	0.5088	17.006	0.5166
		45	0.03155	0.1961	0.0595	16.806	0.5302
		60	0.03273	0.1984	0.0602	16.611	0.5435

\* The average  $\frac{V}{S} = 0.0599$  cm.    x The average  $\frac{V}{S} = 0.06045$  cm.    + The average  $\frac{V}{S} = 0.05943$  cm.  
 x The average  $\frac{V}{S} = 0.06045$  cm.    \* The average  $\frac{V}{S} = 0.0615$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}P$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{cm.^2}{cm.^3}$	cm. <sup>2</sup>
12x	120	120	0.03522	0.2033	0.0617	16.207	0.5708
		180	0.03756	0.2078	0.0630	15.873	0.5962
		240	0.03840	0.2096	0.0636	15.723	0.6038
		360	0.04040	0.2130	0.0646	15.479	0.6254
15*	130	0	0.0264	0.1803	0.0457	18.282	0.4505
		5	0.03801	0.1884	0.0571	17.513	0.4905
		10	0.02883	0.1901	0.0577	17.331	0.4997
		20	0.03022	0.1932	0.586	17.064	0.5157
		30	0.03130	0.1956	0.0593	16.863	0.5278
		45	0.03264	0.1981	0.0601	16.638	0.5431
		60	0.03414	0.2012	0.0610	16.393	0.5597
		120	0.03755	0.2077	0.0630	15.873	0.5960
		180	0.03956	0.2114	0.0641	15.600	0.6171
		240	0.04107	0.2140	0.0649	15.408	0.6328

x The average  $\frac{V}{S} = 0.06045$  cm.    \* The average  $\frac{V}{S} = 0.0615$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_V$	$\frac{V}{S}$	$\frac{S}{V^2}$	$S$
:	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{cm.^2}{cm.^3}$	cm. <sup>2</sup>
15*	130	300	0.04274	0.2171	0.0659	15.174	0.6485
		360	0.04424	0.2191	0.665	15.037	0.6652
		420	0.04557	0.2217	0.0672	14.880	0.6781
13x	140	0	0.2464	0.1803	0.0547	18.282	0.4505
		5	0.02805	0.1885	0.0572	17.482	0.4904
		10	0.02905	0.1909	0.0579	17.271	0.5017
		20	0.03058	0.1941	0.0589	16.977	0.5192
		30	0.03214	0.1971	0.0598	16.722	0.5374
		45	0.03364	0.2004	0.0608	16.447	0.5533
		60	0.03506	0.2030	0.0616	16.233	0.5691
		120	0.03886	0.2101	0.0637	15.698	0.6100
		180	0.04140	0.2148	0.0652	15.337	0.6350
240	0.04374	0.2189	0.0664	15.060	0.6587		
x	The average $\frac{V}{S} = 0.0613$ cm.		* The average $\frac{V}{S} = 0.0616$ cm.				
x	The average $\frac{V}{S} = 0.06045$ cm.		* The average $\frac{V}{S} = 0.0615$ cm.				

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_V$	$\frac{V}{S}$	$\frac{S}{V^2}$	3
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{cm.^2}{cm.^3}$	cm. <sup>2</sup>
13x	140	360	0.04774	0.2250	0.0682	14.662	0.7000
19*	140	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02805	0.1885	0.0572	17.482	0.4904
		10	0.02905	0.1909	0.0579	17.271	0.5017
		20	0.03058	0.1941	0.0589	16.977	0.5192
		30	0.03214	0.1971	0.0598	16.722	0.5374
		45	0.03364	0.2004	0.0608	16.447	0.5553
		60	0.03631	0.2052	0.0622	16.077	0.5838
		120	0.04065	0.2134	0.0647	15.455	0.6282
		180	0.04340	0.2180	0.0661	15.128	0.6566
19*	140	240	0.04541	0.2213	0.0671	14.903	0.6767
		360	0.04708	0.2240	0.0679	14.727	0.6933
x The average $\frac{V}{S} = 0.0613$ cm.			* The average $\frac{V}{S} = 0.0616$ cm.				

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	$S$
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
16x	150	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02871	0.1901	0.0577	17.331	0.4976
		10	0.03022	0.1932	0.0586	17.064	0.5157
		20	0.03180	0.1967	0.0597	16.750	0.5327
		30	0.03714	0.2012	0.0610	16.393	0.5600
		45	0.03593	0.2048	0.0621	16.103	0.5786
		60	0.03748	0.2078	0.0630	15.873	0.5949
		120	0.04148	0.2149	0.0652	15.337	0.6362
		180	0.04424	0.2190	0.0664	15.060	0.6663
		240	0.04774	0.2250	0.0682	14.662	0.7000
		300	0.05067	0.2297	0.0697	14.347	0.7270
		360	0.05158	0.2310	0.0701	14.265	0.7358
		420	0.05259	0.2321	0.0704	14.204	0.7470
14*	158	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.02905	0.1909	0.0579	17.271	0.5017

\* The average  $\frac{V}{S} = 0.0616$  cm. x The average  $\frac{V}{S} = 0.0636$  cm. \* The average  $\frac{V}{S} = 0.0650$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
14*	158	10	0.03077	0.1944	0.0590	16.949	0.5215
		20	0.03289	0.1988	0.0603	16.583	0.5454
		30	0.03539	0.2038	0.0618	16.181	0.5726
		45	0.03698	0.2069	0.0628	15.923	0.5888
		60	0.03881	0.2101	0.0637	15.698	0.6092
		120	0.04482	0.2208	0.0670	14.925	0.6689
		180	0.05003	0.2289	0.0694	14.409	0.7216
		240	0.05229	0.2322	0.0704	14.204	0.7427
		300	0.05506	0.2360	0.0716	13.966	0.7690
		360	0.05826	0.2407	0.0730	13.698	0.7980
		420	0.05985	0.2428	0.0736	13.586	0.8131
17x	170	0	0.2464	0.1803	0.0547	18.282	0.4505
		5	0.02964	0.1920	0.0582	17.182	0.5093
		15	0.03355	0.2000	0.0607	16.474	0.5527

\* The average  $\frac{V}{S} = 0.0650$  cm.      x The average  $\frac{V}{S} = 0.0674$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_F$	$F_V$	$\frac{V}{S}$	$\frac{S}{V^2}$	S
	$^{\circ}F$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}}$	cm. <sup>2</sup>
17x	170	30	0.03773	0.2802	0.0632	15.822	0.5970
		45	0.04057	0.2132	0.0647	15.455	0.6270
		60	0.04274	0.2170	0.0658	15.197	0.6495
		120	0.05158	0.2310	0.0701	14.265	0.7358
		180	0.05835	0.2410	0.0731	13.679	0.7962
		240	0.06252	0.2461	0.0746	13.404	0.8380
		300	0.06870	0.2540	0.0770	12.987	0.8922
		420	0.07429	0.2610	0.0792	12.626	0.9380
18*	179	0	0.02464	0.1803	0.0547	18.282	0.4505
		5	0.03022	0.1933	0.0586	17.064	0.5157
		15	0.03506	0.2031	0.0616	16.233	0.5691
		30	0.03973	0.2118	0.0642	15.576	0.6188

\* The average  $\frac{V}{S} = 0.0692$  cm.

\* The average  $\frac{V}{S} = 0.0650$  cm.

x The average  $\frac{V}{S} = 0.0674$  cm.

Table 4. (cont'd)

Run No.	Temp.	Time	$V_p$	$r_v$	$\frac{V}{S}$	$\frac{S}{V}$	S
	$^{\circ}P$	min.	cm. <sup>3</sup>	cm.	cm.	$\frac{\text{cm.}^2}{\text{cm.}^3}$	cm. <sup>2</sup>
18*	179	45	0.04224	0.2162	0.0656	15.243	0.6439
		60	0.04557	0.2218	0.0673	14.858	0.6771
		120	0.05676	0.2381	0.0722	13.850	0.7861
		180	0.06569	0.2503	0.0759	13.175	0.8655
		240	0.07242	0.2582	0.0783	12.771	0.9210
		300	0.07913	0.2664	0.0808	12.376	0.9793
		360	0.08314	0.2706	0.0821	12.180	1.0126

\* The average  $\frac{V}{S} = 0.0692$  cm.

Table 5. Generalized correlations of data, using empirical relations for the diffusion coefficients on moisture gains and volume gains.

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
1	80	0.0258	0.05164	0.0983	0.0643
		0.0808	0.07304	0.1545	0.0909
		0.0978	0.10330	0.1746	0.1285
		0.1187	0.12650	0.1947	0.1574
		0.1594	0.15500	0.2333	0.1927
		0.1671	0.17890	0.2398	0.2226
		0.3557	0.25300	0.4256	0.3148
		0.3558	0.3578	0.4759	0.4451
		0.4327	0.4002	0.4960	0.4978
		0.5152	0.4735	0.5863	0.5890
2	80	0.0258	0.0571	0.0983	0.0625
		0.0808	0.0808	0.1545	0.0884
		0.9078	0.1143	0.1746	0.1251
		0.1187	0.1400	0.1947	0.1532
		0.1594	0.1714	0.12333	0.1876
		0.1671	0.1980	0.2333	0.2166
		0.4593	0.3429	0.4357	0.3752
		0.5048	0.3960	0.4859	0.4333
		0.5389	0.4427	0.5161	0.4844
		0.6319	0.5238	0.6164	0.5732

Table 5. (cont'd)

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
9	85	0.0456	0.0607	0.1123	0.0787
		0.0931	0.0859	0.1645	0.1113
		0.1120	0.1214	0.1847	0.1575
		0.1310	0.1487	0.2048	0.1928
		0.1689	0.1822	0.2450	0.2366
		0.2159	0.2104	0.2950	0.2727
		0.2781	0.2975	0.3549	0.3857
		0.4677	0.3644	0.5660	0.4724
		0.5362	0.4208	0.6466	0.5454
8	90	0.0635	0.0662	0.1324	0.0810
		0.0901	0.0936	0.1595	0.1145
		0.1120	0.1323	0.1846	0.1620
		0.1376	0.1621	0.2127	0.1984
		0.1850	0.1985	0.2648	0.2430
		0.2325	0.2293	0.3051	0.2806
		0.3615	0.3242	0.4356	0.3968
		0.4820	0.3971	0.5662	0.4860
		0.5350	0.4585	0.6164	0.5612
	0.6527	0.5616	0.7470	0.6873	
4	100	0.1215	0.1346	0.1947	0.1553
		0.1689	0.1904	0.2850	0.2197

Table 5. (cont'd)

