DIFFUSION OF WATER IN KERNELS OF CORNS AND SORGHUMS

by

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NOMENCLATURE

A	=	effective surface area of a solid, cm^2.
c	=	concentration of diffusion substance at a point in a solid, g/cm^3.
c_o	=	initial, uniform concentration, g/cm^3.
c_s	=	concentration at the bounding surface, g/cm^3.
$\overline{c}$	=	average concentration, g/cm^3.
D	=	diffusivity cm^2/sec.
D_o	=	constant in Arrhenius equation, cm^2/sec.
D_v	=	volume expansion coefficients, cm^2/sec.
E	=	energy of activation, KCal./mole.
f	=	function.
$f'f''$	=	first and second, derivatives of f.
F	=	diffusion current (i.e., the specific rate of mass transfer) $g/(cm.^2)$ (sec.).
m_o	=	initial, uniform moisture content, dry basis, g./g.
m_s	=	moisture content at the bounding surface, dry basis g./g.
$\overline{m}$	=	average moisture content dry basis g./g.
$\overline{m}-m_o$	=	average moisture weight gain, dry basis g./g.
m_i	=	initial moisture weight gain, dry basis g./g.
v_o	=	initial, uniform volume content dry basis cm^3/cm^3.
v_i	=	initial volume gain, dry basis, cm^3/cm^3.
v_s	=	volume content at the bounding surface, dry basis cm^3/cm^3.
$\overline{v}$	=	average volume content, dry basis, cm^3,cm^3.
$\overline{v}-v_o$	=	average volume gain, dry basis cm^3,cm^3.
n	=	an integer.
R	=	gas constant, cal./mal.^oK.

r, s = spacial coordinates, cm.

T = temperature.

t = time, sec.

V = volume of a solid, cm^3.

x, y, z = cartesian coordinates, cm.

= density, $g./cm^3$.

= sphericity.

= porosity.

= angular coordinate,

Dimensionless Factor in Diffusion Equation

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

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

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

$$Z = \frac{s}{2\sqrt{Dt}}$$

$$X = \frac{A}{V}\sqrt{Dt}$$

$$Y = \frac{1 - \bar{C}}{X}$$

INTRODUCTION

Corn and sorghum are two major sources of starch for industry. Generally, the starch is manufactured by a wet process. In this process, the grain is softened by steeping in water (13) (15). The diffusion of water into the grains of corn and sorghum during steeping has been the subject of several papers (1) (6) (11), but the heterogeneity of composition and irregularity in shape of the grains make the diffusion problem a complicated one, and therefore a theoretical and mathematical treatment of the diffusion of water into these grains is lacking.

The purpose of this work was to investigate the possibility of correlating such diffusion data qualitatively with the operating variables.

THEORY

The object of this section is to formulate an equation for unsteady state diffusion to be employed in this work.

According to Fick's first law of diffusion (9), the rate of transfer of a diffusing substance through a unit area is expressed by:

$$F = -D\frac{\partial c}{\partial L} \tag{1}$$

where F is the rate of transfer per unit area, c is the concentration of diffusing substance, L is the space coordinate measured normal to the section, $\frac{\partial c}{\partial L}$ the concentration gradient measured normal to the section, and D the diffusion coefficient or diffusivity. Considering an elemental volume in the rectangular coordinate system, the following equation is obtained by a material balance:

$$\frac{\partial c}{\partial t} + \frac{\partial F_x}{\partial x} + \frac{\partial F_y}{\partial y} + \frac{\partial F_z}{\partial z} = 0 \qquad (2)$$

If the diffusivity, D, is considered as constant, equations 1 and 2 lead to:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \qquad (3)$$ for one dimensional diffusion.

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2}\right) \qquad (4)$$ for two dimensional diffusion.

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) \qquad (5)$$ for three dimensional diffusion.

It is assumed that symmetry exists about a point, line, or plant. Then, by assuming that the concentration is a function of r and t only, equation 4 can be transformed into a cylindrical coordinate by letting x = rcoso , y = rsino as:

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial r^2} + \frac{1}{r}\frac{\partial c}{\partial r}\right) \qquad (7)$$

Similarly, equation 5 can be transformed into a spherical coordinate form as:

$$\frac{\partial c}{\partial t} = D\left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}\right) \qquad (8)$$

If we let x = r, then equation 3 can be expressed as:

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial r^2} \qquad (6)$$

Hence, equations 6, 7, and 8 can be expressed in a general form as:

$$\frac{\partial c}{\partial t} = D\left[\frac{\partial^2 c}{\partial r^2} + \frac{n}{r}\frac{\partial c}{\partial r}\right] \tag{9}$$

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, unity for axial symmetry, and two for spherical symmetry.

Diffusion in a solid of arbitrary shape with the following initial and boundary conditions is considered in this work:

$$\begin{aligned} c &= c_o \quad \text{at} \quad t=o \quad o<s<r \\ c &= c_s \quad \text{at} \quad s=o \quad t>o \\ c &= c_o \quad \text{at} \quad s\to\infty \quad t>o \end{aligned} \tag{10}$$

where s is a general coordinate whose origin is at the bounding surface and whose axes are everywhere perpendicular to the surface. The relation between r and s is $s = r_o = r$. Where r is the distance from the center of symmetry to the surface.

In examining the general form of the solutions over the range of $t=o$ to $t\to\infty$, it can be seen that near $t=o$, concentration changes in the solid will be confined to the neighborhood of the surface. Therefore, in the first instant of diffusion, the condition near the surface approximates the case of a semi-infinite plane-faced solid (2). For this case, the solution of equation 6 can be obtained as follows

Since

$$s = r_o - r$$

$$\frac{\partial c}{\partial s} = \frac{\partial c}{\partial r} \cdot \frac{\partial r}{\partial s} = \frac{\partial c}{\partial r} (-1) = -\frac{\partial c}{\partial r}$$

$$\frac{\partial^2 c}{\partial s^2} = \frac{\partial}{\partial s} \left(\frac{\partial c}{\partial s}\right) = \frac{\partial}{\partial s} \left(-\frac{\partial c}{\partial r}\right) = -\frac{\partial}{\partial s} \left(\frac{\partial c}{\partial r}\right) = -\frac{\partial}{\partial r} \left(\frac{\partial c}{\partial r}\right) \cdot \frac{\partial r}{\partial s}$$

$$= -\frac{\partial^2 c}{\partial r^2} (-1) = \frac{\partial c}{\partial r^2}$$

equation 6 becomes:

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial s^2} \qquad (11)$$

and the initial and boundary conditions become:

I.C.	$c = c_o$	at $t=o$	$o < s < r_o$	
	$c = c_s$	at $s=o$	$t > o$	
	$c = c_o$	at $s \rightarrow \infty$	$t > o$	(12)

Expressing the concentration in a dimensionless form as:

$$U = \frac{c - c_o}{c_s - c_o} \qquad (13)$$

equation 11 becomes:

$$\frac{\partial U}{\partial t} = D \frac{\partial^2 U}{\partial s^2} \qquad (11a)$$

the I.C. and B.C. become:

$$U\ (s,o) = o \tag{12a}$$

$$U\ (o,t) = 1 \tag{12b}$$

$$U\ (\infty,t) = o \tag{12c}$$

The Lapalace transform of equations 11a, 12a, 12b, and 12 c are as follows (8):

$$p\bar{U} - \bar{U}(s,o^{+}) = D\frac{\partial^{2}\bar{U}}{\partial s^{2}} \tag{14}$$

and

$$\bar{U}(s,o) = o \tag{15a}$$

$$\bar{U}(o,p) = \frac{1}{p} \tag{15b}$$

$$\bar{U}(\infty,p) = o \tag{15c}$$

Because of the initial condition 15a, equation 14 reduces to:

$$p\bar{U} = D\frac{\partial^{2}\bar{U}}{\partial s^{2}}$$

which has a general solution as:

$$\bar{U} = Ae^{\sqrt{\frac{p}{b}}s} + Be^{-\sqrt{\frac{p}{b}}s} \tag{16}$$

Because of the conditions 15b and 15c, equation 16 becomes:

$$\bar{U} = \frac{1}{p}e^{-\sqrt{\frac{p}{b}}s} \quad \text{or} \quad U = 1 = \text{erf}\left(\frac{s}{2\sqrt{Lt}}\right) \tag{17}$$

Since $U = \dfrac{c - c_o}{c_s - c_o}$,

equation 17 can be written in an alternate form as:

$$\frac{c - c_o}{c_s - c_o} = U = 1 - \frac{2}{\sqrt{\pi}}\int_{o}^{z} \exp(-z^{2})dz \tag{18a}$$

Where $z = \frac{s}{2\sqrt{D_t}}$ and $\frac{2}{\sqrt{\pi}}\int_o^z \exp(-z^2)dz$ is the Gaussian error integral.

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

then
$$1\text{-}C = \frac{c - c_o}{c_s - c_o} = U$$

Therefore, equation 18a becomes:

$$1\text{-}C = \frac{2}{\sqrt{\pi}} \int_o^z \exp(-z^2)\ dz \qquad (18b)$$

The average concentration in a finite solid as a function of time near t=o can be obtained by making a material balance about the bounding surface as:

$$(c_o - \bar{c})\ V = \int_o^t FAdt \qquad (19)$$

where V is the volume of the solid, A, the surface area of the solid and by Fick's first law:

$$F = -D\left(\frac{\partial c}{\partial s}\right)_{s=o} \qquad (20)$$

(Note that, with a constant diffusion coefficient, F approaches constancy over the surface as the time t approaches zero).

The concentration gradient at the surface, $\left(\frac{\partial c}{\partial s}\right)_{s=o}$, is obtained by differentiating equation 18b. The mathematical operations are:

$$\frac{dc}{c_s - c_o} = \frac{2}{\sqrt{\pi}} \exp(-z^2)dz$$

$$\frac{dc}{dt} = \frac{2}{\sqrt{\pi}} \exp(-z^2)\ (c_s - c_o)$$

Since $\frac{\partial c}{\partial s} = (\frac{\partial z}{\partial s})(\frac{dc}{dz})$ and $\frac{\partial z}{\partial s} \quad \frac{1}{2\sqrt{Dt}}$

$$\frac{\partial c}{\partial s} = \frac{2}{\sqrt{\pi}} \frac{1}{2\sqrt{Dt}} \exp(-z^2)(c_s - c_o)$$

$$= \frac{c_s - c_o}{\sqrt{\pi Dt}} \exp(-\frac{s^2}{2\sqrt{Dt}}) \tag{21}$$

When s approaches zero:

$$\frac{\partial c}{\partial s} = \frac{c_s - c_o}{\sqrt{\pi Dt}} \tag{22}$$

substituting equation 22, into equation 20, we get:

$$F = -D(\frac{\partial c}{\partial s})_{s=o} = -D(\frac{c_s - c_o}{\sqrt{\pi Dt}}) = \frac{-\sqrt{D}\ (c_s - c_o)}{\sqrt{\pi t}} \tag{23}$$

Substituting this result back into equation 19, and assuming that the ratio, $\frac{A}{V}$ is constant at time near zero, the general solution is obtained from equation 19 as:

$$\frac{\bar{c} - c_o}{c_s - c_o} = \frac{2}{\sqrt{\pi}} (\frac{A}{V}) \sqrt{Dt} \tag{24}$$

Now if we let

$$\frac{A}{V}\sqrt{Dt} = X, \text{ and } \bar{C} = \frac{c_s - \bar{c}}{c_s - c_o}$$

then, since $1-\bar{C} = \frac{\bar{c} - c_o}{c_s - c_o}$, equation 24 can be written as:

$$1-\bar{C} = \frac{2}{\sqrt{\pi}} \bar{X} \tag{25}$$

These results provide a first order approximation to the general solution valid in the neighborhood of t=o, of the unsteady state diffusion equation.

Equation 25 implies that, for t o, in general:

$$\bar{C} = f \quad (X) \tag{26}$$

To obtain a higher order approximation, we assume that f(X) can be expanded in the neighborhood of X = o, as a series in X; that is:

$$f(X) = f(o) + f'(o)\,X + \frac{f''(o)}{2!}X^2 + \ldots + \frac{f^n(o)}{n!}X^n + \ldots \tag{27}$$

Since the series should converge rapidly near X o, terms higher than f"(o) will be neglected. Thus, the second order approximation is obtained as:

$$\bar{C} = f(o) + f'(o)X + \frac{f''(o)}{2!}X^2 \tag{28}$$

From equation 25, it is evident that f(o) = 1, and $f'(o) = -\frac{2}{\sqrt{\pi}}$.

Therefore, equation 28 becomes:

$$\bar{C} = 1 - \frac{2}{\sqrt{\pi}}X + \frac{f''(o)}{2!}X^2 \tag{29}$$

The constant f"(o), is dependent on the shape of the solid, i.e., for different solid shapes, it has different values. The range of validity of this equation, and the values of f"(o) may be obtained by comparing it with specific solutions of equation 9 with the conditions shown by equation 10, or by empirical methods. Some of the known solutions are: (a) for a sphere, (b) for a plate of infinite area and (c) for an infinitely long cylinder. Since comparison with the solution for a sphere is of most importance in this work only this solution will be discussed later.

PART I

THE WEIGHT INCREASE OF THE CEREAL GRAINS DURING STEEPING

TREATMENT OF EXPERIMENTAL DATA

This section will describe the methods used to correlate the experimental data based on the equations derived in the previous chapter. One of the procedures was to treat the data by a first order approximation to the general solution. Since

$$\bar{C} = \frac{c_s - \bar{c}}{c_s - c_o} \qquad \text{and} \qquad X = \frac{A}{V}\sqrt{Dt}$$

equation 25 can be written in the alternative:

$$\bar{c} - c_o = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{Dt} \, (c_s - c_o) \tag{31}$$

Equation 25 was derived under the assumptions that the ratio of $\frac{A}{V}$, the diffusivity D, and the effective surface concentration c_s, are all constant. Hence, equation 31 can be expressed in term of the experimentally measurable variables as:

$$\bar{c} - c_o = K_1 \sqrt{t} \tag{32}$$

where

$$K_1 = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{D} \, (c_s - c_o) \tag{33}$$

This means that, if this mathematical model is applicable, there should be a linear relationship between $(\bar{c} - c_o)$ and $\sqrt{t}$.

A second procedure was to treat the data by a second order approximation. In this case equation 29 was rearranged to:

$$1 - \bar{C} = \frac{2}{\sqrt{\pi}} X - \frac{f''(o)}{2!} X^2 \tag{34}$$

Equation 34 can be expressed in terms of the experimentally measurable variables as:

$$k = k_o - b\sqrt{t} \tag{35}$$

where

$$k = \frac{\bar{c} - c_o}{\sqrt{t}} \tag{36}$$

$$k_o = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{D} \; (c_s - c_o) \tag{37}$$

$$b = \frac{f''(o)}{2!} \left(\frac{A}{V}\right)^2 D \; (c_s - c_o) \tag{38}$$

Equation 35 means that there should be a linear relation between k and $\sqrt{t}$.

The diffusivity, D, can be evaluated from either of these approximations. According to the first order approximation the diffusivity can be obtained from

$$D = \left[\frac{K_1}{\frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) (c_s - c_o)}\right]^2 \tag{39}$$

using experimentally determined values of K_1k $\left(\frac{A}{V}\right)$, and $(c_s - c_o)$. According to the second order approximation the diffusivity can be obtained from

$$D = \left[\frac{k_o}{\frac{2}{\sqrt{\pi}}\left(\frac{A}{V}\right) (c_s - c_o)}\right]^2 \tag{40}$$

using experimental values of k_o, $\left(\frac{A}{V}\right)$, and $(c_s - c_o)$.

In this work, the surface area to volume ration $\frac{A}{V}$, was determined from the sphericity of the material tested. The sphericity, ψ , is defined as the ratio of the surface area of a sphere to the surface area of the solid particles which have the same volume as the sphere. Its mathematical expression is:

$$\psi = \frac{\left(\frac{A}{V}\right)_{\text{sphere}}}{\left(\frac{A}{V}\right)_{\text{solid}}} \tag{41}$$

Equation 41 shows that the ratio of $(\frac{A}{V})$ of the solid particle can be evaluated provided both the volume V and the sphericity ψ are known. It can be assumed that the sphericity of a swelling solid is constant unless the swelling is unusually anisotropic.

Since the dimension of the solid was assumed to be constant at time near zero during diffusion, it is logical to choose the initial value of the ratio of $(\frac{A}{V})$ in the latter correlations. The method to evaluate this will be described later.

Equation 25 was derived by assuming that in moisture diffusion the dimension of the solid at time near zero is constant. In other words, the surface area-volume ration, $(\frac{A}{V})$, is constant. Hence, in this case, $\bar{c}$ is exactly equal to $\bar{m}$, and the dimensionless concentration, $\bar{C}$ can be replaced by the dimensionless moisture content, $\bar{M}$ which is defined as:

$$\bar{M} = \frac{m_s - \bar{m}}{m_s - m_o} \tag{42}$$

where $\bar{m}$ is the average moisture content at the given absorption time, m_s is the effective surface moisture content, and m_o is the initial moisture content. All of these quantities are expressed in grams of water per gram of dry material of the sample in this work.

The effective surface moisture content, m_s, was evaluated from the following considerations. In equation 31 for the first order approximation, the quantities $\frac{A}{V}$, $\sqrt{Dt}$, c_s, and c_o are all constant. Equation 31 can, therefore, be expressed as:

$$\bar{c} - c_o = K_A(c_s - c_o) \tag{43}$$

where
$$-K_A = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{Dt} \tag{44}$$

Equations 43 and 44 show that, in case the diffusion time is kept constant, the quantity $(\bar{c} - c_o)$ should be a linear function of c_o with a slope of $-K_A$ and $c_o = c_s$ when $(\bar{c} - c_o)$ equals zero. Based on this relationship, the value of c_s can be experimentally evaluated.

For the second order approximation, equations 35 to 38 give:

$$\bar{c} - c_o = \left[\frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{Dt} - \frac{f''(o)}{2!}\left(\frac{A}{V}\right)^2 Dt\right] (c_s - c_o) \tag{45}$$

It is evident that in case the diffusion time is kept constant, equation 45 can be expressed as:

$$\bar{c} - c_o = K_B \, (c_s - c_o) \tag{46}$$

where
$$K_B = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{Dt} - \frac{f''(o)}{2!}\left(\frac{A}{V}\right)^2 Dt \tag{47}$$

Thus it appears that in the second order approximations, as well as the first order, the quantity c_s can be evaluated from a plot of $\bar{c} - c_o$ versus c_o.

MATERIALS

The materials used in this study were pop corn, K1859 Hybrid corn, Gold Rash sweet corn, white kafir grain sorghum, and Atlas Sorgo. The average composition of these materials were:

	K-4 Hybrid pop corn %	Gold Rash sweet corn %	K1859 Hybrid corn %	White Kafir grain sorghum %	Atlas Sorgo %
Protein	10.69	10.88	9.44	10.69	8.88
Ether Extract	3.69	8.18	4.13	3.24	3.55
Crude Fiber	3.25	1.99	1.99	1.87	1.76
Moisture	9.78	10.10	10.96	10.74	9.73
Ash	1.45	1.83	1.40	1.72	1.51
N-free extract	72.14	67.02	72.08	71.74	74.57
Carbohydrates	74.39	69.01	74.07	73.61	76.33
Average initial surface area per grain, $cm.^2$	1.0655	2.334	2.2745	0.3363	0.3193
Average initial volume per grain, $cm.^3$	0.1038	0.1874	0.2634	0.0150	0.0141
Density, $g/cm.^3$	1.3333	1.3228	1.25	1.2755	1.3360

The steeping water was taken from the Manhattan City system. The analysis of water was reported as follows:

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

METHODS

As shown in Fig. 1, the weighed samples (thirty grams for wheat and twenty grams for sorghum) were placed in wire gauze baskets and immersed in a stirred water bath controlled within 1°F of the set temperature. At the end of each absorption period the samples were quickly removed from the water bath and superficially dried on a large filter paper. After the surface water on the samples was removed, the weight of the samples were determined immediately by weighing on a balance. The moisture gain was calculated from the weight of the water absorbed by the samples. It was determined on a dry basis as grams of water per gram of dry material.

Initial moisture content was determined by a two-stage air-oven method (16). For samples containing more than 13 percent moisture, the loss of moisture upon grinding is likely to be excessive. Hence the following two-stage procedure was used.

The first stage: The weight of the sample was recorded and the sample in the weighing container was placed in a warm, well-ventilated place protected from dust, so that the samples would dry reasonably fast and reach an approximately air-dry condition within fourteen to sixteen hours. By weighing the air-dried samples, the percentage moisture loss in air drying could be calculated.

The second stage: After grinding the air-dry sample into powder and weighing about three to four grams of the well mixed ground sample on a balance accurate to 1/1000 of a gram, it was placed in an oven kept at 130°C ($\pm 3^{\circ}$c) for one hour. Then the sample was placed in a desiccator and weighed as soon as it cooled down to room temperature. The dried residue was considered as the dry material within the sample, and the percentage of the loss of moisture in the second stage could be calculated.

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

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

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.

As mentioned in a previous section, the ratio of $\frac{A}{V}$ is related to the sphericity, ψ. The sphericity, ψ, in turn, can be related to the porosity, ϵ , of the cereal grains in a packed bed (4).

For measuring the porosity, the weighed samples were charged into a 2-inch diameter plastic column and immersed in the water tank, inside which the water temperature was controlled at a desired temperature (see Fig. 1). By recording the initial bed height as soon as the packed bed was completely formed, and measuring the volume of the sample, the initial porosity of the sample could be calculated.

The moisture pick-up by the grains within a very short time (about 5 sec.) was considered as due to capillary action, which was measured for each sample at several temperature levels.

As described previously, for the case of weight increase in moisture diffusion, equations 43 and 46 can be expressed in the same form as:

$$\bar{m}-m_o = K_A (m_s - m_o) \qquad (48)$$

$$\bar{m}-m_o = K_B (m_s - m_o) \qquad (49)$$

where $\bar{m}$ is the average moisture content at the given absorption time, m_o is the initial moisture content, m_s is the effective surface moisture content; and the quantity $(\bar{m}-m_o)$ is the weight gain per grain of dry material of the sample during steeping.

Both equations 48 and 49 show that when the weight gain, $\bar{m}-m_o$, is plotted as a function of the initial moisture content m_o, a linear relationship with a slope of $-K_A$ and an intercept at $(\bar{m}-m_o) = o$ of $m_o = m_s$ should result. Thus, the quantity m_s can be experimentally evaluated.

The experiments for measuring the weight increase of the samples during diffusion were carried out over a wide temperature range from 32°F to 212°F; and the periods of absorption time ranged from several minutes to six hours.

CORRELATION AND DISCUSSION OF RESULTS

Case A. First Order Approximation

In Figs. 2 and 3, the weight of K-4 Hybrid pop corn and white kafir grain sorghum at each absorption time, are plotted as a function of the absorption time. The results show that at the beginning the rates of weight increase for both samples were quite rapid, but they decreased gradually as the absorption time increased. Similar results were obtained for other samples. The experimental data for all five samples tabulated in Tables 1 to 5 in the Appendix.

The Relation Between $(\bar{m}-m_o)$ and $\sqrt{t}$. As described in the previous chapter, equation 32 shows that the concentration gain should be approximately proportional to the square root of the absorption time. In the case of weight increase, equation 32 can be expressed as:

$$\bar{m} - m_o = K_m \sqrt{t} \qquad (50)$$

where

$$Km = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{D_m} \; (m_s - m_o) \qquad (51)$$

Hence for each of the samples, the experimental data, $(\bar{m}-m_o)$ were plotted as a function of $\sqrt{t}$ for all temperature levels to determine the applicability of equation 50. Plots of pop corn and white kafir are shown in Figs. 4 and 5 respectively. Data of $(\overline{m}-m_o)$ versus $\sqrt{t}$ for all five samples are tabulated in Tables 6 to 10 in the appendix.

Fig. 4 shows that the relation between $(m-m_o)$ and $\sqrt{t}$ for pop corn is essentially linear in the neighborhood of t=o. At temperatures from 30°F to 80°F, this linear relationship holds up to two hours, but at higher temperatures between 100°F and 160°F it holds for shorter periods of time. This result indicates that the range of applicability of equation 50 is dependent on the temperature.

As the temperature was increased to 180°F, it was found that the ranges, during which the above stated linear relationship is valid, become longer than those at the temperatures between 100°F and 160°F, and becomes shorter again at a higher temperature.

This phenomenon might be due to the fact that at temperatures higher than 160°F the pop corn grains were rapidly denatured or gelatinized within a very short time during steeping. Hence, two sequences of different results appeared. Similar results were obtained with the other grains used except Gold Rash sweet corn.

The plot of the $(\overline{m} - m_o)$ vs $\sqrt{t}$ for Gold Rash sweet corn shows that the linear relationship held up to six hours for all temperatures except at 212°F. This means that, for this sweet corn, there is no difference in the range of validity of this linear relationship for any of the temperatures. In other words, the applicability of equation 50 is at least reasonable up to six hours for sweet corn.

<u>The Initial Moisture Weight Gain, m_i.</u> In studying the diffusion of the water into cereal grains, and testing the fitness of the experimental data to the derived diffusion equation, the quantity of rapid initial weight

gain, m_i, which has been well known to be due to the phenomenon of capillary action, should be considered. Beaker (3) and Fan, Chung and Shellenberger (10) have explained this capillary action for water diffusing into wheat as the result of the shallow pores in the pericarp, or the outer most layer of the wheat kernel. This capillary action is not caused by diffusion. Therefore, the quantity m_i should be substracted in calculating the weight gain according to the diffusion equation.

The quantity m_i, was measured for each of the five different samples at temperature levels ranging from 32^oF to 212^oF, assuming five seconds as the time needed for these samples to complete their capillary action. The results were expressed in grams of water per gram of dry material, and are tabulated in Table 11 for all five samples.

Figs. 6 and 7 show two typical results for the measured m_i. For pop corn, this quantity is seen as nearly constant; but for white kafir m_i increased with the temperature. The pericarp, or outer most layer of White Kafir, was less hard and more flexible so that the capillary pores in the pericarp become larger at higher temperatures. As the temperature increased above 160^oF, the measured m_i decreased. This was due to the vaporization of water during the process of superficial drying, and it should be considered as an experimental error.

For pop corn, the structure in the outer most layer was so hard that no such temperature effect resulted.

The Effective Surface Moisture Content, m_s. A large number of samples which had different initial moisture contents, m_o, were steeped in water for fifteen minutes to measure their weight gain. The experimental results are plotted in Fig. 8 for pop corn, and Fig. 9 for white kafir. These figures indicate that the linear relationship was obeyed by plotting $(m-m_o)$ as a function of m_o. The values of m_s were evaluated by extrapolating the straight line to the intercept with the abscissa, where $(\bar{m}-m_o)$ was equal to zero.

For pop corn, m_s was 0.515 grams per gram at 100°F, and 0.545 grams per gram at 160°F. The numerical values were nearly constant, hence the average value of 0.530 was used for the general correlation.

For white kafir, the values were 0.61 grams per gram at 100°F, 0.66 grams per gram at 130°F, and 0.71 grams per gram at 160°F. The values of m_s for other samples are listed in Table 12.

<u>The Surface Area to Volume Ratio</u> $\frac{A}{V}$. As mentioned previously, the surface area to volume ratio of the samples can be evaluated from their sphericity and volume. Since the volume of a sphere is

$$V = \frac{4}{3} \pi r^3 \tag{53}$$

from equation 41, the ratio of $\left(\frac{A}{V}\right)$ for the cereal grains can be expressed as:

$$\left(\frac{A}{V}\right)_{solid} = \frac{\frac{4 \pi r^2}{V}}{\psi} \tag{a}$$

but

$$r = \sqrt[3]{\frac{3V}{4\pi}}$$

therefore,

$$\left(\frac{A}{V}\right)_{solid} = \frac{\frac{4\pi}{V} \left(\frac{3V}{4\pi}\right)^{2/3}}{\psi} \tag{b}$$

and finally,

$$\left(\frac{A}{V}\right)_{solid} = \frac{4.83}{\psi V^{1/3}} \tag{55}$$

It is evident from equation 55 that the surface area to volume ratio of each sample can be evaluated from the known value of and V.

As described in the previous section, the initial surface-volume ratio of each sample was used to correlate the experimental results because the suggested diffusion model was originally derived by assuming that the ratio of $\frac{A}{V}$ is constant. As previously shown the sphericity is related to the bed porosity of the grains. In Fig. 10 the sphericity is plotted as a function of the porosity as given by Brown et al. (4). The experiments were carried out at several temperature levels to determine the initial porosity for each sample. These were 0.3647 for pop corn, 0.4364 for white kafir, 0.4178 for K1859 Hybrid corn, 0.5205 for Sweet corn and 0.4210 for Atlas Sorgo. In this work, the condition of the packed bed was considered as a normal packing.

General Correlation. If the diffusion model used in this work is valid for the water-cereal grain diffusion, there should be a linear relationship between the dimensionless weight gain $(1-\bar{M})$ and the new variable X_m with a slope of $\frac{2}{\sqrt{\pi}}$. In order to test this, the data which follows equation 50 were correlated in this manner. The results were tabulated in Table 13 and plotted in Figs. 11 and 12 for pop corn and white kafir.

Figs. 11 and 12 show that the experimental data for all temperature levels agreed well with the theoretical line. It was found experimentally that this correlation only held for short time range steeping data. Generally, it was valid for not more than two hours with some exceptions.

Evaluation of the Diffusion Coefficient D_m. In the case of the weight increase in moisture diffusion, equation 39 can be expressed as:

$$D_m = \left[\frac{K_m}{\frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) (m_s - m_o)} \right]^2 \qquad (56)$$

The diffusion coefficient D_m can be evaluated from equation 56 with the known quantities of $(\frac{A}{V})$, $(m_s - m_o)$, and K_m. From equation 50, it is evident that K_m is the slope of the linear portion in the plot of $(\bar{m}-m_o)$ vs $\sqrt{t}$. Therefore, the value of the quantity K_m can be determined experimentally. The calculated values of the diffusion coefficients, D_m, found from equations 56 are tabulated in Table 14.