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
4	100	0.2543	0.2693	0.3453	0.3107
		0.3397	0.3293	0.4256	0.3805
		0.4659	0.3808	0.5261	0.4393
		0.5580	0.4664	0.6164	0.5381
		0.6270	0.5386	0.6868	0.6213
		0.7154	0.6596	0.7872	0.7609
6	116	0.0931	0.1048	0.1615	0.1174
		0.1500	0.1482	0.2249	0.1661
		0.2211	0.2096	0.3000	0.2348
		0.2448	0.2567	0.3252	0.2876
		0.3123	0.3143	0.3956	0.3522
		0.4317	0.3630	0.5060	0.4067
		0.6489	0.5133	0.6968	0.5752
		0.7297	0.6287	0.7872	0.7045
		0.7762	0.7259	0.8375	0.8135
0.9090	0.8896	0.9181	0.9963		
12	120	0.1973	0.1757	0.2751	0.1956
		0.2638	0.2485	0.3453	0.2766
		0.3308	0.3044	0.4158	0.3388
		0.3966	0.5314	0.4859	0.3912
		0.5389	0.4970	0.6365	0.5532
		0.7249	0.6087	0.7771	0.6775

Table 5. (cont'd)

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
12	120	0.7676	0.7029	0.8274	0.7823
		0.8804	0.8609	0.9479	0.9581
15	130	0.1262	0.1175	0.2027	0.1322
		0.1689	0.1662	0.2519	0.1869
		0.2477	0.2350	0.3353	0.2643
		0.3112	0.2878	0.4000	0.3238
		0.3853	0.3525	0.4808	0.3965
		0.4725	0.4071	0.5713	0.4578
		0.6813	0.5757	0.7819	0.6475
		0.7998	0.7051	0.8976	0.7930
		0.8899	0.8141	0.9879	0.9157
		0.9848	0.9102	1.0880	1.0238
13	140	1.0607	0.9971	1.1788	1.1215
		1.1413	1.0770	1.2590	1.2114
		0.1215	0.1352	0.2047	0.1530
		0.1765	0.1912	0.2650	0.2164
		0.2638	0.2704	0.3573	0.3061
		0.3464	0.3312	0.4508	0.3749
		0.3417	0.4056	0.5411	0.4591
0.5247	0.4684	0.6263	0.5301		

Table 5. (cont'd)

Run No.	Temp. °P	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
13	140	0.7744	0.6624	0.8555	0.7497
		0.8947	0.8113	1.0081	0.9182
		1.0320	0.9368	1.1486	1.0603
		1.2628	1.1473	1.3897	1.2986
19	140	0.1215	0.1469	0.2047	0.1611
		0.1765	0.2077	0.2650	0.2279
		0.2638	0.2937	0.3573	0.3223
		0.3464	0.3597	0.4508	0.3947
		0.4318	0.4406	0.5411	0.4834
		0.6148	0.5088	0.7018	0.5582
		0.8804	0.7794	0.9629	0.7894
		1.0600	0.8812	1.1286	0.9669
1.1840	1.0180	1.2491	1.1164		
16	150	0.1671	0.16621	0.2449	0.1800
		0.2475	0.2350	0.3353	0.2545
		0.3397	0.3324	0.4307	0.3599
		0.4706	0.4071	0.5713	0.4408
		0.5778	0.4985	0.6784	0.5398
		0.6813	0.5757	0.7222	0.6234
		0.9090	0.8141	1.0132	0.8816
		1.0700	0.9971	1.1836	1.0797

Table 5. (cont'd)

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
16	150	1.2788	1.1513	1.3896	1.2467
		1.437	1.2672	1.5654	1.3940
		1.519	1.4101	1.6206	1.5270
14	158	0.1880	0.2030	0.2651	0.2153
		0.2829	0.2871	0.3685	0.3045
		0.4014	0.4060	0.4959	0.4306
		0.5437	0.4973	0.6470	0.5274
		0.6339	0.6090	0.74203	0.6459
		0.7667	0.7032	0.8825	0.7458
		1.1116	0.9945	1.2139	1.0547
		1.4117	1.2180	1.5303	1.2918
		1.5350	1.4065	1.6628	1.4916
		1.7296	1.5725	1.830	1.6676
1.936	1.7226	2.022	1.8268		
	2.0142	1.8606	2.1177	1.9732	
17	170	0.2556	0.2750	0.3002	0.2906
		0.4346	0.4764	0.5261	0.5034
		0.7097	0.6737	0.7871	0.7120
		0.8615	0.8251	0.9579	0.8720
		0.9896	0.9528	1.0885	1.0069
		1.5018	1.3473	1.6206	1.4240

Table 5. (cont'd)

Run No.	Temp. °F	$1-\bar{M}$	$X_{ml}$	$1-\bar{V}$	$X_{vl}$
17	170	.9048	1.6543	2.0274	1.7439
		2.1462	1.9056	2.2784	2.0137
		2.474	2.1305	2.650	2.2513
		2.778	2.5208	2.986	2.6637
18	179	0.2543	0.3449	0.3353	0.3533
		0.539	-----	0.6265	0.6120
		0.7951	-----	0.9077	0.8655
		0.9658	-----	1.0583	1.060
		1.1556	-----	1.25921	1.224
		1.6387	1.6895	1.93121	1.7311
		1.8840	-----	2.4693	2.1220
		2.787	2.3893	2.8558	2.4481
		3.177	2.7311	3.2775	2.7983
3.290	2.9263	3.5186	2.9983		

Table 6. Diffusion coefficients of mass and volume.

Run No.	Temp. °F.	$D_{m1} \times 10^{8*}$ cm. <sup>2</sup> /sec.	$D_{m2} \times 10^{8+}$ cm. <sup>2</sup> /sec.	$D_{v1} \times 10^{8*}$ cm. <sup>2</sup> /sec.	$D_{v2} \times 10^{8+}$ cm. <sup>2</sup> /sec.
1	80	2.660	2.972	4.117	4.597
2	80	3.258	3.651	3.901	4.368
9	85	3.679	4.129	6.205	6.962
8	90	4.366	4.994	6.543	7.480
4	100	6.027	7.0958	8.020	9.4372
6	116	10.949	13.153	13.749	16.508
12	120	10.266	12.539	12.716	15.531
15	130	13.772	17.283	17.422	22.058
13	140	18.233	22.911	23.358	29.338
19	140	21.511	27.258	25.898	32.818
16	150	27.542	37.239	32.296	43.666
14	158	41.010	58.060	46.226	65.309
17	170	75.447	114.522	84.254	127.871
18	179	118.614	189.888	124.523	199.346

\* $D_{m1}$  and  $D_{v1}$  based on the initial  $\frac{V}{S}$ .

+ $D_{m2}$  and  $D_{v2}$  based on the average  $\frac{V}{S}$ .

Table 7. The diffusion constants,  $D_0$ , and the energies of activation in Arrhenius relation for mass and volume.

The range of temperature	In the case of mass		In the case of volume	
	$D_0$ cm. <sup>2</sup> / sec. :	E K.cal./mole	$D_0$ cm. <sup>2</sup> / sec. :	E K.cal./mole
Below 150°F*	4.65	11.231	1.068	10.129
Above 150°F*	$2.50 \times 10^7$	21.645	$3.42 \times 10^6$	20.200
Below 150°F†	21	12.066	4.93	10.976
Above 150°F†	$1.405 \times 10^9$	24.174	$1.96 \times 10^8$	22.720

\* Based on the initial  $\frac{V}{S}$

† Based on the average  $\frac{V}{S}$

Table 8. Summary of statistical analysis of data.

Correlation	Correlation between $f_{\Sigma\Delta V} \text{ \& } \Sigma\Delta W$	Correlation between $f_{\Sigma\Delta V} \text{ \& } \text{adjusted } \Sigma\Delta W$	Correlation between $1-\bar{M} \text{ \& } X_m$	Correlation between $1-\bar{V} \text{ \& } X_v$
Sample regression coefficient, $b$	.9993	.9985	1.1127	1.1225
Sample standard error of regression coefficient, $S_b$	0.002677	0.002898	0.01387	0.007637
Sample correlation coefficient, $r_b$	.9995	.9994	.9900	.9970
Hypothesis $H_0$	$\beta = 1$	$\beta = 1$	$\beta = \frac{2}{\sqrt{\pi}}$	$\beta = \frac{2}{\sqrt{\pi}}$
Calculated $t^* = \frac{b-\beta}{S_b}$	-0.2391	-0.5176	-1.122	-0.7660
$t^*$ in Table (13)	at 0.05 level $\pm 1.98$ at 0.01 level $\pm 2.617$	at 0.05 level $\pm 1.98$ at 0.01 level $\pm 2.617$	at 0.05 level $\pm 1.98$ at 0.01 level $\pm 2.617$	at 0.05 level $\pm 1.98$ at 0.01 level $\pm 2.617$
Decision on $H_0$	accept $H_0: \beta=1$ at 0.05 and also 0.01 levels	accept $H_0: \beta=1$ at 0.05 and also 0.01 levels	accept $H_0: \beta=2/\sqrt{\pi}$ at 0.05 and also at 0.01 levels	accept $H_0: \beta=2/\sqrt{\pi}$ at 0.05 and also at 0.01 levels