The diffusion coefficient, D_m, for all the five different cereal grains were plotted versus the reciprocal of the absolute temperature on a semi-logarithmic scale in Figs. 13, 14, 15, 16 and 17. The results show that the relation between the diffusion coefficient and the absolute temperature follows the Arrhenius-type equation:

$$D = D_o \exp \left\{ - \frac{E}{RT} \right\}$$

where E is the energy of activation, R is the universal gas constant, and T is the absolute temperature. The constants D_o, and the slopes $(\frac{E}{R})$ of the linear regression lines of the Arrhenius relation were estimated by the method of least squares, and the energy of activation E was evaluated by multiplying the slope $(\frac{E}{R})$ by the gas constant R. For pop corn, the value of the activation energy was 6.853 K cal per mole, and the value of D_o was 1.535×10^{-2} cm^2 per sec. For white kafir, the value of the activation energy was 8.339 K cal per mole, and the value of D_o was 4.47×10^{-2} cm^2 per sec. For other samples, the values of activation and the values of the constant D_o were:

K1859 Hybrid corn:	E = 7.578 KCal/mole	D_o = 1.077×10^{-1} cm^2/sec
Gold Rash sweet corn:	E = 8.167 KCal/mole	D_o = 8.535×10^{-2} cm^2/sec
Atlas Sorgo:	E = 8.424 KCal/mole	D_o = 6.196×10^{-2} cm^2/sec

Case B. Second Order Approximation

Evaluation of the Diffusion Coefficient. In the case of weight increase, equations 35 to 38 can be expressed as:

$$k = k_o - b\sqrt{t} \tag{35}$$

where

$$k = \frac{\bar{m} - m_o}{\sqrt{t}} \tag{36a}$$

$$k_o = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{D_m} \; (m_s - m_o) \tag{37a}$$

$$b = \frac{f''(o)}{2!} \left(\frac{A}{V}\right)^2 D_m \; (m_s - m_o) \tag{38a}$$

Equations 35 and 36a show that a linear relationship with a slope of -b and an intercept of k_o should result if k is plotted as a function of $\sqrt{t}$.

In order to test this, the experimental data of both pop corn and white kafir were plotted as shown in Figs. 18 and 19 respectively, and the data of these plots are given in Table 15 in the appendix. These plots show that the experimental results of both pop corn and white kafir sorghum follow the desired linear relationship suggested by equations 35 and 36a, the values of K_o were obtained by extrapolation. They are listed in Table 16.

Table 16. Values of k_o evaluated in the temperature range from 80°F to 160°F for pop corn and white kafir.

Material	Temperature °F	k_o gm./gm/(sec.)1/2
K-4 Hybrid pop corn	160	4.2×10^{-3}
	140	3.55×10^{-3}
	120	3.25×10^{-3}
	100	2.70×10^{-3}
	80	1.95×10^{-3}
white kafir (grain sorghum)	160	8.15×10^{-3}
	140	6.65×10^{-3}
	120	5.15×10^{-3}
	100	3.73×10^{-3}
	80	2.65×10^{-3}

By analogy with equation 40

$$D_m = \left[\frac{k_o}{\frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) (m_s - m_o)} \right]^2 \qquad (57)$$

Hence, the value of D_m could be evaluated from the known values of k_o, $\frac{A}{V}$, and $(m_s - m_o)$. Equation 48 and 49 show that the value of m_s which was evaluated in case (A), can also be used for the present case. Similarly, values of $\frac{A}{V}$ which were used in case (A) can be used here. The values of D_m for both pop corn and white kafir were evaluated by this means and are plotted as a function of the reciprocal of the absolute temperature in a semi-logarithum scale, in Figs. 20 and 21, and the data of these plots are listed in Table 17, appendix. The results showed that the relation between the diffusion coefficients and the temperature again follows the Arrhenius-type equation.

$$D = D_o \exp \left(- \frac{E}{RT} \right)$$

The values of E and D_o found for these two samples were:

	D_o	E
K-4 Hybrid pop corn	3.716 cm^2/sec	5.811 KCal/mole
White kafir (grain sorghum)	7.516 cm^2/sec	8.458 KCal/mole

The values of E and D_o which were obtained for both case A and case B for these two samples are tabulated in Table 17.

Table 17. Values of D_o and E evaluated for both case A and case B for pop corn and white kafir.

Material	D_o (cm^2/sec)		E (KCal/mole)	
	Case A	Case B	Case A	Case B
K-4 Hybrid pop corn	1.535 $\times 10^{-2}$	3.716	6.853	5.811
White kafir (grain sorghum)	4.47 $\times 10^{-2}$	7.516	8.339	8.458

General Correlation. As mentioned in a previous section, the correlation according to the second order approximation is:

$$1 - \bar{C} = \frac{2}{\sqrt{\pi}} X - \frac{f''(o)}{2!} X^2 \qquad (29)$$

Equation (29) can be expressed as:

$$\frac{1-\bar{C}}{X} = \frac{2}{\sqrt{\pi}} - \frac{f''(o)}{2!} X \qquad (29a)$$

The solution for unsteady state diffusion in a sphere is:

$$\bar{C} = \frac{6}{\pi^2} = \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(- \frac{n^2 \pi^2}{9} X^2\right) \qquad (30)$$

(Derivation of equation 30 is in appendix).

In order to see the range of validity of equation 29, the quantity $\frac{1 - \bar{C}}{X}$, which was calculated according to equation 30, was plotted as a function of X in Fig. 22. From this plot, it is seen that in the neighborhood of X = o, the curve is essentially linear. The linear approximation covering the range of X from zero to 1.6 ($\bar{C}$ = 0.0459) gives the value of the slope $\frac{f''(o)}{2!}$ as 0.34 for a sphere. The error due to the approximation is less than 2 percent. Hence it can be concluded that equation 29 accurately represents the solution in the neighborhood of X = o.

The numerical calculation for the analysis is shown in Tables 17 and 18.

The values of $\overline{C}$ in Table 18 were calculated from equation 30 with the given values of X. In Table 19 the column, m, shows the values of the slope, which were calculated from following relation:

$$m = \frac{\frac{2}{\sqrt{\pi}} - Y}{X} \qquad (59)$$

Table 18. Values of $\overline{C}$ and Y calculated according to equation 30 for the given value of X.

X	$\overline{C}$	$\frac{1 - \overline{C}}{X} = Y$
0.1	0.89088	1.09120
0.2	0.78754	1.06233
0.3	0.69637	1.01212
0.4	0.60076	0.99810
0.5	0.51674	0.96652
0.6	0.44299	0.92835
0.8	0.31300	0.85875
1.0	0.20501	0.79499
1.2	0.12564	0.72863
1.4	0.07090	0.66364
1.6	0.04590	0.59630
1.8	0.01736	0.54590
2.0	0.00757	0.49620

Table 19. Error analysis for $(1-\bar{C})$ due to the second order approximation.

X	Y	m	Y_m	$(1-\bar{C})_m$	$1-\bar{C}$	error %
0	1.12838					
0.1	1.0912	-0.37180	1.0944	0.10944	0.10912	+0.29
0.2	1.06233	-0.33025	1.0604	0.21208	0.21246	-0.18
0.3	1.01212	-0.38753	1.0264	0.30792	0.30364	+1.41
0.4	0.99810	-0.32570	0.99236	0.49694	0.39924	-0.58
0.5	0.96652	-0.32372	0.95836	0.47918	0.48327	-0.85
0.6	0.92835	-0.33338	0.92436	0.55462	0.55701	-0.43
0.8	0.85875	-0.33704	0.85635	0.68508	0.68700	-0.28
1.0	0.79499	-0.33339	0.78834	0.78834	0.79499	-0.84
1.2	0.72863	-0.33313	0.72033	0.86440	0.87436	-1.14
1.4	0.66364	-0.33196	0.65232	0.91325	0.92910	-1.711
1.6	0.59630	-0.32355	0.58431	0.93490	0.95410	-2.012

mav. = -0.34001

where
$$Y = \frac{1 - \bar{C}}{X} \tag{60}$$

The results show that the values of m are very close to constant, hence the average value of m which equals -0.34001 may be used in the range from X = 0 up to X = 16. Y_m, are the values of Y, which were calculated from equation 59 with the average value of m. $(1-\bar{C})_m$ are the values calculated by dividing Y_m with X. $(1-\bar{C})$ are the values calculated by dividing with X. The percentage deviations were calculated from the $(1-\bar{C})_m$ and $(1-\bar{C})$. Then, for a spherical solid, equation (58) becomes:

$$\frac{1 - \bar{C}}{X} = \frac{2}{\sqrt{\pi}} - 0.34\ X \tag{61}$$

or in the case of weight increase in moisture diffusion, equation (61) can be expressed as:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - 0.34\ X \tag{62}$$

where

$$1 - \bar{M} = \frac{\bar{m} - m_o}{m_s - m_o}$$

In Fig. 22, the experimental data of pop corn were plotted in form of $\frac{1 - \bar{M}}{X}$ vs X. Since the sphericity of the pop corn used was practically equal to one, the plot showed that the experimental results of pop corn agreed closely to the theoretical line for spherical particles. Hence equation 62 can be considered as the correlation equation for pop corn. The sphericity of white kafir was equal to 0.822. For such particles, equation 62 can not be applied, but equation 29, which is for any shape, can be used. For the experimental data of white kafir, the plot of the $\frac{1 - \bar{M}}{X}$ as a function of X in Fig. 23 shows that the value of $\frac{f''(o)}{2!}$ obtained empirically was 0.4206. Hence, the final correlation equation obtained is:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - 0.4206\, X \qquad (63)$$

In examining equations (62) and (63), it is very interesting to notice that if the $\frac{f''(o)}{2!}$ value of the sphere 0.34, is divided by the sphericity, 0.822, of the white kafir, a quotient of 0.4136 is obtained. This value is very close to the experimentally determined value of the coefficient in equation 63. Therefore, for a non-spherical solid with high sphericity, the correlation equation can be approximated by the following equation:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - \frac{0.34}{\psi}\, X \qquad (64)$$

where is the sphericity of the non-spherical particles. The lines representing equation (64) are shown in Fig. 24. Figs. 22 and 23 show that there are still some deviations between the experimental results and the correlation lines. This deviation might be caused by the following factors.

a) The accuracy of the equipment.

b) The surface area-volume ratio of the solid during steeping is not a constant.

c) The applicability of the constant value of m_s. Nevertheless, both equations (62) and (63) may be considered satisfactory correlation models for the diffusion of water into cereal grain.

CONCLUSION

The results obtained in these experiments show that the experimentally measured steeping data of all the five samples obey the diffusion equation based on Fick's law. The equation based on the first order approximation, holds for all temperatures from 32°F to 210°F. The diffusion coefficients D_m were evaluated from the experimental data and plotted as a function of the reciprocal of the absolute temperature on a semi-logarithmic scale. The results show that the relation between D_m and $\frac{1}{T}$ follows the Arrhenius-type equation:

$$D = D_o \exp\left(-\frac{E}{RT}\right)$$

where E is the energy of activation, D_o is a diffusion constant. The general correlation equation is:

$$1 - \bar{M} = \frac{2}{\sqrt{\pi}} X_m$$

The experimental results show that this correlation equation only holds for a short steeping time. Generally, it is valid for the time range of not more than two hours, with some exceptions.

The equation based on the second order approximation holds for temperature levels from $80^{\circ}F$ to $160^{\circ}F$. The diffusion coefficient, D_m, was evaluated from equation 57. Similar to the case of the first order approximation, the relation between D_m and $\frac{1}{T}$ follows the Arrhenius equation.

The general correlation equations obtained for pop corn ($\psi \doteq 1$) is:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - 0.34\ X$$

and for white kafir ($\psi = 0.822$) is:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - 0.4206\ X$$

It is very interesting to notice in these two results that for other non-spherical materials with high sphericity, the correlation equation can be approximated by:

$$\frac{1 - \bar{M}}{X} = \frac{2}{\sqrt{\pi}} - \frac{0.34}{\psi}\ X$$

where   is the sphericity of the material.

It is known that Arrhenius plots of water-wheat diffusivities often results in two linear regression lines which intercept at approximately $150^{\circ}F$. The results of the present work show that the diffusivities of water in the grains of corn and sorghum are of the same order as those in wheat, but they can be always correlated by a single linear regression line. This difference may be due to the following reason. The linear relationship of equation 50, which was used to evaluate the diffusivities, holds for as long as seven hours of steeping. Water must diffuse through a gelatinized mass of starch during this period at temperatures above $150^{\circ}F$. For corns and sorghums, however, the validity of equation 50 holds up to not more than two hours of steeping time. Hence, the diffusion process during this period must be mainly limited to the outer portion of the kernels (hull and the protein rich portion), which is considerably thicker than that of the wheat and not affected by the gelatinization even at higher temperature.

PART II

THE VOLUME INCREASE OF THE CEREAL GRAINS DURING STEEPING

GENERAL DESCRIPTION

In part (I), it was demonstrated that Fick's law of molecular diffusion can be employed to correlate the weight increase of corn and sorghums during steeping in liquid water. The equation developed is:

$$\overline{C} = 1 - \frac{2}{\sqrt{\pi}} X + \frac{f''(o)}{2!} X^2 \qquad (29)$$

where $\overline{C} = \frac{\overline{c} - c_s}{c_o - c_s}$ is a dimensionless concentration, $\overline{c}$ is the average concentration, c_o is the initial concentration, and c_s is the concentration at the bounding surface; $X = \frac{A}{V}\sqrt{Dt}$; and $f''(o)$ is a constant dependent on the shape of the solid.

In regard to the weight increase of the cereal grains (such as corn and sorghum), it was shown in part (I) that equation 29 was successfully applied to correlate the experimental results. Since Figs. 25 and 26 (experimental data of the volume increase versus time for all five samples are listed in Tables 20, 21, 22, 23 and 24 in appendix), show that the volume-time curves of the samples are very similar to their weight-time curves, it may be expected that the volume change of the cereal grains during steeping may be expressed by similar equations when it is considered that the volume increase of the cereal grains is due to the transport of volume associated with mass from one phase (liquid phase) into another phase (solid phase) of the material system.

The volume increase of the cereal grain was postulated to be due to the formation of empty spaces in cracks inside of the kernels, and the penetration of water into the kernels is mainly due to the flow of water into the cracks formed. The mathematical expression for this assumption can be given by the simple material balance (65):

$$\rho_f \sum \Delta V = \sum \Delta W \tag{65}$$

where ρ_f is the density of water, $\sum \Delta V$ is the total volume increase, and $\sum \Delta W$ is the total weight increase. The experimentally measured data were plotted in Figs. 27 and 28 for the pop corn and the white kafir respectively. The results show that the relationship between weight increase and volume increase was closely linear as expressed by equation 65. This, in turn, indicates that equation 65 may be considered as a model to correlate the experimental results of the volume increase.

EXPERIMENTAL PROCEDURE

The liquid displacement method was used to measure the volume increase. Toluene was used as the liquid. After the weight of the sample was measured at the end of each immersion time, the sample was charged into a burette which was filled with a known amount of toluene. The displaced volume of toluene was taken as the volume of the sample.

The initial volume content was also measured by the liquid displacement method after the initial moisture content was determined by a two-stage air-oven method. Initial volume content was defined as the volume of water, as liquid, originally contained within the sample per unit volume of the dry material. This definition is analogous to that of the initial moisture content.

In order to evaluate the effective surface volume content, samples were prepared with initial volume contents ranging from 0.38cc/cc to 0.625cc/cc for pop corn; and from 0.49cc/cc to 0.78cc/cc for white kafir. The samples were immersed in water at different temperature levels, and their final volumes were measured after 15 minutes of immersion.