## FIGURES

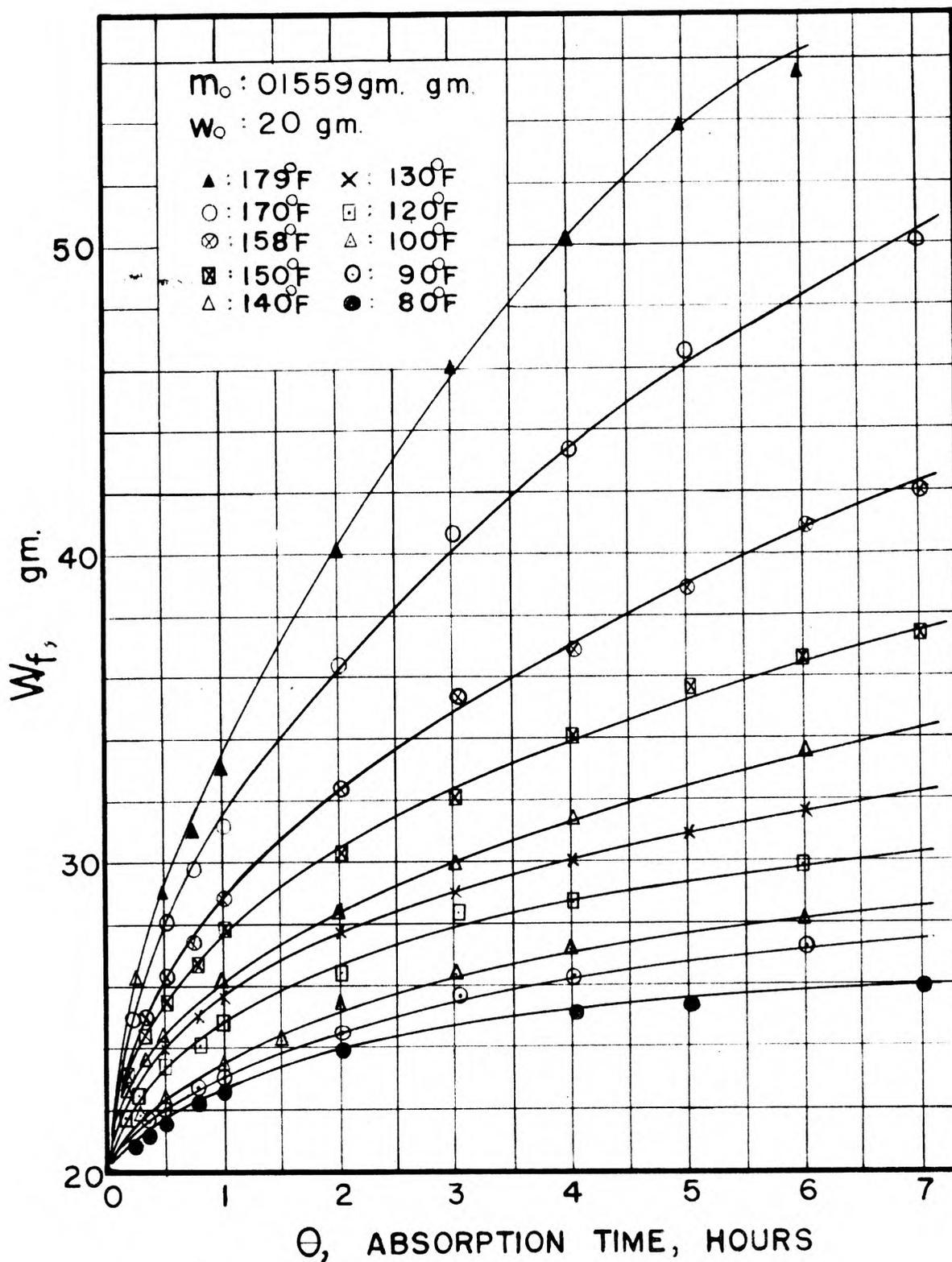


Fig. 2 Weight of sample at a given absorption time as a function of absorption time.

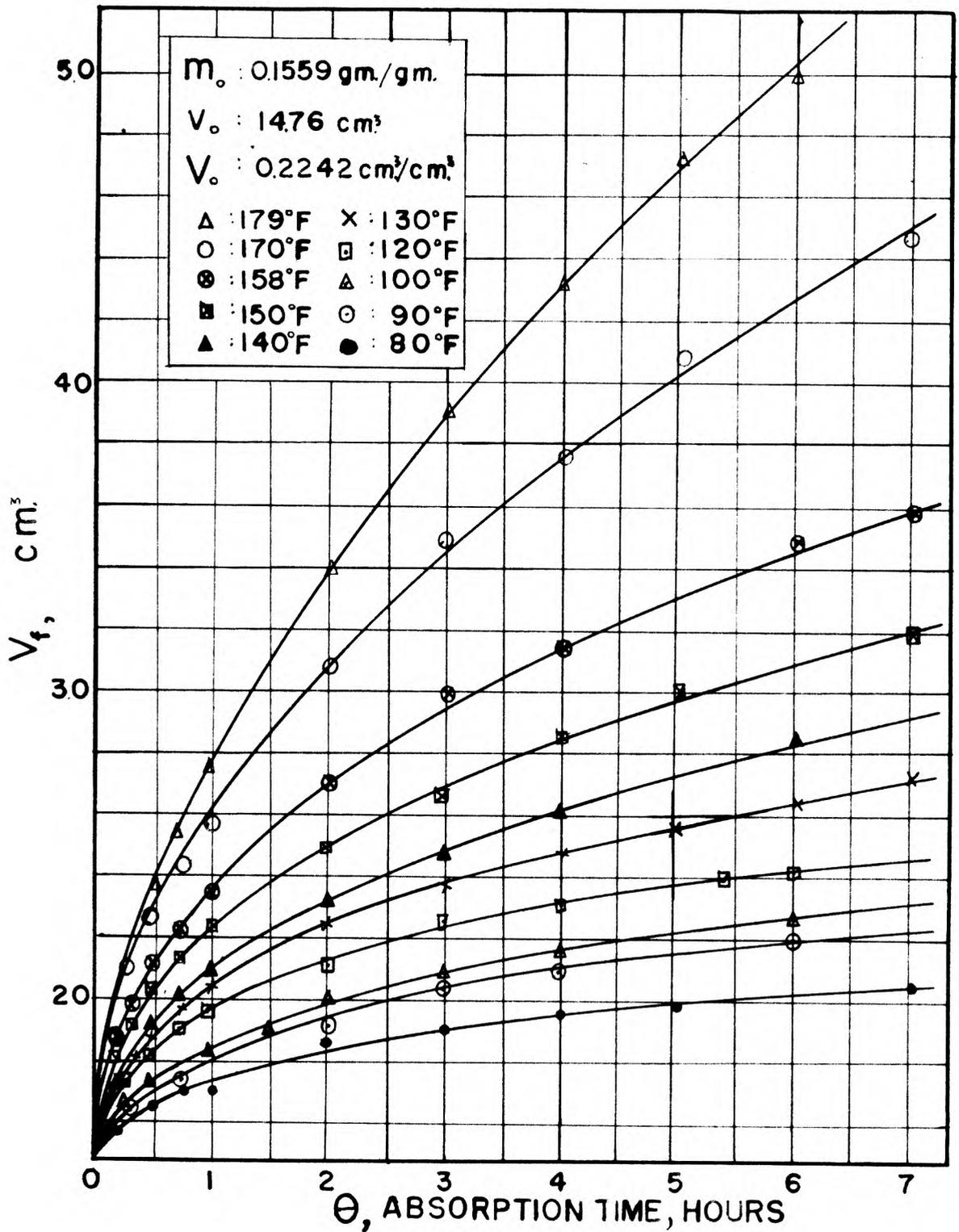


Fig. 3 Volume of sample at a given absorption time as a function of absorption time.

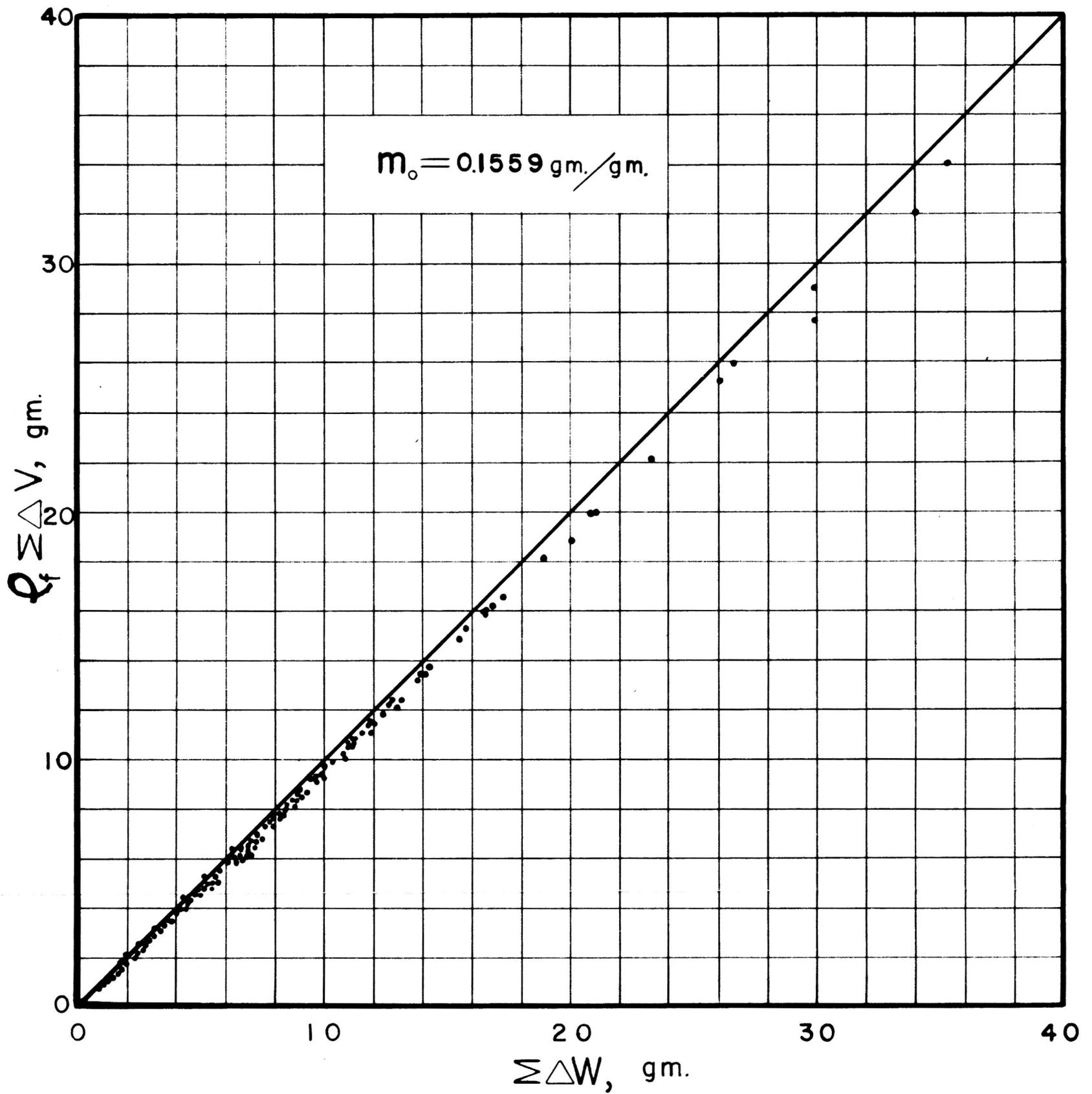


Fig. 4 The product of density of fluid and volume gain as a function of moisture gain, showing exact linear relation between volume gain and moisture gain.

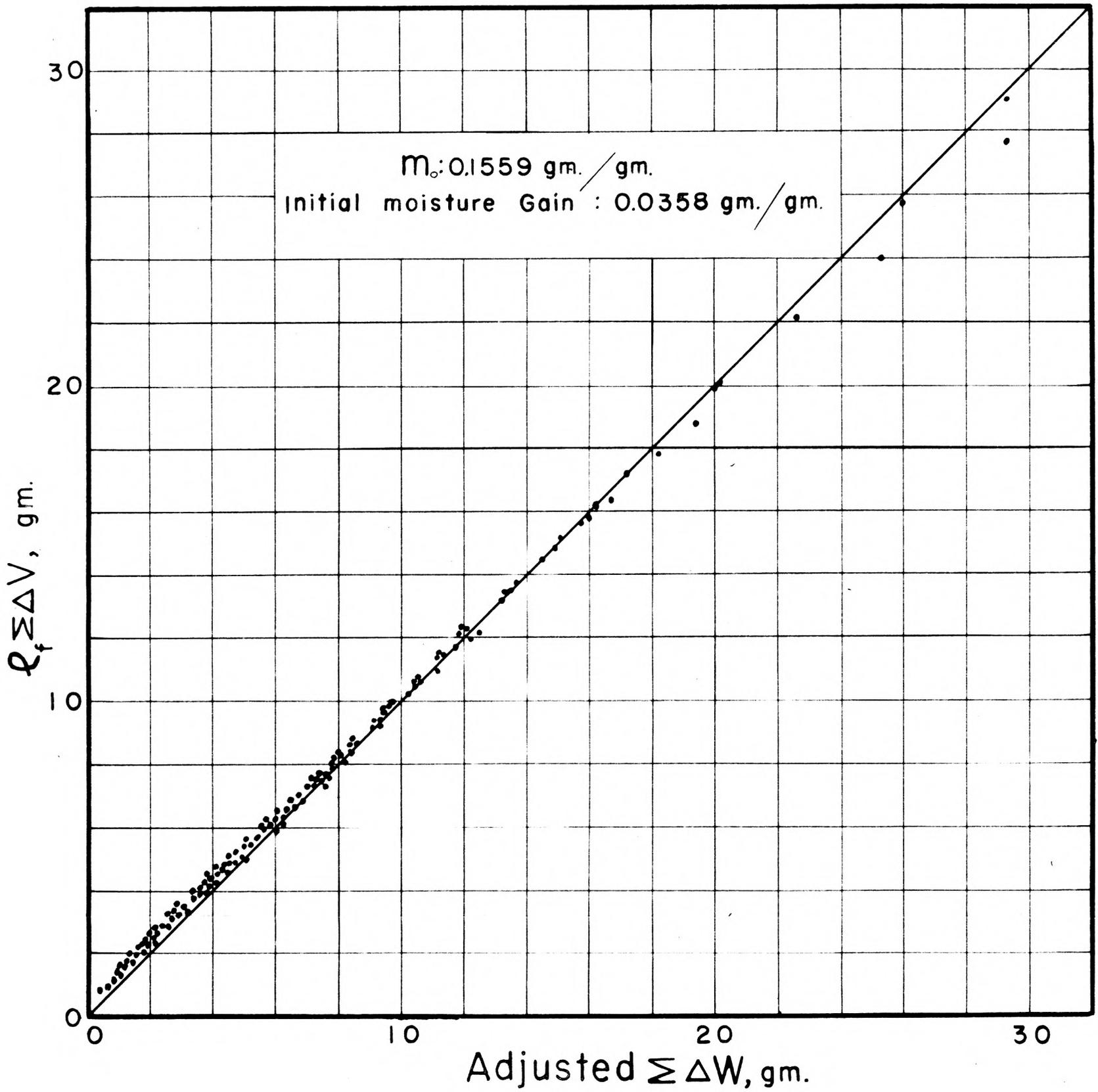


Fig. 5 The volume gain as a function of the moisture gain from which initial moisture gain by capillary action was subtracted, showing exact linear relation between the volume gain and the moisture gain.

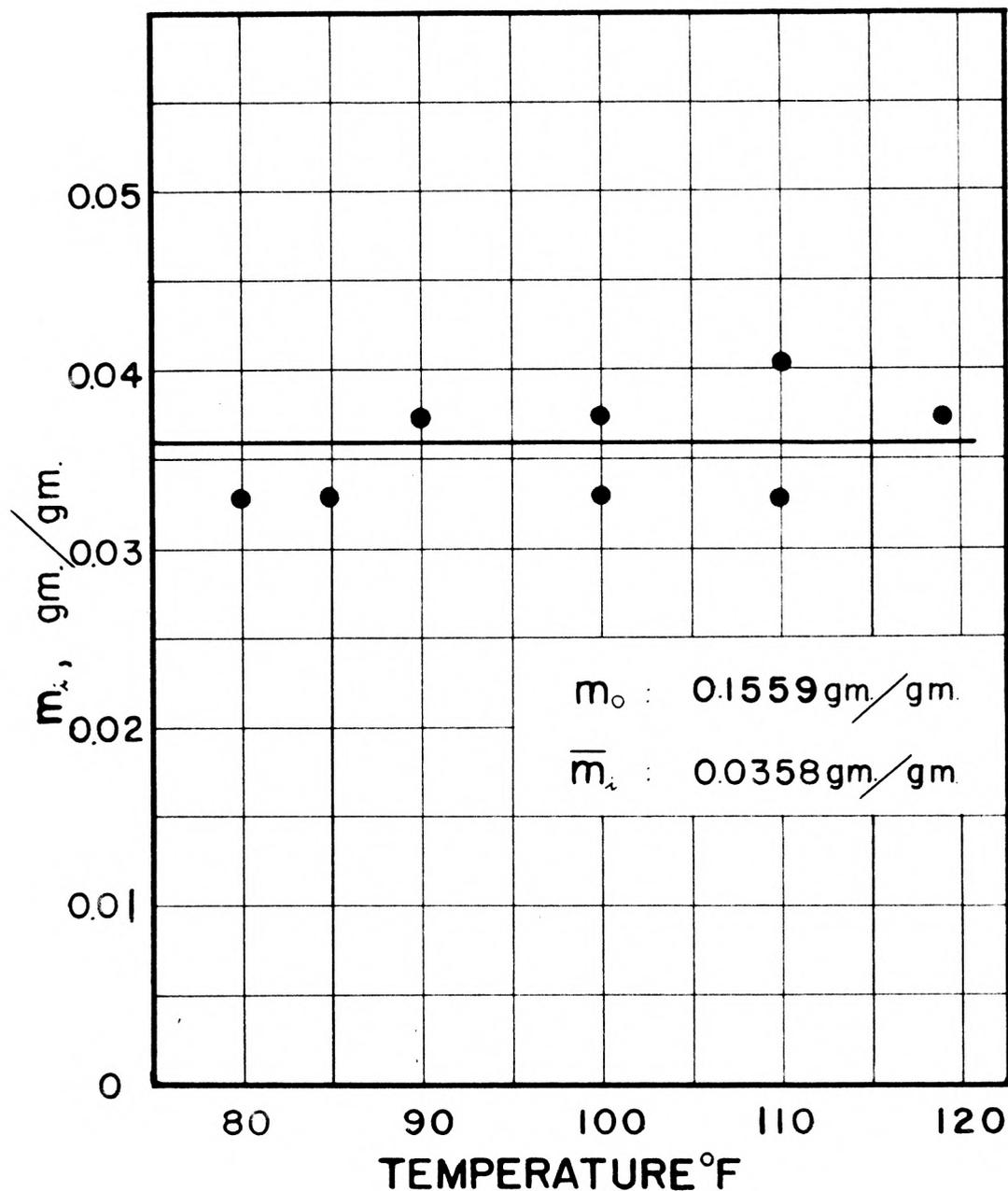


Fig. 6 Initial moisture gain by capillary action versus temperature, showing that average initial moisture gain of 0.0358 gm./gm. and independent of temperature levels.

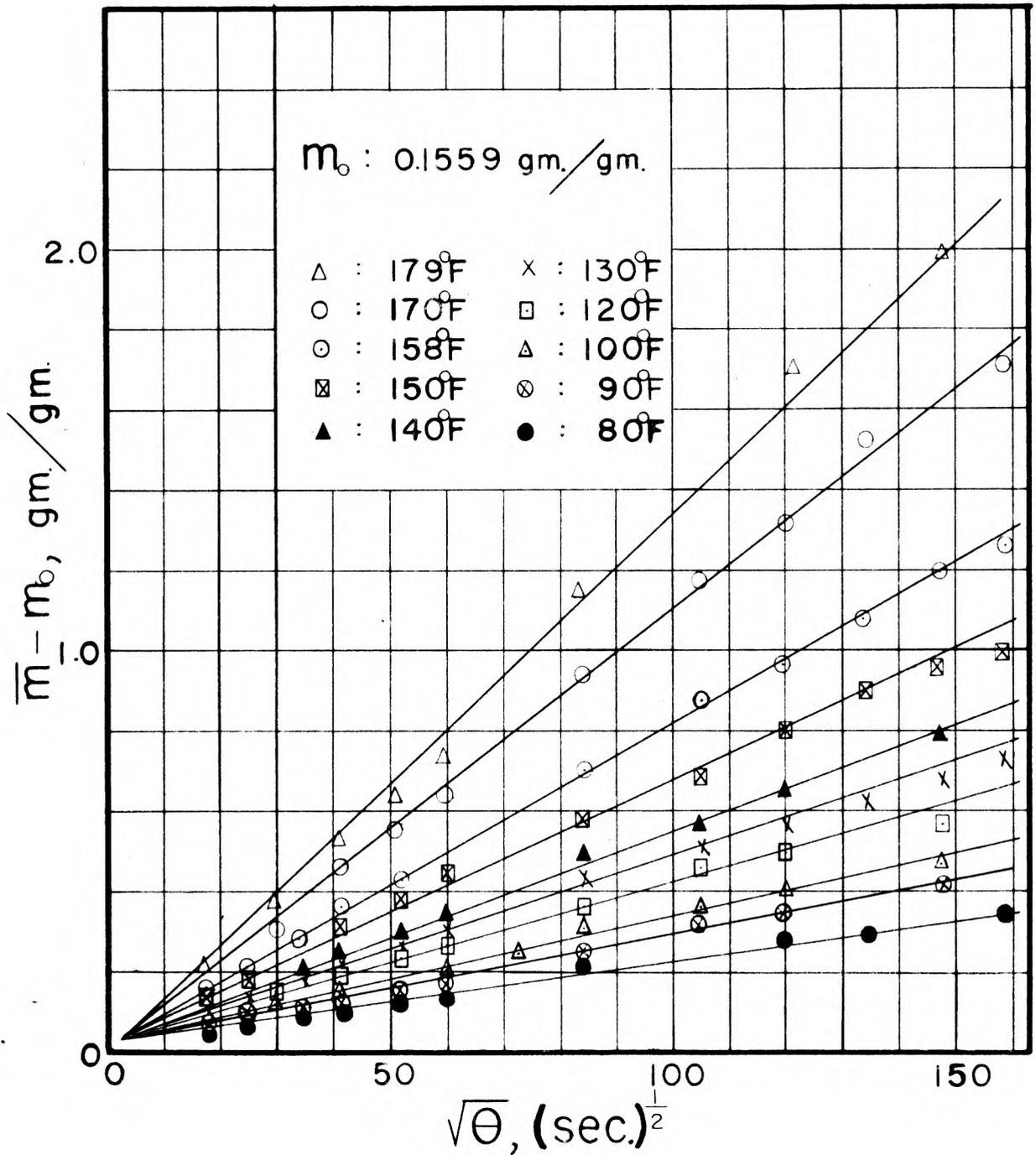


Fig. 7 The linear relation between the moisture gain and the square root of the absorption time.