CORRELATION AND DISCUSSION OF RESULTS

In the case of the volume increase, equation 29 should be rewritten:

$$\bar{V} = 1 - \frac{2}{\sqrt{\pi}} X_v + \frac{f''(o)}{2!} X_v^2 \tag{66}$$

where $\bar{V} = \dfrac{\bar{v} - v_s}{v_o - v_s}$ is a dimensionless expression of volume, v_s is the effective surface volume content, v_o is the initial volume content, $\bar{v}$ is the average volume, X_v is $\frac{A}{V}\sqrt{D_v t}$, and D_v is the volumetric coefficient of expansion.

For small values of X_v, equation (66) approximates to:

$$1 - \bar{V} = \frac{2}{\sqrt{\pi}} X_v \tag{67}$$

or in terms of experimental variables:

$$\bar{v} - v_o = K_v \sqrt{t} \tag{68}$$

where
$$K_v = \frac{A}{V}(v_s - v_o)\sqrt{D_v} \tag{69}$$

Therefore, the volume increase of the kernels of the samples during steeping should be approximately a linear function of the square root of the absorption time with a slope of K_v. To determine the validity of equation 68, the experimental data, $(\bar{v} - v_o)$, were plotted as a function of $\sqrt{t}$. Fig. 29 is such a plot for pop corn, and Fig. 30 is for white kafir. Data of $(\bar{v} - v_o)$ vs $\sqrt{t}$ for all the five samples are tabulated in Tables 25, 26, 27, 28 and 29 in appendix.

Fig. 29 shows that the relation between $(\bar{v} - v_o)$ and $\sqrt{t}$ for pop corn is very similar to its $(\bar{m} - m_o)$ vs $\sqrt{t}$ plot. That is, in the neighborhood of t = o, the relationship between $(\bar{v} - v_o)$ and $\sqrt{t}$ obeys the linear model of equation 68. But, the range of the applicability is dependent on the temperature. Similar results were obtained for other samples.

In part (I), it was mentioned that at the very beginning of steeping, there was a quantity of water, taken up through capillary action, and which should be substracted in calculating the weight gain, $(m - m_o)$, to be used in the diffusion equation. In the case of volume increase, an equivalent quantity, v_i, was found. For pop corn, the values of v_i were independent of temperature. For white kafir, the values of v_i were affected by the temperature. Values of v_i for all the five samples are listed in Table 30.

In the case of the volume increase, equations 43 and 44 can be expressed as:

$$\bar{v} - v_o = K_v(v_s - v_o) \tag{70}$$

$$K_v = \frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \sqrt{D_v t} \tag{71}$$

The plots $(v - v_o)$ vs v_o show that the experimental data follow this linear relationship for all the five samples. Thus, by extrapolating the straight line up to the intercept where $(v - v_o)$ is zero, the values of v_s could be obtained. From Figs. 31 and 32 it is seen that for pop corn, the values of v_s obtained were 0.725 cc/cc at 100°F, 0.750 cc/cc at 160°F, for white kafir, the values of v_s were 0.79 cc/cc at 100°F, 0.855 cc/cc at 130°F and 0.930 cc/cc at 160°F. v_s for all the samples are listed in Table 31 in the appendix.

For corn, the values of v_s evaluated at different temperatures were almost constant, but for sorghums, they were affected by the temperature.

Similarly to the procedure of part (I), if equation 67 is valid, there should be a linear relationship between the dimensionless volume gain (1 - V) and X_V with a slope of $\frac{2}{\sqrt{\pi}}$. Figs. 33 and 34 show that the experimental results for both pop corn and white kafir follow this linear relationship. The data for all five samples are listed in Table 37 in the appendix.

In the case of the volume increase, equation 39 can be expressed as:

$$D_V = \left[\frac{K_V}{\frac{2}{\sqrt{\pi}} \left(\frac{A}{V}\right) \left(v_s - v_o\right)} \right]^2 \qquad (72)$$

Therefore, the values of the volume expansion coefficient, D_V, could be evaluated from the known values of K_V, $\left(\frac{A}{V}\right)$ and $(v_s - v_o)$. The values of D_V evaluated for all the five samples are plotted as a function of the reciprocal of the absolute temperature on a semi-logarithmic scale in Figs. 35, 36, 37, 38 and 39. The results show that the relation between the volume expansion coefficient and the absolute temperature follows the Arrhenius-type equation:

$$D_V = D_o \exp\left[- \frac{E}{RT} \right] \qquad (73)$$

where E is the energy of activation, R the universal gas constant, and T is the absolute temperature. The values of the constant, D_o, and the slopes $\left(\frac{E}{R}\right)$ of the linear regression lines of the Arrhenius relation were estimated by the method of least squares, and the values of E were evaluated by multiplying the slope $\frac{E}{R}$ by the gas constant R. The values of D_o and E obtained for all the five samples are as follows:

	D_o, cm^2/sec.	E, KCal/mole
K-4 Hybrid pop corn	1.96×10^{-1}	8.418
Gold Rash sweet corn	9.612×10^{-2}	8.153
K1859 Hybrid corn	5.055×10^{-2}	7.102
White kafir (grain sorghum)	7.84×10^{-2}	8.894
Atlas Sorgo	6.358×10^{-2}	10.157

Values of D_V for all the five samples are listed in Table 32 of the appendix.

CONCLUSION

The experimental data indicated that the relationship between the weight increase and volume increase of the samples during steeping is closely linear as expressed by equation 65. Therefore, equation 25, the first order approximation of the diffusion equation was used to correlate the volume increase data. The results show that the equation successfully correlates the experimental data (up to two hours of diffusion time) for all the five samples. The general correlation obtained is:

$$1 - \overline{V} = \frac{2}{\sqrt{\pi}} X_v$$

The volume expansion coefficient, D_V, obeyed the Arrhenius equation.

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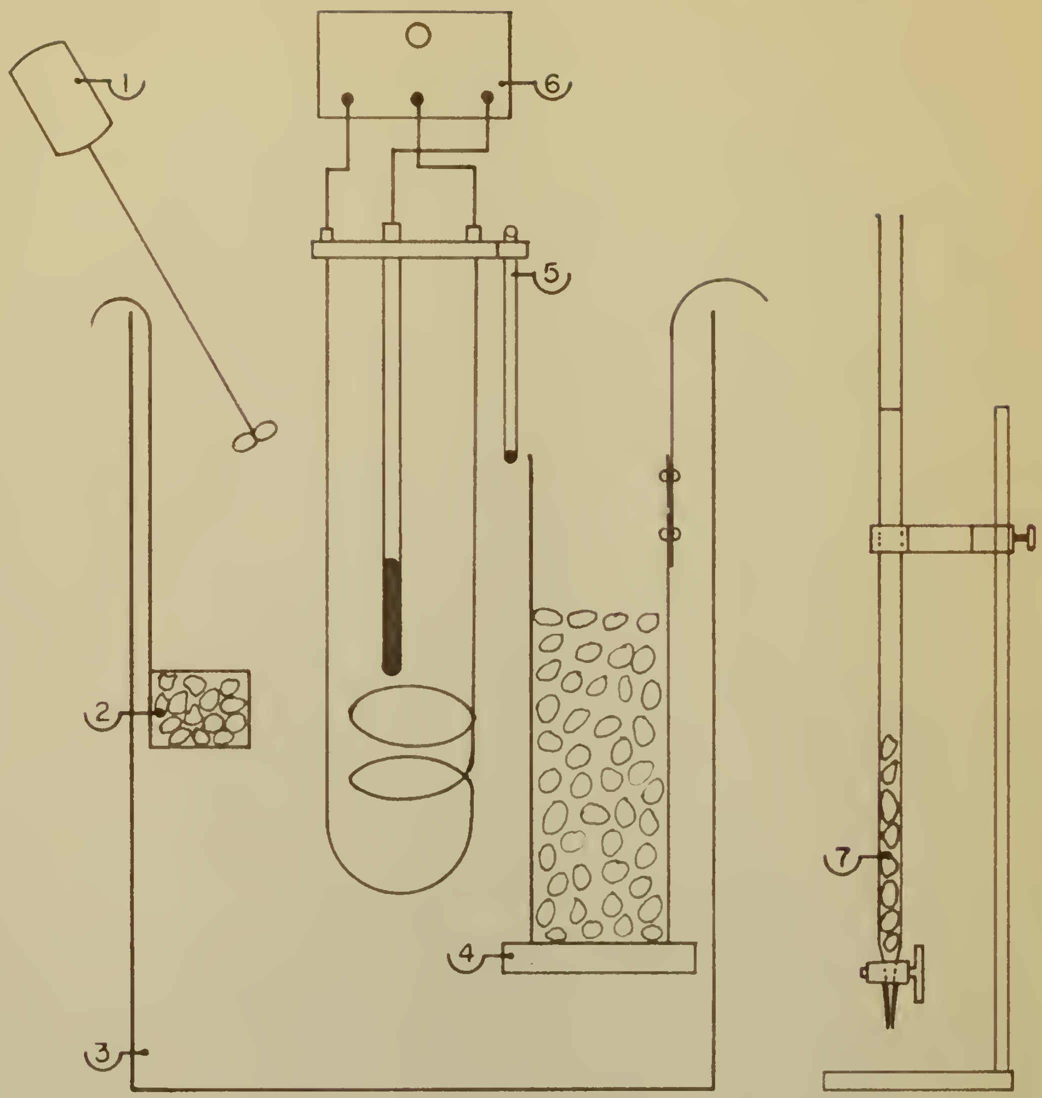
APPENDIX



1. STIRRER 2. SAMPLE 3. WATER TANK 4. CYLINDER 5. THERMOMETER 6. HEATER AND REGULATOR 7. BURETTE FOR VOLUME MEASUREMENT.

Fig. 1. Schematic diagram of equipment.

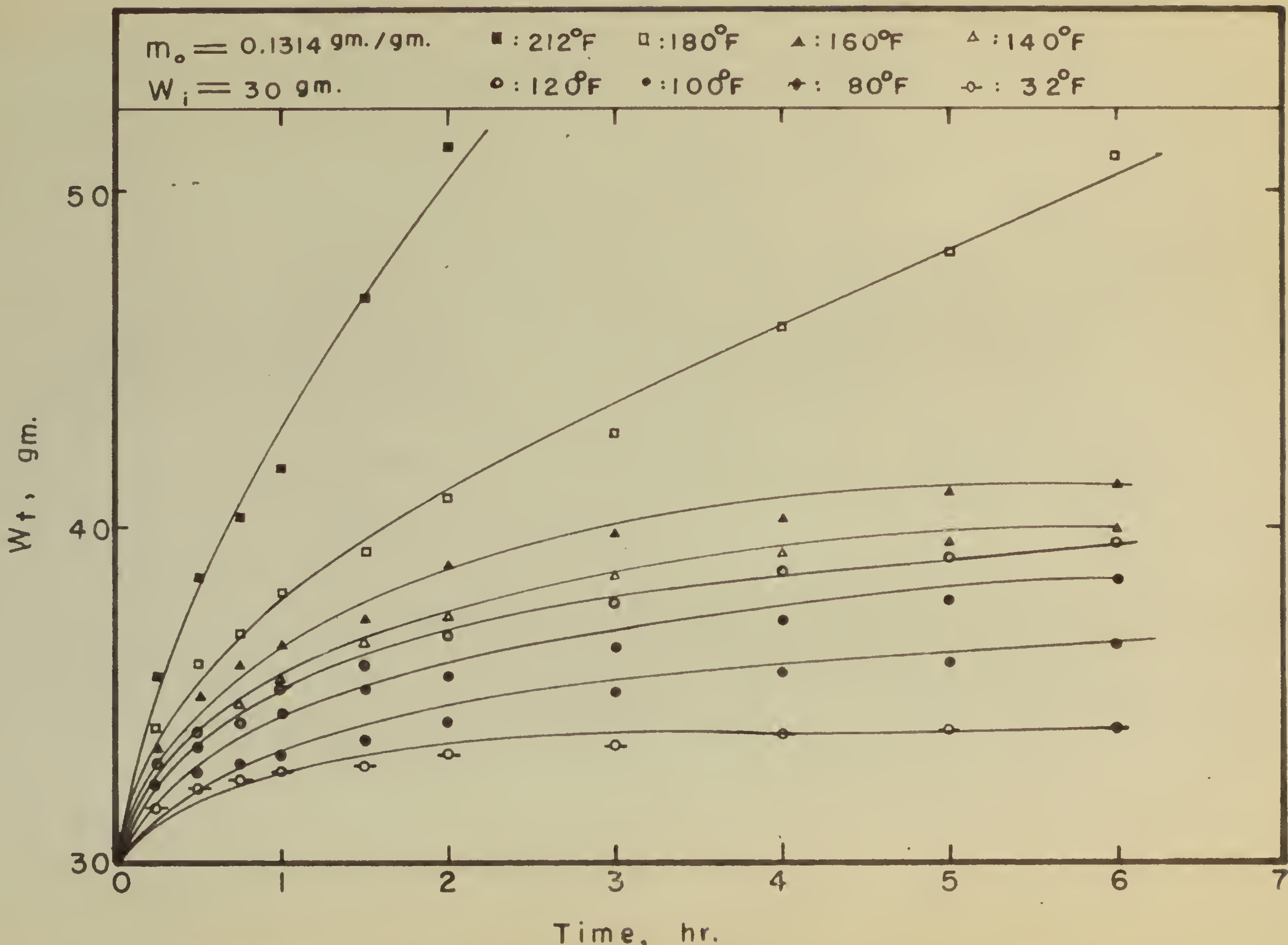


Fig. 2 **Weight** of Pop Corn as a function of absorption time.

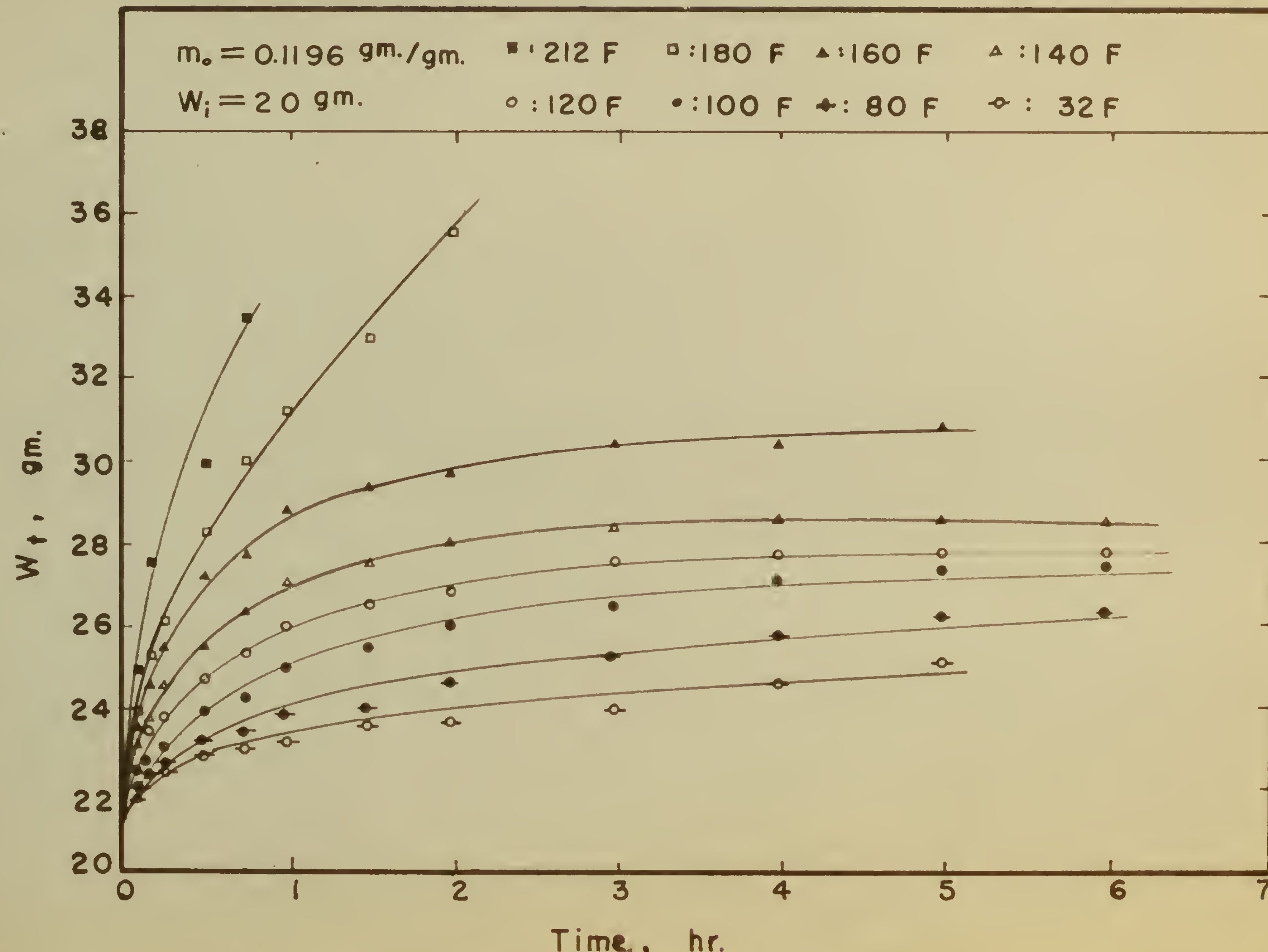


Fig. 3. Weight of White Kafir (grain sorghum) as a function of absorption time.

Table 1. Experimental data on weight increase of K-4 hybrid pop corn during steeping at different temperatures.

Time	weight, gm.							
(min.)	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
2	30.82	31.10	31.44	31.50	31.65	31.67	31.65	32.28
5	31.12	31.75	32.00	32.30	32.10	32.38	32.50	33.70
10	31.55	31.95	32.60	32.88	33.05	33.02	33.35	34.75
15	31.70	32.35	32.88	33.00	33.20	33.65	34.00	35.55
30	32.30	32.70	33.50	34.00	33.95	35.00	36.00	38.18
45	32.50	33.00	33.90	34.61	34.85	35.90	36.90	40.34
60	32.72	33.30	34.50	35.40	35.45	36.55	38.10	41.92
90	32.86	33.70	36.20	36.00	36.60	37.36	39.40	46.92
120	33.32	34.30	35.60	36.85	37.35	39.00	40.95	51.46
180	33.75	35.12	36.50	37.83	38.65	39.94	42.80	58.60
240	33.90	35.74	37.30	38.80	39.30	40.40	46.00	
300	34.03	35.95	37.94	39.15	39.65	41.10	48.25	
360	34.07	36.53	38.54	39.62	39.90	41.22	51.10	

Table 2. Experimental data on weight increase of K1859 hybrid corn (dent corn) during steeping at different temperatures.

Time	weight, gm.							
(min.)	32°F	84°F	90°F	110°F	120°F	150°F	173°F	212°F
0	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
2	31.26	31.28	31.28	31.41	31.51	31.57	31.82	32.69
5	31.54	31.68	31.31	31.70	32.03	32.28	32.66	34.23
10	31.63	31.37	31.89	32.08	32.47	32.89	33.66	36.03
15	31.80	32.33	32.00	32.30	32.60	33.00	34.40	36.85
30	32.00	32.83	33.00	33.50	33.80	34.50	35.70	39.80
45	32.25	33.32	33.75	34.00	34.50	33.90	37.10	42.55
60	32.40	33.82	34.10	34.60	35.50	36.70	38.45	43.30
90	32.80	34.36	34.90	35.60	36.30	37.90	40.30	48.65
120	33.30	35.40	35.80	36.10	37.50	39.60	42.20	51.20
180	33.50	36.10	37.00	38.00	38.70	40.90	44.20	60.70
240	33.80	37.20	38.00	39.00	39.80	42.20	46.60	68.45
300	34.20	38.00			41.50	43.30	47.60	71.80
360	34.40	38.48	39.00		42.10	44.30	48.90	78.30

Table 3. Experimental data on weight increase of Gold Rush sweet corn during steeping at different temperatures.

Time	weight, gm.							
(min.)	32°F	82°F	100°F	120°F	140°F	160°F	180°F	210°F
0	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
2	31.10	30.90	32.25	32.22	32.06	32.77	32.75	33.65
5	31.38	32.35	32.55	33.15	33.75	33.69	33.90	33.35
10	31.77	32.75	33.25	33.60	34.00	34.90	35.75	37.60
15	32.10	32.80	33.50	34.75	34.25	36.68	37.45	39.20
30	32.30	34.00	34.60	35.70	36.20	38.25	40.45	44.61
45	32.70	34.40	35.45	37.05	39.10	40.70	43.10	47.25
60	33.00	34.95	36.37	38.00	40.40	42.25	45.70	51.15
90	33.33	35.90	37.60	39.90	42.20	44.75	48.80	55.95
120	33.68	37.15	38.71	42.10	44.40	46.80	52.90	59.65
180	34.20	38.40	40.89	43.90	47.70	51.20	56.30	65.20
240	34.42	40.42	43.10	46.83	50.76	55.20	62.00	
300	34.61	41.85	44.70	49.40	53.65	58.08	65.61	
360	34.97	42.86	46.30	50.40	56.10	60.50	68.90	

Table 4. Experimental data on weight increase of White kafir (grain sorghum) during steeping at different temperatures.

Time	weight, gm.							
(min.)	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
2	21.49	21.65	22.15	22.10	22.35	22.50	22.80	22.83
5	22.16	21.80	22.44	22.67	23.00	23.45	23.85	24.84
10	22.22	22.40	22.70	23.40	23.70	24.50	25.30	27.55
15	22.56	22.66	23.05	23.75	24.50	25.40	26.10	29.07
30	22.92	23.20	23.88	24.75	25.50	27.25	28.30	
45	23.04	23.40	24.24	25.36	26.30	27.70	29.90	
60	23.19	23.80	24.97	25.90	27.03	28.80	31.20	
90	23.59	24.00	25.45	26.55	27.50	29.40	33.00	
120	23.65	24.66	26.03	26.80	28.00	29.70	35.60	
180	24.00	25.30	26.50	27.60	28.40	30.45	41.30	
240	24.10	25.80	27.20	27.85	28.60	30.53	47.50	
320	24.72	26.30	27.40	28.10	28.60	30.90	50.70	
360	25.20	26.40	27.55	28.25	28.60		55.40	

Table 5. Experimental data on weight increase of Atlas sargo during steeping at different temperatures;

Time	weight, gm.							
(min.)	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	20.00	20.00	20.00	20.00	20.00	20.00	20.00	20.00
2	20.65	20.70	21.00	21.20	21.25	21.72	21.85	22.02
5	20.75	21.09	21.40	21.80	22.10	22.10	22.80	23.32
10	20.90	21.59	21.80	22.20	22.79	23.40	24.00	26.68
15	21.00	21.79	22.00	22.50	23.60	24.20	25.18	29.62
30	21.30	22.26	22.62	22.80	25.54	25.61	26.79	37.02
45	21.60	22.45	23.15	24.30	25.71	26.50	27.80	46.00
60	21.80	22.77	23.61	25.32	26.40	27.58	28.90	53.44
90	22.15	23.30	25.35	25.85	27.30	27.90	31.05	59.00
120	22.18	23.64	25.00	26.18	27.50	28.25	33.20	
180	22.63	24.30	25.80	26.76	27.63	28.60	38.25	
240	22.85	24.80	26.30	27.85	28.78	48.35		
300	22.95	25.10	26.50	27.58	28.00	28.70	54.05	
360	23.10	25.35	26.75	27.70	28.20	28.70	67.25	

Table 6. Values of $(\bar{m} - m_o)$ vs t for K-4 hybrid pop corn steeped at different temperatures.

t, (sec.)$^{1/2}$	$\bar{m} - m_o$ (gm./gm.)							
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.014	0.0226	0.0298	0.0320	0.0377	0.0385	0.0415	0.0612
17.32	0.0245	0.0471	0.0509	0.0622	0.0547	0.0652	0.0735	0.1188
24.50	0.0415	0.0147	0.0735	0.0841	0.0905	0.0894	0.1056	0.1584
30.00	0.0471	0.0698	0.0841	0.0886	0.0962	0.1143	0.1301	0.1886
42.40	0.06977	0.0830	0.1075	0.1263	0.1244	0.1640	0.2055	0.3028
52.00	0.0773	0.0943	0.1226	0.1493	0.1584	0.1980	0.2395	0.3692
60.00	0.09089	0.1056	0.1452	0.1791	0.1810	0.2225	0.2847	
73.50	0.09315	0.1206	0.1716	0.2018	0.2244	0.2530	0.3338	
85.00	0.1083	0.1433	0.1867	0.2338	0.2527	0.3149	0.3922	
104.00	0.1245	0.1742	0.2206	0.2708	0.3017	0.3504		
120.00	0.1301	0.1976	0.2508	0.3074	0.3262	0.3677		
134.20	0.1350	0.2055	0.2749	0.3205	0.3394	0.3941		
147.00	0.1365	0.2274	0.2975	0.3383	0.3488	0.3986		

Table 7. Values of $(\bar{m} - m_o)$ vs t for K1859 hybrid corn (dent corn) steeped at different temperatures.

$t\ (sec.)^{1/2}$	$\bar{m} - m_o$ (gm./gm.)							
	32°F	84°F	90°F	110°F	120°F	150°F	173°F	212°F
0	0	0	0	0	0	0	0	0
10.96	0.02956	0.03032	0.03034	0.03526	0.0389	0.0412	0.0123	0.08213
17.32	0.04012	0.0452	0.0465	0.0460	0.0180	0.06732	0.0812	0.1400
24.50	0.04325	0.0503	0.0530	0.0601	0.074	0.08946	0.1180	0.2081
30.00	0.0496	0.0690	0.0569	0.0679	0.079	0.0936	0.1450	0.2350
42.40	0.0569	0.0874	0.0936	0.1120	0.123	0.1487	0.1928	0.3434
52.00	0.0661	0.1054	0.1212	0.1340	0.1377	0.2001	0.2442	0.4444
60.00	0.0716	0.1238	0.1340	0.1524	0.1855	0.2295	0.2938	0.4719
73.50	0.0863	0.1436	0.1634	0.1891	0.2222	0.2736	0.3617	0.6684
85.00	0.1047	0.1838	0.1965	0.2075	0.2626	0.3360	0.4315	0.7657
104.00	0.1120	0.2075	0.2185	0.2773	0.3030	0.3838	0.5049	1.1109
120.00	0.1230	0.2479	0.2626	0.3140	0.3434	0.4315	0.5931	1.3955
134.20	0.1377	0.2773				0.4719	0.6298	1.5185
147.00	0.1450	0.2949	0.3140		0.4038	0.5086	0.6716	1.7572

Table 8. Values of $(\bar{m} - m_o)$ vs t for Gold Rush sweet corn steeped at different temperatures.

$t\ (sec.)^{1/2}$	$\bar{m} - m_o$ (gm./gm.)							
	32°F	82°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.01639	0.0459	0.0546	0.0535	0.0695	0.0717	0.0692	0.0947
17.32	0.0266	0.0583	0.0655	0.0874	0.1074	0.1238	0.1111	0.1566
24.50	0.0408	0.0728	0.0910	0.1038	0.1183	0.1493	0.1784	0.2385
30.00	0.0528	0.0746	0.1001	0.1456	0.1274	0.2141	0.2403	0.2968
42.40	0.06009	0.1183	0.1402	0.1875	0.1985	0.2713	0.3496	0.4938
52.00	0.0747	0.1329	0.1711	0.2312	0.3041	0.3605	0.4461	0.1899
60.00	0.0856	0.1529	0.2047	0.2676	0.3414	0.4170	0.5408	
73.50	0.0976	0.1875	0.2494	0.3332	0.4170	0.5080		
85.00	0.1103	0.2331	0.2899	0.4133	0.4971	0.5826		
104.00	0.1293	0.2786	0.3693	0.4789	0.6173			
120.00	0.1366	0.3521	0.4497	0.5856				
134.20	0.1442	0.4042	0.5080					
147.00	0.1573	0.4410	0.5663					

Table 9. Values of $(\bar{m} - m_o)$ vs t for White kafir (grain sorghum) steeped at different temperatures.

$t\ (\text{sec.})^{1/2}$	$\bar{m} - m_o$ (gm./gm.)							
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.0251	0.0285	0.0457	0.0371	0.0574	0.0485	0.0742	0.0788
17.32	0.0634	0.0371	0.0622	0.0696	0.0885	0.1028	0.1342	0.1935
24.50	0.0668	0.0713	0.0770	0.1113	0.1284	0.1627	0.2169	0.3482
30.00	0.0862	0.0862	0.0970	0.1313	0.1713	0.2141	0.2626	0.4350
42.40	0.1068	0.1170	0.1444	0.1884	0.2284	0.3197	0.3882	0.6857
52.00	0.1136	0.1284	0.1650	0.2232	0.2740	0.3452	0.4795	0.9780
60.00	0.1222	0.1513	0.2067	0.2540	0.3157	0.4082	0.5538	1.2394
73.50	0.1450	0.1627	0.2341	0.2911	0.3425		0.6565	
88.00	0.1484	0.2004	0.2642	0.3054				
104.00	0.1684	0.2369						
120.00	0.1741	0.2655						
134.20	0.2095	0.2940						
147.00	0.2369							

Table 10. Values of $(\bar{m} - m_o)$ vs t for Atlas sargo steeped at different temperatures;

t (sec.)$^{1/2}$	$\bar{m} - m_o$ (gm./gm.)							
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.0213	0.0218	0.0311	0.0382	0.0410	0.0519	0.0628	0.0803
17.32	0.0268	0.0431	0.0530	0.0710	0.0819	0.0736	0.0929	0.0803
24.50	0.0350	0.0705	0.0748	0.0929	0.1196	0.1437	0.1803	
30.00	0.0404	0.0814	0.0857	0.1092	0.1639	0.1874	0.2447	
42.40	0.0568	0.1071	0.1196	0.1603	0.2152	0.2644	0.3327	
52.00	0.0732	0.1174	0.1486	0.2076	0.2791	0.3130	0.3979	
60.00	0.08413	0.1349	0.1737	0.2633	0.3168	0.3720	0.4480	
73.50	0.1033	0.1639	0.2141	0.2923	0.3660		0.5654	
85.00	0.1049	0.1803	0.2551	0.3103		0.6829		
104.00	0.1295	0.2185	0.2988					
120.00	0.1415	0.2458						
134.20	0.147							
147.00	0.155							

Table 11. Values of m_i at various temperatures for steeping samples.

Temp. °F	m_i (gm./gm.)				
	K-4 hybrid pop corn	K1859 hybrid corn (dent corn)	Gold Rush sweet corn	White kafir	Atlas sargo
32	0.019				0.01093
80	0.019	0.01653	0.02731	0.06565	0.01639
100	0.0245	0.01653	0.02731	0.07707	0.02349
120	0.0245	0.01690	0.02731	0.08278	0.02732
140	0.0245	0.01653	0.02731	0.08564	0.03278
160	0.0245	0.0169	0.02913	0.09420	0.04207
180	0.02074	0.01616	0.03095	0.08564	0.03824
210	0.02074	0.01579	0.03824	0.08278	0.03004

Table 12. Values of surface moisture content, m_s, at different temperatures.