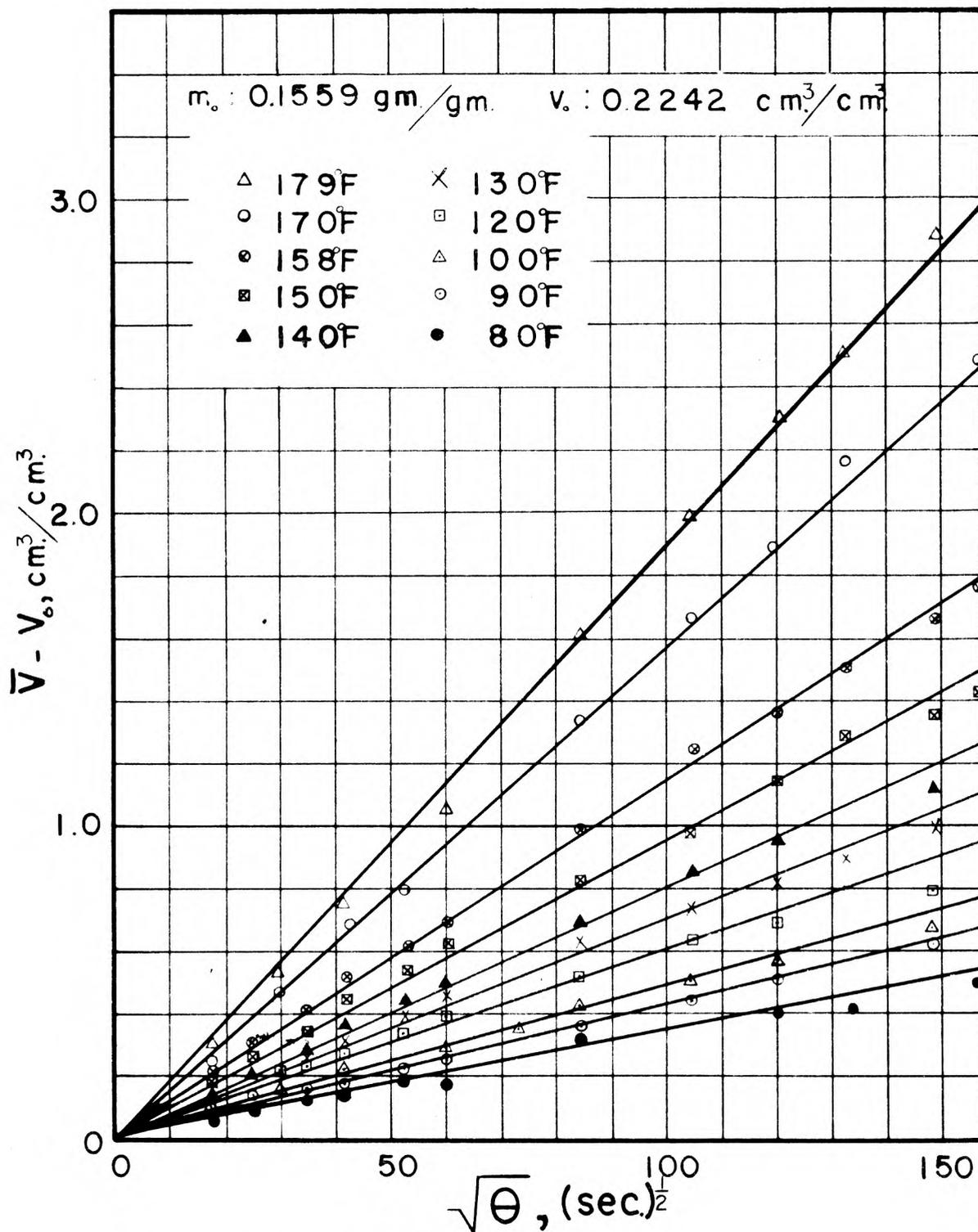


Fig. 8 The linear relation between the volume gain and the square root of absorption time.

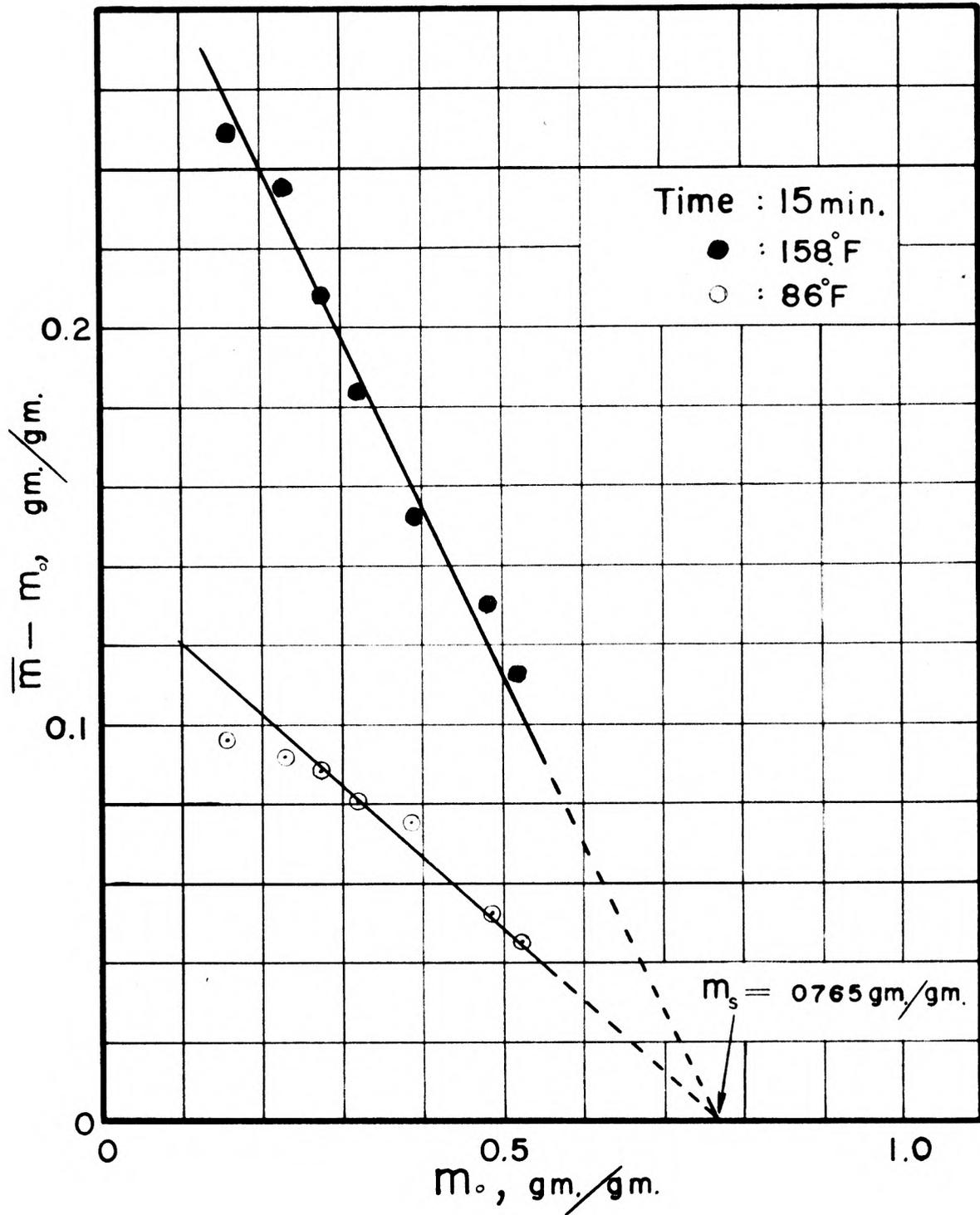


Fig. 9 The moisture gain as a function of initial moisture content at 158°F and 86°F, showing the linear regression on an effective surface moisture content of 0.765 gm./gm.

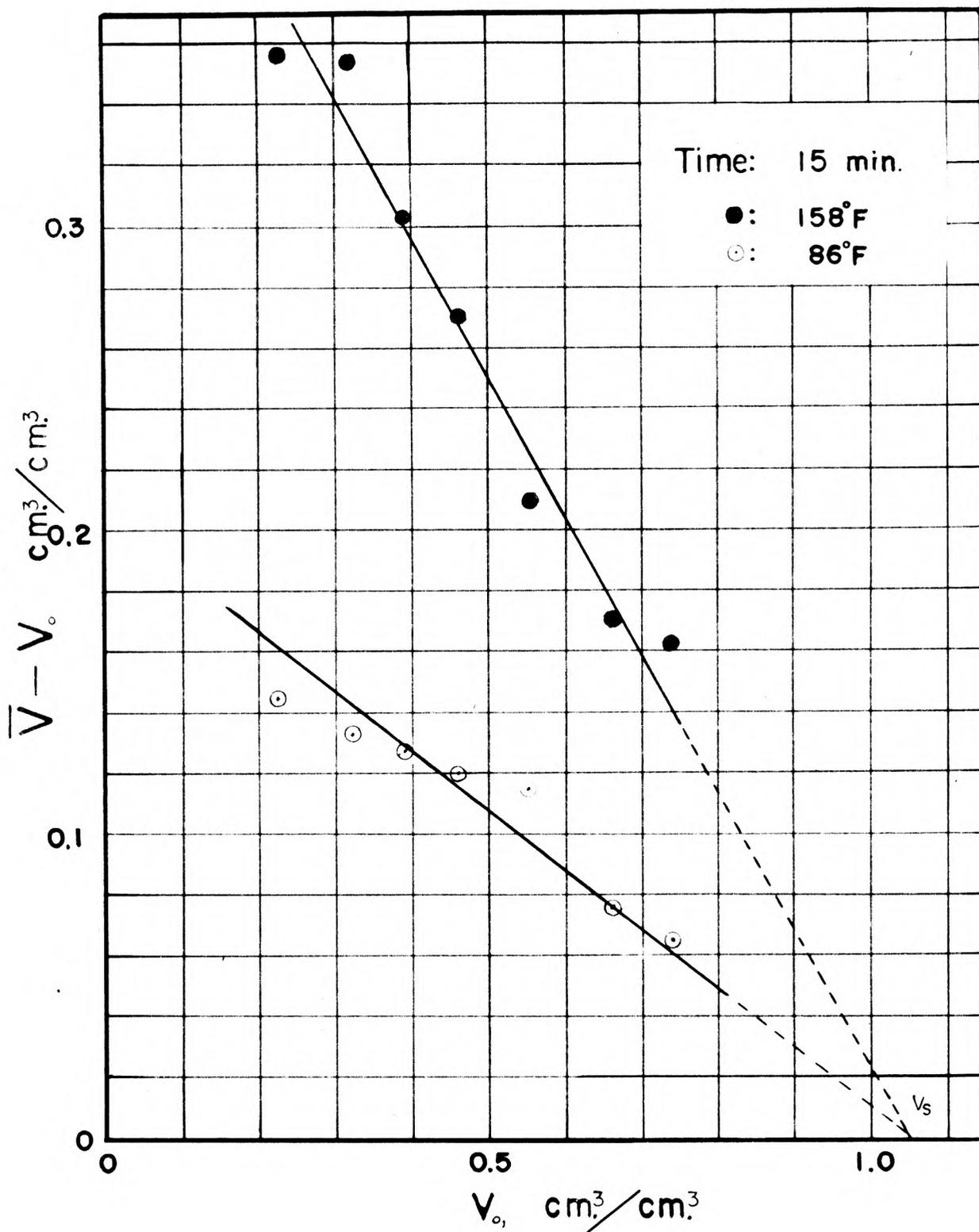


Fig. 10 The volume gain as a function of initial volume content at 158°F and 86°F, showing the linear regression on an effective surface volume content of 1.05 cm.<sup>3</sup>/cm.<sup>3</sup>