Material	Temperature °F	m_s, (gm./gm.)
K-4 hybrid pop corn	100	0.515
	160	0.545
K1859 hybrid corn (dent corn)	84	0.454
	150	
Gold Rush sweet corn	84	0.73
	120	
	150	
White kafir	100	0.61
	130	0.66
	160	0.71
Atlas sargo	100	0.50
	130	0.525
	160	0.545

Table 13. Values of $(1-\bar{M})$ vs X_m for steeping samples at different temperatures.

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
32	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m
	0.0338	0.0289	0.1407	0.0869	0.0257	0.0195	0.0536	0.0384	0.0523	0.0296
	0.0592	0.0450	0.1615	0.1229	0.0417	0.0303	0.1354	0.0607	0.0658	0.0468
	0.1003	0.0637	.1876	0.1507	0.0699	0.0428	0.1427	0.0858	.0859	0.0662
	0.1139	0.0780	.2032	0.1739	0.0828	0.0524	0.1841	0.1051	.0992	0.0811
	0.1687	0.1102	.2449	0.2133	0.0942	0.074	0.2281	0.1485	.1394	0.1146
	0.1869	0.1352	.2971	0.2463	0.1172	0.0909	0.2426	0.1821	.1797	0.1405
	0.2198	0.1560	.3178	0.3016	0.1343	0.1049	0.2610	0.2101	.2065	0.1622
	0.2252	0.1910	.3490	0.3477	0.1531	0.1284	0.3097	0.2574	.2536	0.1986
	0.2618	0.2210	.3907	0.3892	0.1730	0.1485	9.3170	0.2977	.2575	0.2297
	0.3010	0.2704			0.2028	0.1817	0.3597	0.3643	.3179	0.2811
	0.3146	0.3120			0.2142	0.2097	0.3718	0.4203	.3473	0.3243
	0.3264	0.3489			0.2262	0.2345	0.4475	0.4700	.3608	0.3527
	0.3300	0.3821			0.2467	0.2569	0.5060	0.5149	.3805	0.3973
80	0.0546	0.0403	0.1615	0.1540	0.0720	0.0430	0.0609	0.0490	0.0535	0.0533
	0.1139	0.0637	0.2480	0.2177	0.0719	0.0679	0.0792	0.0774	0.1058	0.0842
	0.1323	0.0901	0.2991	0.2670	0.1142	0.0960	0.1523	0.1095	0.1730	0.1191
	0.1688	0.1103	0.3513	0.3081	0.1170	0.1176	0.1841	0.1341	0.1998	0.1459
	0.2007	0.1559	0.4075	0.3770	0.1855	0.1662	0.2499	0.1895	0.2629	0.2062
	0.2280	0.1912	0.5159	0.4364	0.2084	0.2038	0.2748	0.2324	0.2882	0.2528
	0.2553	0.2207	0.5888	0.5345	0.2398	0.2352	0.3232	0.2681	0.3311	0.2917
	0.2918	0.2703	0.7035	0.6162	0.2941	0.2881	0.3475	0.3285	0.4023	0.3574
	0.3465	0.3126	0.7869	0.6896	0.3656	0.3332	0.4280	0.3799	0.4426	0.4133
	0.4212	0.3825			0.4370	0.4077	0.5060	0.4648	0.5363	0.5057
	0.4778	0.4413			0.5522	0.4704	0.5671	0.5363	0.6033	0.5835
	0.4060	0.4936			0.6339	0.5260	0.6279	0.5997		
0.5498		0.5406	(*84°F)	(*84°F)	0.6917	0.5762				

Table 13. Cont'd

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
100	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m
	0.0721	0.0560	0.1958	0.1937	0.0856	.05514	0.0976	0.0681	0.0763	0.0695
	0.1213	0.0886	0.3178	0.2737	0.1027	.08714	0.1328	0.1077	0.1301	0.1098
	0.1777	0.1253	0.3802	0.3557	0.1427	.1233	0.1645	0.1523	0.1836	0.1553
	0.2033	0.1535	0.4525	0.3873	.1570	.1509	0.2072	0.1865	0.2104	0.1901
	0.2599	0.2169	0.5366	0.4751	.2199	.2133	0.3084	0.2636	0.2036	0.2687
	0.2964	0.2660	0.5888	0.5487	.2684	.2616	0.3524	0.3233	0.3648	0.3295
	0.3510	0.3069	0.7869	0.6920	.3210	.3019	0.4415	0.3331	0.4264	0.3802
	0.4149	0.3760	0.8910	0.7747	.3412	.3598	0.5000	0.4570	0.5255	0.4658
	0.4115	0.4348			.4547	.4276	0.5707	0.5285	0.6276	0.5386
	0.5334	0.5320			.5792	.5232			0.7334	0.6590
			(*110°F)	(*110°F)	.7053	.6037				
					.7967	.6752				
120	0.0774	0.0671	0.2242	0.2204	.0839	0.0724	0.0740	0.0789	0.0904	0.0898
	0.1504	0.1061	0.3490	0.3115	.1370	0.1145	0.1389	0.1248	0.1680	0.1419
	0.2033	0.1501	0.3907	0.3821	.1628	0.1619	0.2220	.1765	0.2199	0.2007
	0.2142	0.1838	0.5264	0.4409	.2284	0.1083	0.2620	0.2161	0.2585	0.2459
	0.2054	0.2597	0.6305	0.5408	.2941	0.2802	0.3759	0.3054	0.3795	0.3475
	0.3610	0.3185	0.7452	0.6246	.3626	.3437	0.4453	0.3746	0.4915	0.4262
	0.4330	0.3675	0.8598	0.7649	.4197	.3966	0.068	0.4322	0.6233	0.4017
	0.4879	0.4502	0.9745	0.8817	.5226	.4858	0.5808	0.5295	0.6920	0.6024
	0.5653	0.5206			.6482	.5618	0.6093	0.6123	0.7346	0.6966
	0.6547	0.6370			.7511	.6874				
					.9184	.7931				
					1.0652	.8870				
					1.1223	.9716				

Table 13. Cont'd

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
140	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m
	0.09115	0.07154			0.1090	0.0895	0.0962	0.0962	0.0937	0.1132
	0.1322	0.1131			.1684	0.1415	0.1657	0.1480	0.1872	0.1789
	0.2188	0.1599			.855	0.2002	0.2404	0.2094	0.2734	0.2531
	0.2326	0.1958			.1998	0.2451	0.3207	0.2564	0.3747	0.3099
	0.3008	0.2768			.3113	0.3464	0.4276	0.3624	0.4920	0.4380
	0.3830	0.3394			.4769	0.4249	0.5129	0.4445	0.6381	0.5372
	0.4376	0.3917			.5511	0.4902	0.5910	0.5129	0.7243	0.6198
	0.5426	0.4798			.6540	0.6005	0.6411	0.6283	0.8368	0.7543
	0.6110	0.5548			.7796	0.6045				
	0.7294	0.6789			.9682	0.8497				
					1.1429	0.9805				
					1.3080	1.0965				
					1.4479	1.2011				
160	0.0904	0.0851	0.2656	0.2764	0.1125	0.1083	0.0836	0.1151	0.1173	0.1301
	0.1576	0.1345	0.4220	0.3906	0.1942	0.1712	0.1809	0.1819	0.1641	0.2056
	0.2162	0.1902	0.5678	0.4791	0.2342	.2422	0.2863	0.2573	0.3248	0.2908
	0.2764	0.2330	0.6512	0.5528	0.3358	.2965	0.3768	0.3150	0.4236	0.3561
	0.3965	0.3292	0.7763	0.6781	0.4255	.4191	0.5539	0.4453	0.5776	0.5033
	0.4787	0.4038	0.9535	0.7831	0.5654	.5140	0.6079	0.5461	0.7075	0.6173
	0.5380	0.4659	1.0891	0.9591	0.6540	.5930	0.7184	0.6301	0.8409	0.7122
	0.6117	0.5707	1.2245	1.1056	0.7967	.7265				
	0.7614	0.6600	1.3391	1.2373	0.9137	.8402				
	0.8472	0.8076			1.1652	1.0280				
					1.3936	1.1862				
			*(150°F)	*(150°)	1.5580	1.3265				
					1.6963	1.4531				

Table 13. Cont'd

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m	$1-\bar{M}$	X_m
180	0.1003	0.1081	0.4115	0.3655	0.1085	0.1270	0.3606	0.1522	0.1420	0.1664
	0.1777	0.1708	0.5471	0.5166	.1742	0.2007	0.2362	0.2406	0.2100	0.2629
	0.2553	0.2416	.6930	0.6335	.2798	.2839	0.3817	0.3403	0.4075	0.3719
	0.3146	0.2958	.8337	0.7310	.3769	.3576	0.4622	0.4167	0.5531	0.4554
	0.4969	0.4180	1.0264	0.8967	.5483	.4913	0.6832	0.5889	0.7520	0.6437
	0.5791	0.5127	1.2245	1.0356	.6997	.6026	0.8439	0.7223	0.8768	0.7894
	0.6883	0.5916	1.4327	1.2682	.8482	.6953	0.9747	0.8334	1.0127	0.9109
	0.8071	0.7247	1.6830	1.4619	1.0253	.8517	1.1554	1.0209	1.2780	1.1158
	0.9483	0.8380	1.7872	1.6362					1.5436	1.2904
	1.1896	1.0253								
			(*173°F)	(*173°F)						
210	0.1576	0.1616	0.0667	0.0612	0.1485	.1672	0.1387	0.2170	0.1815	0.1797
	0.2872	0.2554	0.0975	0.0865	0.2456	.2456	.3405	0.3429	0.3420	0.2840
	0.3830	0.3613	0.1261	0.1060	0.3741	.3738	.6128	0.4850		
	0.4560	0.4424	0.1339	0.1223	0.4655	.4577	.7656	0.590		
	0.7321	0.6253			0.7745	.6468				
	0.8926	0.7668			0.9252	.7933				
	1.0367	0.8848			1.1481	.9153				
			(*212°F)	(*212°F)						

Table 14. Values of D_m vs temperature for steeping samples according to first order approximation.

Temp. °F	$\frac{1}{T} \times 10^3$, K^{-1}	$D_m \times 10^8$ cm^2/sec.					
		K-4 hybrid pop corn	K1859 hybrid corn	Gold Rush sweet corn	White kafir	Atlas sargo	ponca wheat
32	3.66	6.5856		1.8049	2.2361	1.3376	
80	3.334	13.1818		9.0897	3.6405	4.3302	3.258
100	3.216	25.4997		14.9598	7.0468	7.3542	6.027
120	3.105	36.5657		25.8177	9.4585	12.3013	10.266
140	3.001	41.5218		39.4544	13.3180	19.5446	18.233
180	21.813	94.7260		79.3564	35.1698	42.2090	41.101 (158°F)
210	2.679	211.9237		137.5422	64.0000	49.0000	118.614 (179°F)
32	3.66		11.26				
85	3.31		35.36				
110	3.27		55.89				
120	3.105		72.40				
150	2.952		113.84				
173	2.845		199.06				
212	2.670		557.67				

Table 15. Value of k vs t for K-4 hybrid pop corn and White kafir (grain sorghum).

t (sec.)$^{1/2}$	k, gm./gm. (sec.)$^{1/2}$				
	80°F	100°F	120°F	140°F	160°F
		K-4 hybrid pop corn			
10.96	0.00206	0.00271		0.00343	
30			0.00295	0.00320	0.00381
42.4	0.00195	0.00253	0.00297	0.00293	0.00386
52	0.00181	0.00235	0.00287	0.00304	0.00381
60	0.00176	0.00242	0.00298	0.00301	0.00370
73.5	0.00164	0.00233	0.00274	0.00305	0.00344
85	0.00160	0.00219	0.00275	0.00297	0.00370
104	0.00167	0.00212	0.00260	0.00290	0.00336
120	0.00164	0.00209	0.00256	0.00271	0.00306
134.2	0.00153	0.00204	0.00238	0.00252	0.00293
147	0.00154	0.00202	0.00230	0.00237	0.00271
		White kafir			
10.96	0.0026				
17.32		0.00359			
24.5			0.00454		
30		.00323	.00437	0.0057	.00713
42.4	0.00276	.00340	.00440	0.00539	
52	.00247	.00317	.00429	0.00527	.00664
60	.00252	.00344	.00423	0.00526	
73.5	.00220	.00320	.00396	0.00466	0.0060
85	.00236	.00314	.00360	0.00436	.0054
104	.00227	.00283	.00337	0.00379	.00483
120	.00221	.00283	.0030	0.00338	.00422
134.2	.00219	.00257	.00283	0.00300	.00393
147	.00200	.00240	.00264	0.00276	

Table 17. Values of D_m vs temperature according to second order approximation for K-4 hybrid pop corn and White kafir.

	$D_m \times 10^8$ cm^2/sec.	
Temp. °F	K-4 hybrid pop corn	White kafir
80	18.6063	4.5685
100	35.6708	9.0752
120	46.6831	15.1000
140	53.0319	22.1559
160	74.2406	29.4144

Table 20. Experimental data for volume increase versus time for K-4 hybrid pop corn steeped at different temperatures.

Time	v (c.c.)							
(min.)	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	22.50	22.50	22.50	22.50	22.50	22.50	22.50	22.50
2	23.00	23.55	24.00	24.10	24.45	24.50	24.47	25.00
5	23.30	24.30	24.60	24.90	25.15	25.34	25.80	26.58
10	23.85	24.70	25.25	25.50	25.90	26.00	26.65	28.46
15	24.00	24.90	25.50	25.75	26.63	26.80	27.00	30.73
30	24.83	25.50	26.05	26.80	26.95	28.00	28.90	32.58
45	25.03	25.90	25.80	27.34	27.75	28.58	29.60	34.00
60	25.22	26.20	27.35	28.00	28.30	29.00	30.60	39.00
90	25.30	26.70	27.80	28.70	29.00	29.65	31.80	44.25
120	25.35	27.28	28.30	29.30	29.50	31.32	33.30	51.60
180	25.75	27.70	29.19	30.00	30.80	32.20	35.00	
240	26.00	28.30	29.88	31.00	31.40	32.37	38.50	
300	26.20	28.40	30.35	341.16	31.80	33.00	40.90	
360	26.36	28.95	30.54	31.50	31.90	33.20	44.45	

Table 21. Experimental data for volume increase versus time for K1859 hybrid corn steeped at different temperatures.

Time	v (c.c.)							
(min.)	32°F	84°F	90°F	110°F	120°F	150°F	173°F	212°F
0	24.00	24.00	24.00	24.00	24.00	24.00	24.00	24.00
2	24.93	25.04	25.16	24.82	24.99	25.12	25.80	26.63
5	25.14	25.44	25.61	25.19	25.89	25.99	26.73	27.80
10	25.42	25.76	26.14	26.48	26.45	26.88	27.48	29.81
15	25.60	25.98	26.20	21.90	27.00	28.80	30.90	
30	25.90	26.58	27.30	27.60	27.90	28.20	30.00	33.70
45	26.40	27.17	28.00	28.30	28.70	29.90	31.65	35.90
60	26.60	28.17	28.60	29.00	29.80	30.60	32.54	36.50
90	26.95	28.36	29.30	29.90	30.60	31.64	34.10	41.50
120	27.30	29.16	30.00	30.70	31.60	32.80	35.74	43.90
180	27.45	30.60	31.00	32.70	33.10	34.00	37.37	53.50
240	27.60	31.09	31.80	32.90	33.70	35.20	39.44	61.20
300	27.80	31.83			35.10	36.20	40.70	64.50
360	28.00	32.33	33.10		35.80	37.05	41.90	71.80

Table 22. Experimental data for volume increase versus time for Gold Rush sweet corn steeped at different temperatures.