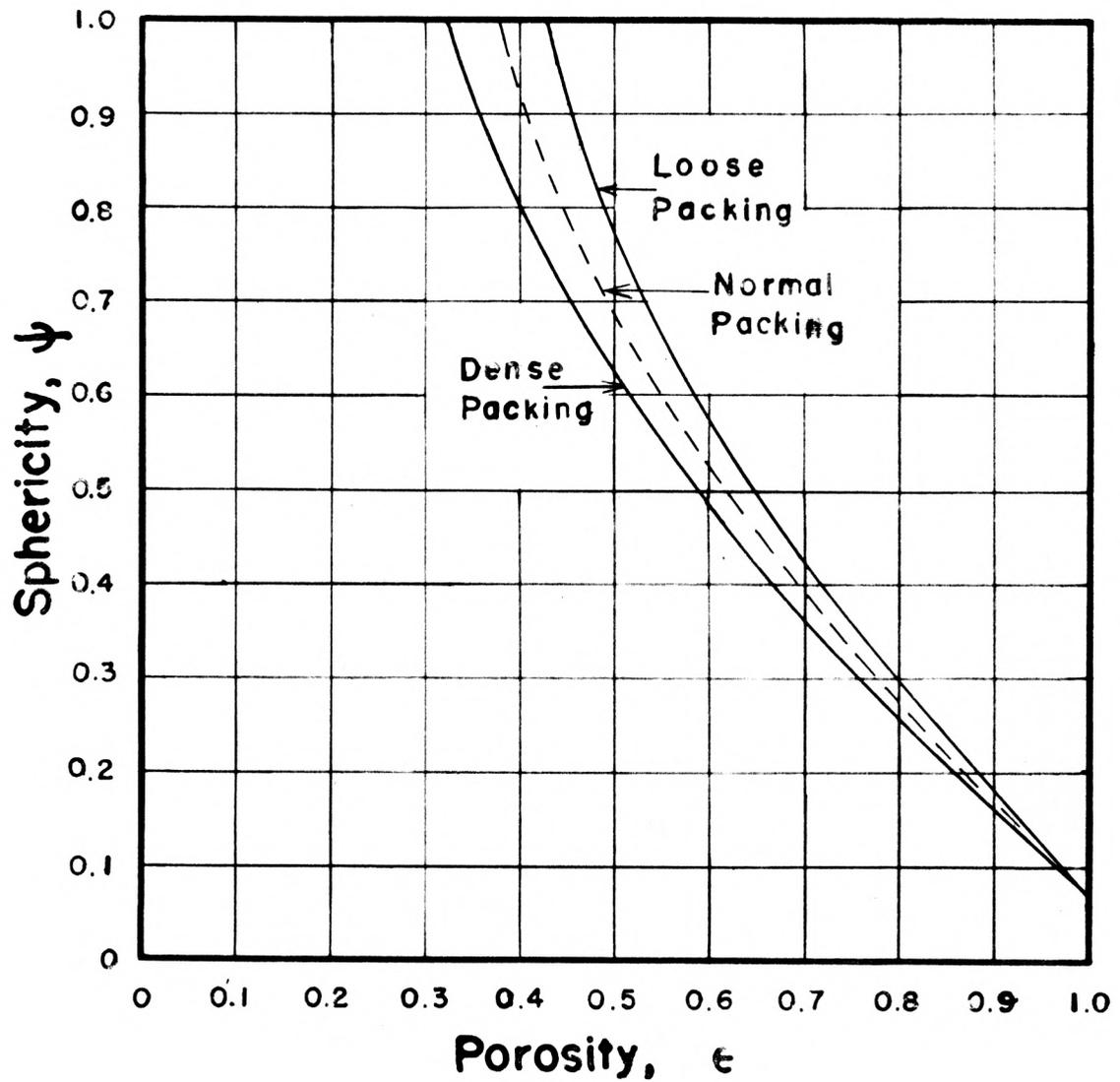


Fig. 11 Sphericity as a function of porosity for random-packed beds of uniform-sized particles.(3)

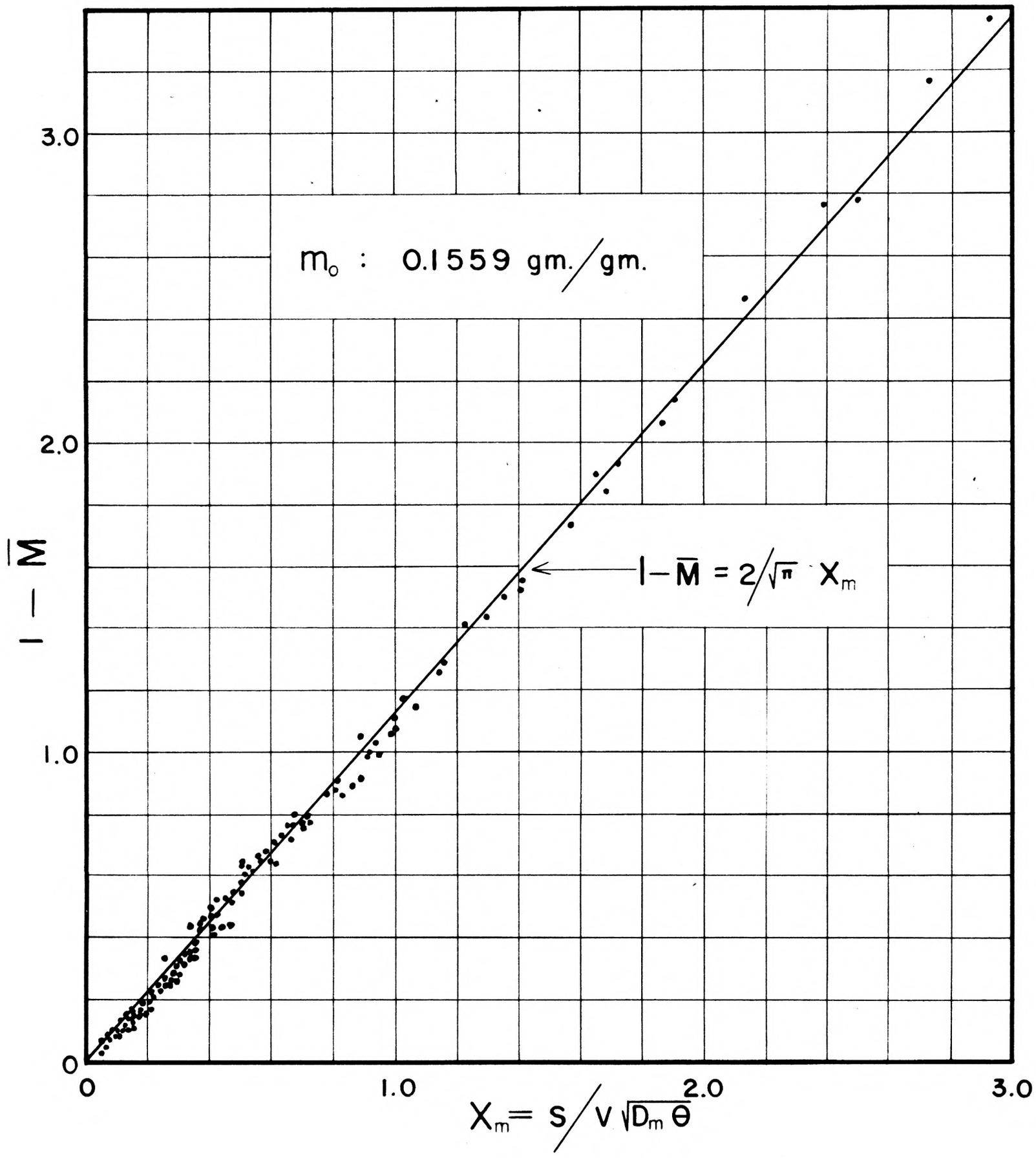


Fig. 12 Generalized correlation of the data, using empirical relations for the diffusion coefficient on moisture gain and initial moisture gain.

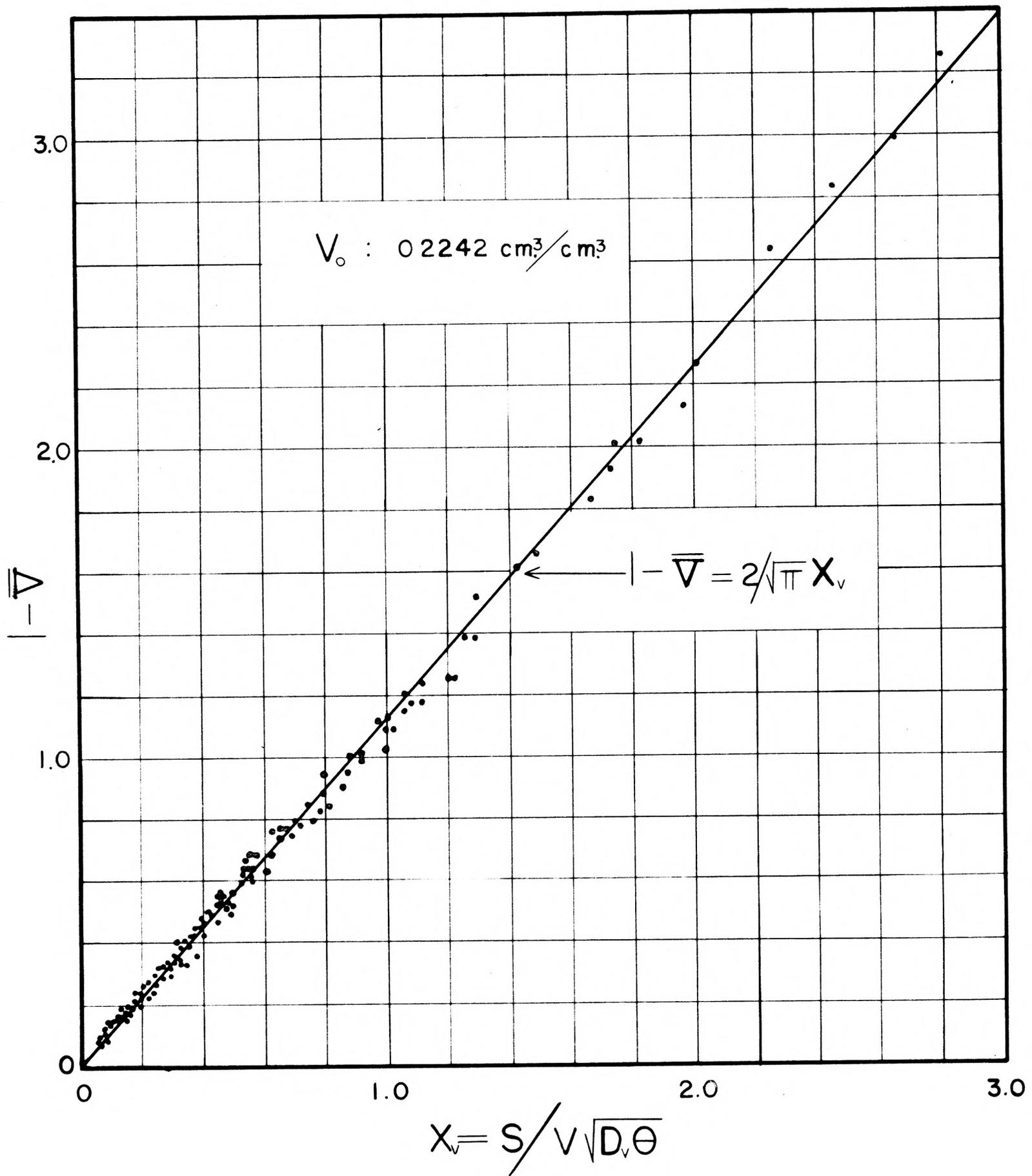


Fig. 13 Generalized correlation of the data, using empirical relation for the diffusion coefficient on volume gain.

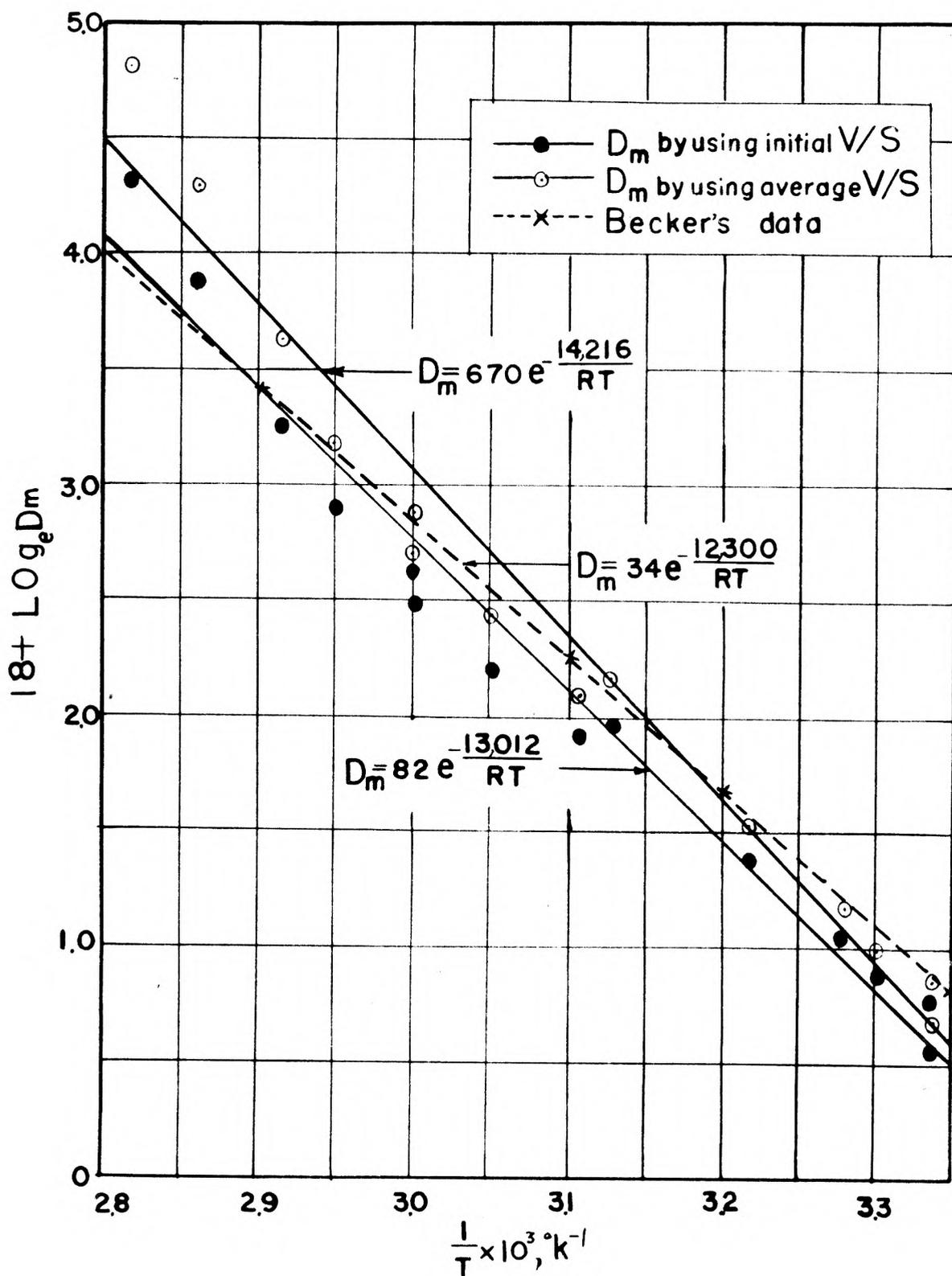


Fig. 14 The diffusion coefficient of mass as a function of the reciprocal of absolute temperature.

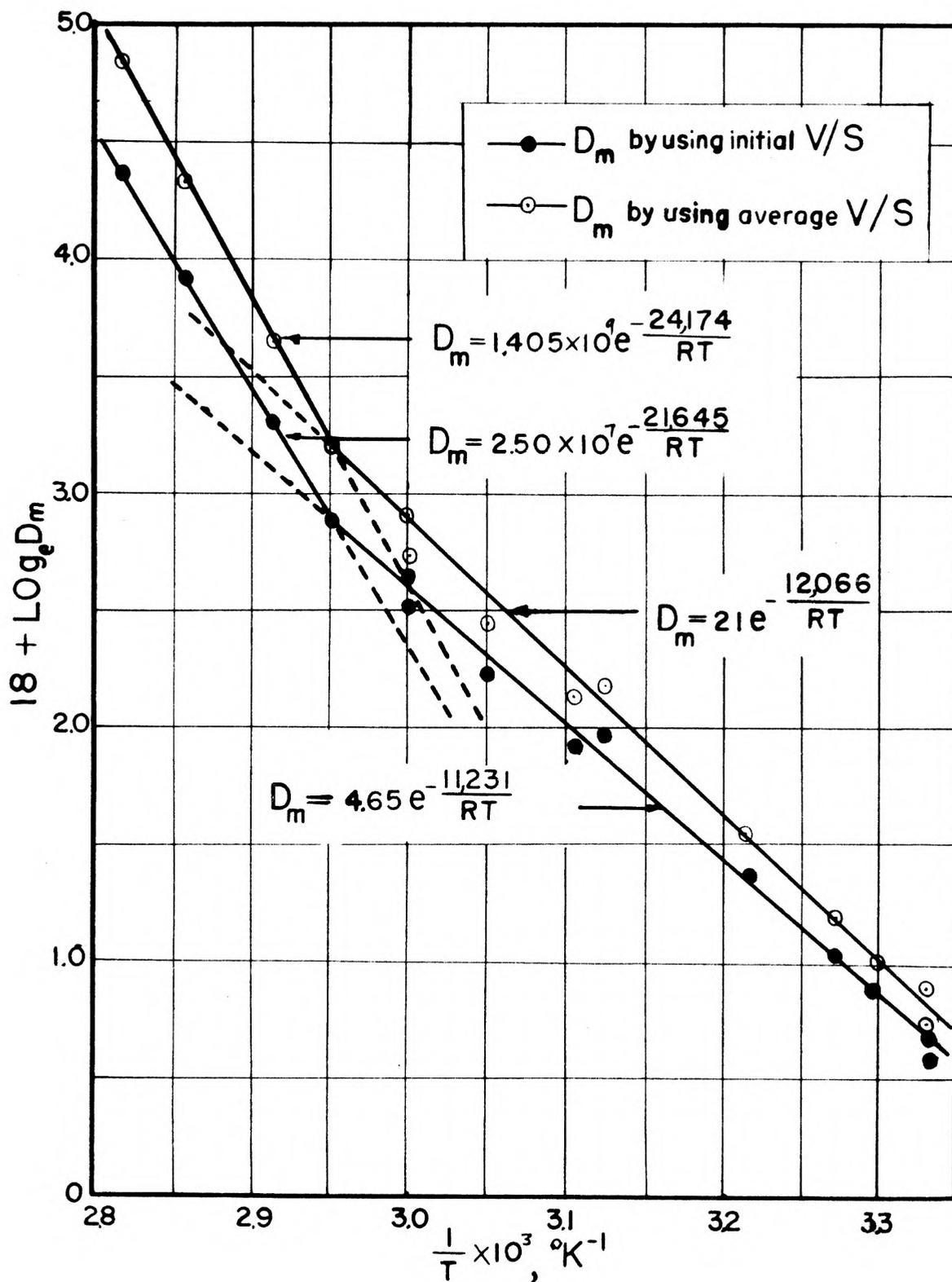


Fig. 15 The diffusion coefficient of mass as a function of the reciprocal of absolute temperature.