Time	v(c.c.)							
(min.)	32°F	82°F	100°F	120°F	140°F	160°F	180°F	210°F
0	22.68	22.68	22.68	22.68	22.68	22.68	22.68	22.68
2	23.90	25.00	25.40	25.60	25.50	26.00	26.60	27.00
5	25.20	25.40	26.00	26.40	27.20	27.50	27.60	29.00
10	24.60	25.60	26.85	27.10	27.50	28.50	29.70	31.10
15	25.00	26.00	27.00	27.20	27.81	29.90	30.90	32.80
30	25.30	27.00	28.00	29.20	30.05	31.40	33.90	37.90
45	25.60	27.50	29.00	30.41	32.61	33.70	36.00	41.00
60	25.80	28.00	29.60	31.51	33.61	35.20	38.60	44.00
90	26.10	29.10	31.00	33.01	35.21	37.50	41.90	49.25
120	25.50	29.90	32.00	35.01	37.41	39.70	46.30	53.50
180	26.80	31.49	34.00	36.91	40.81	44.00	51.00	59.35
240	27.00	33.20	26.50	39.60	43.48	48.30	56.00	
300	27.20	34.20	37.20	41.41	45.60	50.80	59.48	
360	27.40	35.40	39.00	43.01	48.41	53.10	65.50	

Table 23. Experimental data for volume increase versus time for White kafir steeped at different temperatures.

Time	v (c.c.)							
(min.)	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	15.68	15.68	15.68	15.68	15.68	15.68	15.68	15.68
2	17.15	17.15	17.70	17.90	18.00	18.04	18.65	18.49
5	17.60	17.66	18.04	18.30	18.44	18.87	19.34	20.40
10	17.66	17.93	18.25	18.90	19.20	19.95	20.64	22.82
15	17.85	18.10	18.48	19.20	19.65	20.70	21.26	23.26
30	18.00	18.75	19.15	20.08	20.62	22.16	22.65	
45	18.22	18.90	19.45	20.55	21.36	22.50	24.75	
60	18.28	19.20	20.15	21.21	21.78	23.32	25.93	
90	18.40	19.36	20.60	21.45	22.10	23.80	28.27	
120	18.65	19.74	21.05	20.73	22.50	24.13	30.55	
180	18.95	20.35	21.35	22.05	22.77	24.77	24.70	36.00
240	19,04	20.70	21.85	22.30	22.95	24.70	42.75	
300	19.45	21.15	22.00	22.47	22.94	25.10	46.80	
360	19,45	21.15	22.15	22.50	22.95		40.10	

Table 24. Experimental data for volume increase versus time for Atlas sargo steeped at different temperatures.

Time	v (c.c.)							
(min.)	32°F	82°F	100°F	120°F	140°F	160°F	180°F	210°F
0	14.97	14.97	14.97	14.97	14.97	14.97	14.97	14.97
2	15.62	15.57	16.30	16.41	17.02	15.98	17.00	17.00
5	1.584	16.10	16.27	16.90	17.00	17.28	17.80	18.20
10	16.00	16.45	16.80	17.38	17.80	18.40	19.00	21.50
15	16.15	16.73	17.00	17.59	18.45	19.10	20.00	24.40
30	16.39	17.10	17.66	18.42	19.50	20.40	21.40	31.90
45	16.71	17.30	18.20	19.25	20.25	21.02	22.20	41.20
60	16.80	17.57	18.50	20.00	20.80	21.85	23.62	48.58
90	17.17	18.00	19.23	20.37	21.40	22.09	25.40	54.97
120	17.23	18.28	19.64	20.60	21.66	22/38	27.58	
180	17.45	18.90	20.27	21.20	21.70	22.60	31.59	
240	1.755	19.22	20.56	22.07	22.70	43.80	21.60	
300	17.65	19.57	20.77	21.72	22.19	22.79	49.00	
360	17.74	19.74	20.97	21.80	22.27	22.85	64.80	

Table 25. Values of $\bar{v} - v_o$ vs t for K-4 hybrid pop corn steeped at different temperatures.

t (sec.)$^{1/2}$	$\bar{v} - v_o$ c.c./c.c.							
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.0026	0.0289	0.0526	0.05287	0.0737	0.0789	0.0842	0.1000
17.32	0.0184	0.0684	0.08420	0.09997	0.1105	0.1231	0.1421	0.1831
24.50	0.0474	0.0894	0.1184	0.1315	0.1500	0.1578	0.1868	0.2315
30.00	0.0552	0.0999	0.1315	0.1443	0.1884	0.1999	0.2052	0.2820
42.40	0.0989	0.1315	0.1605	0.1999	0.2053	0.2631	0.3052	0.4046
52.00	0.1094	0.1526	0.1999	0.2283	0.2473	0.2973	0.2936	0.3420
60.00	0.1194	0.1684	0.2289	0.2631	0.2762	0.3157	0.3946	0.5735
73.50	0.1236	0.1947	0.2525	0.2999	0.3131	0.3499	0.4578	
85.00	0.1263	0.2236	0.2884	0.3315	0.3394	0.4378	0.5367	
104.00	0.1473	0.2573						
120	0.1605	0.2789						
134.20	0.1710	0.2841						
147.00	0.1794	0.3131						

Table 26. Experimental data for volume increase versus time for K1859 hybrid corn steeped at different temperatures.

t (sec.)$^{1/2}$	$\bar{v} - v_0$ c.c./c.c.							
	32°F	84°F	90°F	110°F	120°F	150°F	173°F	212°F
0	0	0	0	0	0	0	0	0
10.96	0.0250	0.03	0.036	0.0200	0.028	0.034	0.066	0.105
17.32	0.0350	0.049	0.057	0.0700	0.070	0.075	0.110	0.160
24.50	0.048	0.064	0.082	0.085	0.098	0.117	0.1450	0.2550
30.00	0.0565	0.0745	0.0848	0.1036	0.1178	0.1225	0.2073	0.3063
42.40	0.0707	0.1027	0.1366	0.1508	0.1649	0.1740	0.2639	0.4382
52.00	0.0942	0.1305	0.1696	0.1838	0.2026	0.2545	0.3416	0.5419
60.00	0.1037	0.1776	0.1743	0.2167	0.2545	0.2921	0.3836	0.5702
73.50	0.1202	0.1866	0.2309	0.2591	0.2921	0.3412	0.5042	0.8050
85.00	0.1367	0.2243	0.2639	0.3393	0.3958	0.5344	0.2969	0.9188
104.00	0.1437	0.2921	0.3110	0.3675	0.4099	0.4524	0.6111	1.3712
120.00	0.1508	0.3152	0.3487	0.4005	0.4382	0.5089	0.7087	1.7340
134.20	0.1602	0.3501				0.5560	0.7680	1.8895
147.00	0.1696	0.3737	0.4100		0.5042	0.5961	0.8246	2.2335

Table 27. Experimental data for volume increase versus time for Gold Rush sweet corn steeped at different temperatures.

$t\ (\text{sec.})^{1/2}$	$\bar{v} - v_o$ c.c./c.c.							
	32°F	82°F	100°F	120°F	140°F	160°F	180°F	212°F
0	0	0	0	0	0	0	0	0
10.96	0.0283	0.0775	0.0973	0.0973	0.1023	0.1242	0.1490	0.1490
17.32	0.0432	0.0974	0.1272	0.1470	0.1868	0.1987	0.1987	0.2484
23.50	0.0631	0.1073	0.1694	0.1709	0.2017	0.2484	0.3030	0.3527
30.00	0.0830	0.1272	0.1768	0.1823	0.2166	0.3179	0.3626	0.4371
42.40	0.0979	0.1768	0.2265	0.2812	0.3259	0.3924	0.5117	0.6905
52.00	0.1128	0.2017	0.2762	0.3457	0.4550	0.5067	0.6160	0.8445
60.00	0.1227	0.2265	0.3060	0.4004	0.5047	0.5802	0.7452	0.9935
73.50	0.1376	0.2812	0.3756	0.4749	0.5842	0.6955	0.9091	
85.00	0.1575	0.3209	0.4252	0.5743	0.6935	0.8048		
104.00	0.1724	0.3999	0.5246	0.6687	0.8475	1.0184		
120.00	0.1823	0.4848	0.6488	0.8028	0.9950	1.2320		
134.20	0.1923	0.5345	0.6835	0.8922	1.1505	1.3562		
147.00	0.2022	0.5941	0.7233	0.9717	1.2399	1.4709		

Table 28. Experimental data for volume increase versus time for White kafir (grain sorghum).

t (sec.)$^{1/2}$	$\bar{v} - v_0$ c.c./c.c.							
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.0265	0.0417	0.0409	0.0495	0.0569	0.0561	0.1099	0.1054
17.32	0.0607	0.0500	0.0667	0.0796	0.0902	0.1190	0.1623	0.2502
24.50	0.0652	0.0743	0.0826	0.1251	0.1478	0.2909	0.2608	0.4337
30.00	0.0796	0.0872	0.1001	0.1478	0.1820	0.2578	0.3078	0.4671
42.40	0.0910	0.1365	0.1509	0.2146	0.2551	0.3435	0.4133	
52.00	0.1077	0.1478	0.1736	0.2502	0.3116	0.3943		
60.00	0.1127	0.1706	0.2269	0.3001	0.3435			
73.50	0.1213	0.1827	0.2608	0.3184	0.3677			
85.00	0.1388	0.2115	0.2949	0.3397				
104.00	0.1630	0.2578						
120.00	0.1698	0.2843						
134.20	0.2009	0.3184						
147.00	0.2161							

Table 29. Experimental data for volume increase versus time for Atlas sargo steeped at different temperatures.

t (sec.)$^{1/2}$	$\bar{v} - v_o$ c.c./c.c.						
	32°F	80°F	100°F	120°F	140°F	160°F	180°F	210°F
0	0	0	0	0	0	0	0	0
10.96	0.0301	0.0234	0.0399	0.06028	0.0625	0.0957	0.0972	0.1130
17.32	0.0467	0.0633	0.0693	0.1055	0.1070	0.1153	0.1575	0.2035
24.50	0.0588	0.0897	0.1017	0.1417	0.1673	0.1997	0.2479	
30.00	0.0701	0.1108	0.1168	0.1575	0.2163	0.2524	0.3233	
42.40	0.0822	0.1386	0.1665	0.2197	0.2954	0.3504	0.4288	
52.00	0.1123	0.1537	0.2215	0.2826	0.3519	0.3971	0.4891	
60.00	0.1191	0.1741	0.2298	0.3391	0.3934	0.4597	0.5961	
73.50	0.1469	0.2057	0.2850	0.3670			0.7302	
85.00	0.1515	0.2276					0.9148	
104.00	0.1680	0.2743						
120.00	0.1756	0.2984						
134.20	0.1831	0.3248						
147.00	0.1899							

Table 30. Values of v_i vs temperature for steeping samples.

Temp. °F	v_i c.c./c.c.				
	K-4 hybrid pop corn	K1859 hybrid corn (dent corn)	Gold Rush sweet corn	White kafir	Atlas sargo
32	0.0263			0.0849	0.01432
80	0.0263	0.01885	0.03776	0.09629	0.02185
100	0.02894	0.01885	0.03776	0.1122	0.03617
120	0.0263	0.01885	0.03776	0.1190	0.03994
140	0.02894	0.01885	0.03776	0.1190	0.04600
160	0.0263	0.01885	0.4074	0.1228	0.05878
180	0.03157	0.01838	0.04570	0.1152	0.05577
210	0.03157	0.01814	0.06558	0.1077	0.03994

Table 31. Value of v_s for steeping samples at different temperature.

Material	v_s c.c./c.c.	Temperature
K-4 hybrid pop corn	0.725	100
	0.750	160
K1859 hybrid corn (dent corn)	0.58	84
		150
Gold Rush sweet corn	0.9750	84
		120
		150
White kafir	0.79	100
	0.855	130
	0.930	160
Atlas sargo	0.665	100
	0.700	130
	0.736	160

Table 32. Values of $1-\bar{V}$ vs X_v for steeping samples at different temperatures.

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
32	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v
	0.0459	0.0291	0.1258	0.0875	0.0333	0.0245	.0441	.0279	0.0561	0.0341
	0.0325	.0460	0.1574	0.1237	.0509	0.0387	.1010	.0440	.870	0.0539
	0.0837	.0651	0.2097	0.1517	.744	0.0547	.1085	.06230	.1095	0.0762
	0.0975	.0798	0.2308	0.1750	.0978	0.0670	.1324	0.07630	.1306	0.0933
	0.1747	.1127	0.2675	0.2146	.1153	0.0947	.1514	.1078	.1643	0.1319
	0.1932	.1383	0.3043	0.2479	.1329	0.1162	.1792	.1322	.2092	0.1617
	0.2109	.1595	0.3198	0.3036	.1446	0.1340	.1875	.1526	.2218	0.1866
	0.2183	.1954	0.3356	0.3500	.1621	0.1642	.2018	.1869	.2736	0.2286
	0.2231	.2260	0.3566	0.3917	.1856	.1899	.2309	.2161	.2822	0.2644
	0.2602	.2765					.2712	.2645	.3129	0.3235
							.2825	.3052		
							.3342	.3413		
							.3595	.3738		
80	0.0510	.04345	0.1658	0.1564	0.09133	.10613	0.0694	0.04209	0.0436	0.0500
	0.1208	.16866	0.2286	0.2211	0.1148	.07290	.9832	0.06650	.1179	.1791
	.1579	.09711	0.2905	0.2711	.1264	.1031	.1236	0.09408	.1671	11119
	.1764	.1189	0.3953	0.3129	.1499	.1263	.1451	0.1152	.2164	.1370
	.2323	.1681	0.4153	0.3838	.2083	.1785	.2271	0.1628	.2581	.1936
	.2695	.2061	0.4992	0.4432	.2377	.2189	.2459	0.1997	.2863	.2374
	.2974	.2378	0.6501	0.5428	.2669	.2526	.2838	0.2304	.3243	.2739
	.3439	.2914	0.7015	0.6257	.3314	.3094	.3039	0.2822	.3831	.3356
	.3949	.3369	0.7792	0.7003	.3782	.3578	.3519	0.3264	.4239	.3880
	.4368	.4123			.4712	.4378	.4289	0.3993	.5109	.4748
	.4926	.4757			.5713	.5051	.4730	0.4608	.5558	.5478
	.5018	.5320			.6299	.5649	.5297	0.5153	.6050	.6127
	.5530	.5827	(*84°F)	(*84°F)	.7001	.6188				

Table 32. Cont'd.