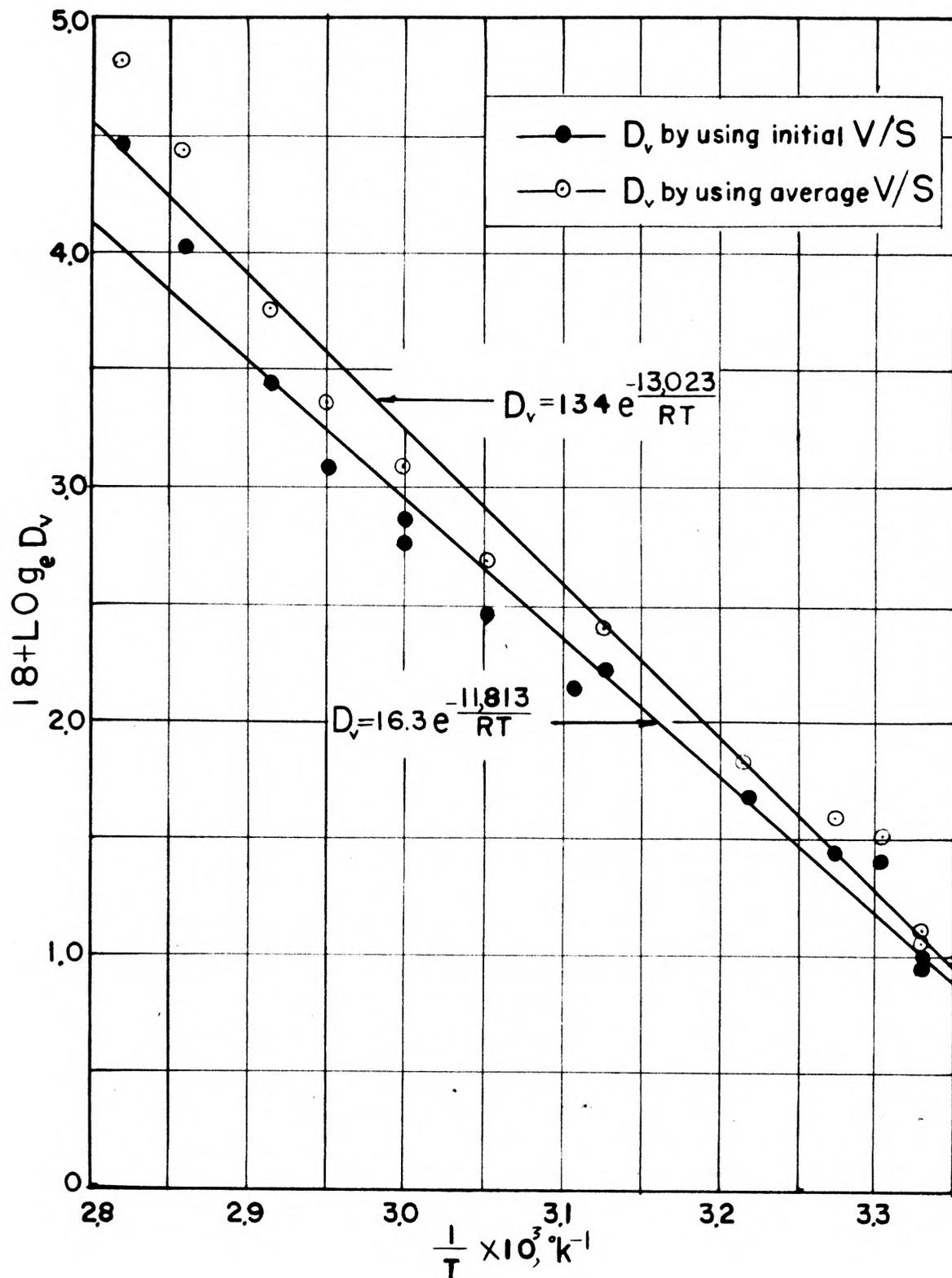


Fig. 16 The diffusion coefficient of volume as a function of the reciprocal of absolute temperature.

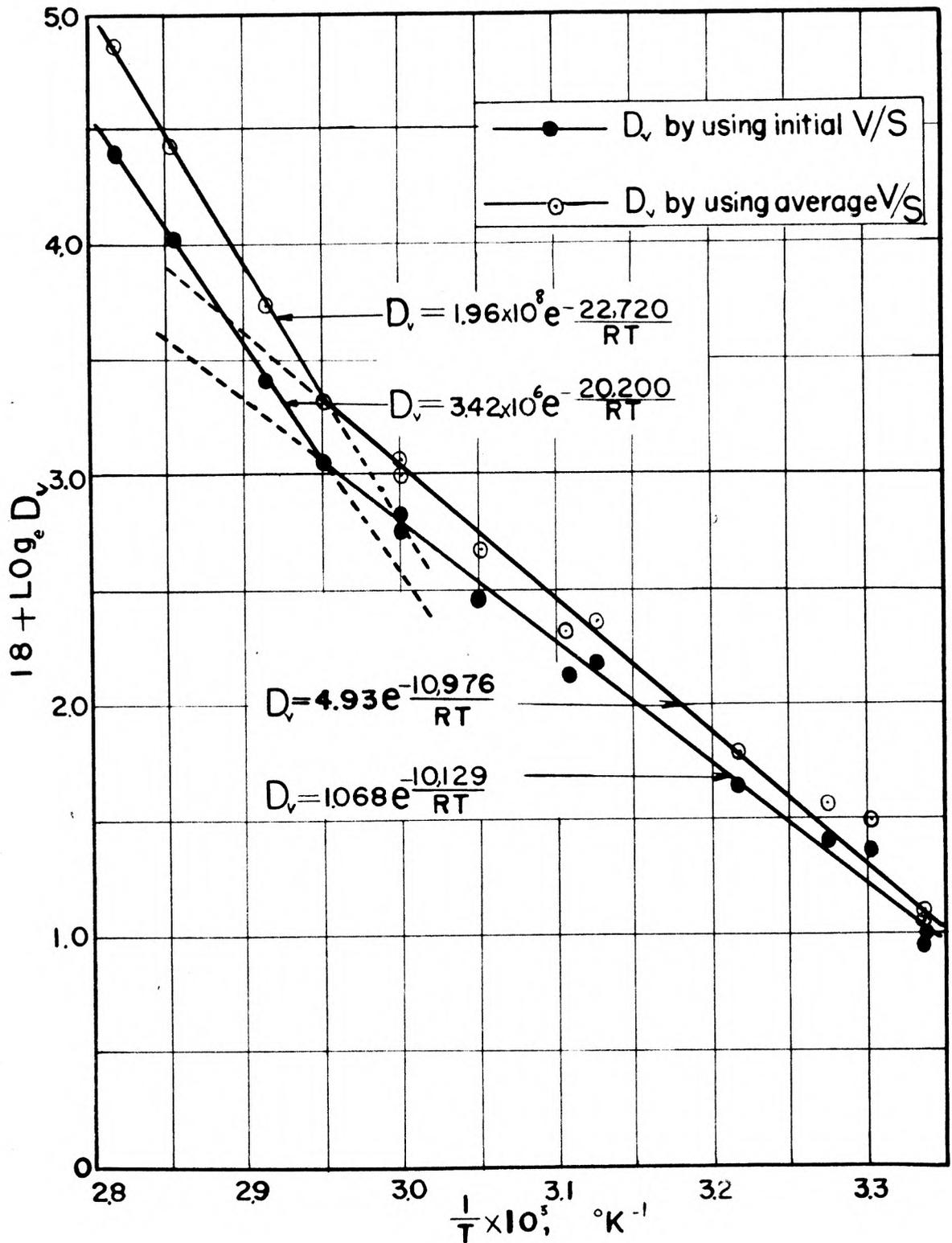


Fig. 17 The diffusion coefficient of volume as a function of the reciprocal of absolute temperature.

SIMULTANEOUS MEASUREMENTS OF WEIGHT AND VOLUME  
CHANGES OF WHEAT KERNELS STEEPED IN WATER

by

DO SUP CHUNG

B. S., PERDUE UNIVERSITY, 1958

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AN ABSTRACT OF A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE UNIVERSITY  
OF AGRICULTURE AND APPLIED SCIENCE

1960

The purposes of the experiment were to determine the relationship between the volume gain and the weight gain during the steeping of wheat, to develop the integral diffusion equation for the volume gain, to test the validity of the diffusion equation for the weight gain derived by Becker (2), and to study the mechanism of water penetration into wheat kernels. There was a very rapid initial moisture gain by capillary action which was not controlled by the diffusion model. The average initial moisture gain due to capillary action was 0.0358 gm./gm., dry basis, and was independent of temperature variations.

The effective moisture content at the surface of an immersed wheat kernel was 0.765 gm./gm. Subsequent absorption was described by the diffusion equation.

$$1 - \bar{M} = \frac{2}{\sqrt{\pi}} S/V \sqrt{D_m \theta}$$

where  $1 - \bar{M}$  is the relative moisture gain,  $S/V$  is the surface to volume ratio, and  $D_m$  is the diffusion coefficient of mass. The average diffusion coefficient of mass was given by the Arrhenius relation.

$$D_{m1} = 4.65 e^{-\frac{11,231}{RT}} \text{ at temperatures below } 150^{\circ}\text{F} \quad \text{based on the initial } V/S$$

$$D_{m1} = 2.50 \times 10^7 e^{-\frac{21,645}{RT}} \text{ at temperatures above } 150^{\circ}\text{F}$$

or

$$D_{m2} = 21 e^{-\frac{12,066}{RT}} \text{ at temperatures below } 150^{\circ}\text{F} \quad \text{based on the average } V/S$$

$$D_{m2} = 1.405 \times 10^9 e^{-\frac{24,174}{RT}} \text{ at temperatures above } 150^{\circ}\text{F}$$

The activation energy at temperatures above  $150^{\circ}\text{F}$  was almost twice as much as the activation energy at temperature below  $150^{\circ}\text{F}$ .

The hypothesis that the volume gain was identical with the weight gain was accepted at 0.05 level and 0.01 level. This hypothesis indicated that the volume gain exactly corresponded to the volume of the moisture gained in the wheat kernel during the steeping process. Based on this fact and by analogy, the integral diffusion equation for the volume gain was newly developed. The diffusion equation for the volume gain was

$$1 - \bar{V} = \frac{2}{\sqrt{\pi}} S/V \sqrt{D_v \theta}$$

where  $1 - \bar{V}$  is the relative volume gain, and  $D_v$  is the diffusion coefficient of volume. The effective surface volume content was  $1.05 \text{ cm}^3/\text{cm}^3$ .

The average diffusion coefficient of volume was given by the Arrhenius relation.

$$D_{v1} = 1.068 e^{-\frac{10,976}{RT}} \text{ at temperatures below } 150^\circ\text{F} \quad \text{based on the initial } V/S$$

$$D_{v1} = 3.42 \times 10^6 e^{-\frac{20,200}{RT}} \text{ at temperatures above } 150^\circ\text{F}$$

$$D_{v2} = 4.93 e^{-\frac{10,976}{RT}} \text{ at temperatures below } 150^\circ\text{F} \quad \text{based on the initial } V/S$$

$$D_{v2} = 1.96 \times 10^8 e^{-\frac{22,720}{RT}} \text{ at temperatures above } 150^\circ\text{F}$$

The activation energy for  $D_v$  at temperatures above  $150^\circ \text{F}$  was also twice as much as the activation energy at temperatures below  $150^\circ \text{F}$ . The studies of the Arrhenius relation for  $D_m$  and  $D_v$  indicated the occurrence of two different mechanisms during the steeping process, above and below the gelatinization temperature, which is approximately  $150^\circ \text{F}$ . The absorption of liquid water by the wheat kernel probably proceeds by a heterogeneous mechanism, below  $150^\circ \text{F}$  and by a homogeneous mechanism at temperatures above  $150^\circ \text{F}$ .

The statistical test showed that the validity of the diffusion equations,  $1 - \bar{M} = \frac{2}{\sqrt{\pi}} S/V \sqrt{D_m \theta}$ , and  $1 - \bar{V} = \frac{2}{\sqrt{\pi}} S/V \sqrt{D_v \theta}$ , were very high.