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v
100	0.0929	0.0658	0.2306	0.2066	0.1147	0.0605	0.0680	0.0570	0.0743	.0717
	0.1487	0.1040	0.3356	0.2919	.1499	0.0956	0.1110	0.0902	0.1291	.1133
	.2091	.1471	0.4091	0.3580	.1996	.1352	0.1374	0.1276	0.1894	.1602
	.2323	.1801	0.4823	0.4131	.2083	.1656	0.1665	0.1562	0.2175	.1962
	.2835	.2545	0.5767	0.5968	.2669	.2340	0.2510	0.2208	0.3101	.2773
	.3531	.3121	0.6608	0.5852	.3255	.2871	0.2888	0.2708	.4126	.3401
	.4043	.3601	0.8179	0.7168	.3606	.3312	0.3771	0.3125	.4280	.3924
	.4460	.4412	0.8914	0.8262	.4426	.4057	0.4339	0.3828	.5308	.4807
	.5094	.5102			.5010	.4692	0.4906	0.4427		
					.6182	.5741				
					.7646	.6624				
					.8054	.7408				
			(*110°F)	(*110°F)	.8523	.8115				
120	0.1022	0.0762	0.2622	0.2316	.1147	0.0764	0.0757	0.0688	0.1079	0.0964
	.1766	.1204	0.3670	0.3274	.1732	.1207	0.1223	0.1088	.1888	.1480
	.2323	.1703	0.4509	0.4015	.2014	.1707	0.1921	0.1538	.2335	.2093
	.2549	.2085	0.5664	0.4633	0.4633	.2148	.2091	0.2270	0.1884	.2563
	.3531	.2947	0.6501	0.5683	.3314	.2955	0.3296	0.2662	.3931	.3622
	.4032	.3614	0.7552	0.6563	.4074	.3624	0.3843	0.3265	.5056	.4443
	.4647	.4170	0.9123	0.8038	.4718	.4181	0.4609	0.3768	.6067	.5126
	.5297	.5101	0.9753	0.8266	.5596	.5122	0.4890	0.4615	.6566	.6279
	.5855	.5908			.6768	.5923	0.5217	0.5337		
					.7880	.7247				
					.9460	.8362				
					1.0514	.9352				
					1.1451	1.0244				

Table 32. Cont'd.

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v
140	0.1302	0.0824			.1206	0.0951	0.0812	0.0784	0.1076	.1124
	.1952	0.1302			.2201	.1503	0.1312	.1238	.1842	.1776
	.2649	.1842			.2377	.2127	0.2108	.1752	.2880	.2513
	.3527	.2255			.2552	.2604	0.2596	.2145	.3724	.3077
	.3626	.3188			.3840	.3680	0.3639	.3031	.5085	.4348
	.4368	.3909			.5362	.4514	0.4444	.3718	.6058	.5333
	.5530	.4511			.5947	.5208	0.4899	.4290	.6772	.6153
	.5994	.5526			.6884	.6380	0.5245	.5255		
					.8172	.7378				
					.9987	.9027				
					1.1725	1.0416				
					1.3558	1.1648				
160	0.1394	0.0963	0.2726	0.2618	0.1436	.1130	.07420	.0994	.1590	.1273
	0.2174	.1521	0.3700	.2342	.1787	.1787	.1574	.1565	.1916	.2012
	0.2787	.2152	0.5664	0.4538	.2927	.2528	.2657	.2214	.3318	.2846
	0.3531	.2635	0.6501	0.5236	.3736	.3095	.3410	.2711	.4193	.3484
	.4647	.3724	0.7594	0.6523	.4624	.4375	.4543	.3822	.5822	.4925
	.5185	.4568	0.8809	0.7418	.5971	.5971	.5365	.5215	.4699	.6040
	.5576	.5270	1.0068	0.9085	.6849	.6190	.6036	.5422	.7637	.6969
	.6180	.6456	1.1326	1.0473	.8196	.7584				
	.7732	.7466	1.2375	1.1721	.9484	.8770				
					1.2001	1.0730				
					1.4518	1.2381				
			(*150°F)	(*150°F)						

Table 32. Cont'd

Temp. °F	K-4 hybrid pop corn		K1859 hybrid corn		Gold Rush sweet corn		White kafir		Atlas sargo	
	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v	$1-\bar{V}$	X_v
180	.1487	.1127	0.4613	0.3648	0.1756	0.1399	0.1454	.1376	.1615	.1626
	.2510	.1780	0.5874	0.5156	0.2342	0.2210	.2147	.2175	.2617	.2569
	.3299	.2518	0.7603	0.6371	0.3127	.3449	.3077	.4119	.3127	.3634
	.3624	.3084	0.7296	0.4273	0.3829	.4071	.3768	.8538	.5371	.4450
	.5390	.4359	1.1222	0.8950	0.6030	0.5411	.5466	.5325	.7124	.6289
	.6050	.5346	1.1894	1.0336	0.7259	0.6636	.7570	.6530	.8126	.7713
	.6969	.6168	1.3601	1.2659	0.8782	0.7657	.8754	.7535	.9904	.8900
	.8085	.7556	1.5773	1.4593	1.0713	0.9380	1.1100	0.9231	1.1213	1.0903
	.9479	.8738	1.7093	1.6332						
	1.1058	1.0691								
			(*173°F)	(*173°F)						
210	0.1766	.1643	0.6817	0.5379	0.1756	0.1794	0.1394	0.1939	0.1877	.1806
	.3234	.2596	0.9753	0.7602	.2927	.2835	0.3310	0.3066	0.3380	.2854
	.4089	.3672	1.2061	0.9324	.4156	.4010	0.5736	0.4337		
	.4980	.4497	1.2691	1.0758	.5150	.4910	0.6178	0.5310		
	.7090	.6355			.8137	.6939				
	.8811	.7794			.9952	.8810				
	1.0129	.8993			1.1707	.9820				
			(*212°F)	(*212°F)						

Table 33. Values of D_v versus temperature for steeping samples.

Temp. °F	$\frac{1}{T} \times 10^3$, K^{-1}	D_v $cm^2/sec. \times 10^8$				
		K-4 hybrid pop corn	K1859 hybrid corn (dent corn)	Gold Rush sweet corn	White kafir	Atlas sargo
32	3.66	6.8888		2.9493	1.1787	1.7718
80	3.334	15.3131		10.4713	2.6877	3.8172
100	3.216	35.1115		18.0103	4.9438	7.8295
120	3.105	47.0709		28.7010	7.1874	13.3681
140	3.001	55.0803		44.5272	9.3172	19.2612
160	2.904	75.1904		62.9165	14.8855	24.7055
180	2.813	102.9846		96.2573	28.7495	40.2971
210	2.699	218.9247		158.3045	57.0833	49.0000
32	3.66		11.4000			
84	3.31		36.4600			
110	3.15		63.5800			
120	3.105		79.9600			
150	2.952		102.1500			
173	2.845		198.3300			
212	2.67		431.1500			

Derivation of equation 23, (7) (9) (12).

$$D\left(\frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}\right) = \frac{\partial c}{\partial t} \qquad (1)$$

Since

$$\frac{\partial}{\partial r}(rc) = r\frac{\partial c}{\partial r} + C$$

and

$$\frac{\partial^2}{\partial r^2}(rc) = r\frac{\partial^2 c}{\partial r^2} + \frac{\partial c}{\partial r} + \frac{\partial c}{\partial r} = r\frac{\partial^2 c}{\partial r^2} + 2\frac{\partial c}{\partial r}$$

$$\therefore \quad \frac{1}{r}\frac{\partial^2}{\partial r^2}(rc) = \frac{\partial^2 c}{\partial r^2} + \frac{2}{r}\frac{\partial c}{\partial r}$$

and

$$D\frac{\partial^2}{\partial r^2}(rc) = r\frac{\partial c}{\partial t} \qquad (2)$$

I.C. at $t=0$ $c = c_o$ $0 \leq r < r_o$
B.C.1 at $t>0$ $c = c_s$ $r = r_o$
B.C.2 at $t>0$ $\frac{\partial c}{\partial r} = 0$ $r = 0$

Let $C = \dfrac{c - c_s}{c_o - c_s}$

I.C. at $t=0$ $C = 1$ $0 \leq r < r_o$
B.C. at $t>0$ $C = 0$ $r = r_o$

Eq. (2) becomes:

$$D\frac{\partial^2}{\partial r^2}(rc) = r\frac{\partial C}{\partial t} \qquad (3)$$

Let $rC = \bar{V}$

then $r\dfrac{\partial C}{\partial t} = \dfrac{\partial \bar{V}}{\partial t}$

Eq. (3) becomes:

$$D\frac{\partial^2 \bar{V}}{\partial r^2} = \frac{\partial \bar{V}}{\partial t} \qquad (4)$$

I.C. at $t=0$ $C = 1$ $\bar{V} = r$ $0 \leq r < r_o$
B.C.1 at $t>0$ $C = 0$ $\bar{V} = 0$ $r = r_o$
B.C.2 at $t>0$ $\frac{\partial C}{\partial r} = 0$ $\bar{V} = 0$ $r = 0$

$$\bar{V}(r,t) = R(r) \circ T(t)$$

$$\frac{\partial^2 \bar{V}}{\partial r^2} = TR'' \qquad \frac{\partial \bar{V}}{\partial r} = RT'$$

$$DTR'' = RT'$$

$$\frac{R''}{R} = \frac{T'}{DT} = -\lambda^2$$

$$R'' + \lambda^2 R = 0 \qquad R = A\cos\lambda r + B\sin\lambda r$$

$$T' + D\lambda^2 T = 0 \qquad T = ce^{-D\lambda^2 t}$$

$$\therefore \bar{V}(r,t) = ce^{-D\lambda^2 t}\,(A\cos\lambda r + B\sin\lambda r)$$

and $\bar{V}(r,t) = \sum_{m=1}^{\infty} (A_m \cos\lambda_m r + B_m \sin\lambda_m r)\, e^{-D\lambda^2_m t}$

B.C.2 $\bar{V}(o,t) = o$ gives $A_m = 0$

B.C.1 $\bar{V}(r_o,t) = o$ gives $\sin\lambda_m r_o = o$ and $\lambda_m = \frac{n\pi}{r_o}$

$$\bar{V}(r,t) = \sum_{n=1}^{\infty} Ee^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \sin\frac{n\pi r}{r_o}$$

$$\bar{V}(r,t) = \sum_{n=1}^{\infty} b_n e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \sin\frac{n\pi r}{r_o}$$

$$\bar{V}(r,o) = \sum_{n=1}^{\infty} b_n \sin\frac{n\pi r}{r_o}$$

Define $\bar{V}(r,o)$ as odd function

then

$$b_n = \frac{2}{r_o}\int_o^{r_o} \bar{V}(r,o)\sin\frac{n\pi r}{r_o}\,dr = \frac{2}{r_o}\int_o^{r_o} r\sin\frac{n\pi r}{r_o}\,dr$$

$$\int r \sin \frac{n\pi r}{r_o}\, dr = \frac{r_o^2}{n^2\pi^2} \int \frac{n\pi r}{r_o} \sin \frac{n\pi r}{r_o}\, d\left(\frac{n\pi r}{r_o}\right)$$

$$= \frac{r_o^2}{n^2\pi^2}\left[\sin\left(\frac{n\pi r}{r_o}\right) - \left(\frac{n\pi r}{r_o}\right)\cos\left(\frac{n\pi r}{r_o}\right)\right]$$

$$\therefore \quad bn = \frac{2r_o}{n^2\pi^2}\left[\sin\left(\frac{n\pi r}{r_o}\right) - \left(\frac{n\pi r}{r_o}\right)\cos\left(\frac{n\pi r}{r_o}\right)\right]_0^{r_o}$$

$$= \frac{2r_o}{n^2\pi^2}\left[-n\pi\cos n\pi\right] = -\frac{2r_o}{n\pi}\left[\cos n\pi\right] = -\frac{2r_o}{n\pi}(-1)^n$$

$$= \frac{2r_o}{n\pi}(-1)^{n+1}$$

Since $\cos n\pi = (-1)^n$

$$\therefore \quad bn = \frac{(-1)^{n+1}}{n}\,\frac{2r_o}{\pi}$$

$$\therefore \quad \bar{V}(r,o) = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}\,\frac{2r_o}{\pi} \sin\frac{n\pi r}{r_o}$$

$$\bar{V}(r,t) = \sum_{n=1}^{\infty} \frac{2r_o}{\pi}\,\frac{(-1)^{n+1}}{n}\, e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \sin\frac{n\pi r}{r_o}$$

$$\bar{V}(r,t) = \frac{2r_o}{\pi}\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}\, e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \sin\frac{n\pi r}{r_o}$$

$$rC = \bar{V}$$

$$C = \frac{\bar{V}}{r} = \frac{2r_o}{\pi}\sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n}\,\frac{1}{r}\, e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \sin\frac{n\pi r}{r_o}$$

vol. of sphere $= \frac{4}{3}\pi r^3$ $\qquad \frac{1}{2}$ vol. $= \frac{2}{3}\pi r^3$

$$V = \frac{4}{3}\pi r^3 \qquad dv = 4\pi r^2 dr$$

$$\text{av. conc. } \bar{C} = \frac{\int_0^{r_o} C\,dv}{\frac{4}{3}\pi r_o^3} = \frac{3}{4\pi r_o^3} \times 4\pi\int_0^{r_o} r^2 C\,dr$$

$$= \frac{3}{r_o^3}\int_0^{r_o} r^2 C\,dr$$

$$\bar{C} = \frac{2r_o}{\pi} \times \frac{3}{r_o^3} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n} e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt} \int_0^{r_o} \frac{1}{r} \times r^2 \sin\frac{n\pi r}{r_o}\,dr$$

$$\int_0^{r_o} r \sin\frac{n\pi r}{r_o}\,dr = \frac{r_o^2}{n^2\pi^2}\int_0^{r_o} \left(\frac{n\pi r}{r_o}\right) \sin\left(\frac{n\pi r}{r_o}\right) d\left(\frac{n\pi r}{r_o}\right)$$

$$= \frac{r_o^2}{n^2\pi^2}\left[\sin\left(\frac{n\pi r}{r_o}\right) - \left(\frac{n\pi r}{r_o}\right)\cos\left(\frac{n\pi r}{r_o}\right)\right]_0^{r_o}$$

$$= \frac{r_o^2}{n^2\pi^2} - n\pi\cos n\pi = \frac{r_o^2}{n\pi}(-1)^{n+1}$$

$$\therefore\ \bar{C} = \frac{6}{\pi r_o^2} \times \frac{r_o^2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1\,2}}{n} e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt}$$

$$= \frac{6}{2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt}$$

$$\frac{\bar{c} - c_s}{c_o - c_s} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt}$$

$$\bar{C} = \frac{\bar{c} - c_s}{c_o - c_s} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\left(\frac{n\pi}{r_o}\right)^2 Dt}$$

$$= \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-n^2\pi^2 \frac{1}{r_o^2} Dt}$$

For a sphere

$$V = \frac{4}{3}\pi r_o^{\,3} \qquad\qquad S = 4\pi r_o^{\,2}$$

$$\frac{s}{v} = \frac{4\pi r_o^{\,2}}{\frac{4}{3}\pi r_o^{\,3}} = \frac{3}{r_o} \qquad\qquad r_o = \frac{3}{\frac{s}{v}} \qquad\qquad r_o^{\,2} = \frac{9}{(\frac{s}{v})^2}$$

$$\therefore \bar{C} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp - n^2\pi^2\frac{Dt}{\frac{9}{(\frac{s}{v})^2}} =$$

$$\frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[- n^2\pi^2\frac{1}{9}\left(\frac{s}{v}\right)^2 Dt\right]$$

$$\bar{C} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-\frac{n^2\pi^2}{9}X^2\right] \quad \text{where } X = \left(\frac{s}{v}\right)\sqrt{D}\sqrt{t}$$

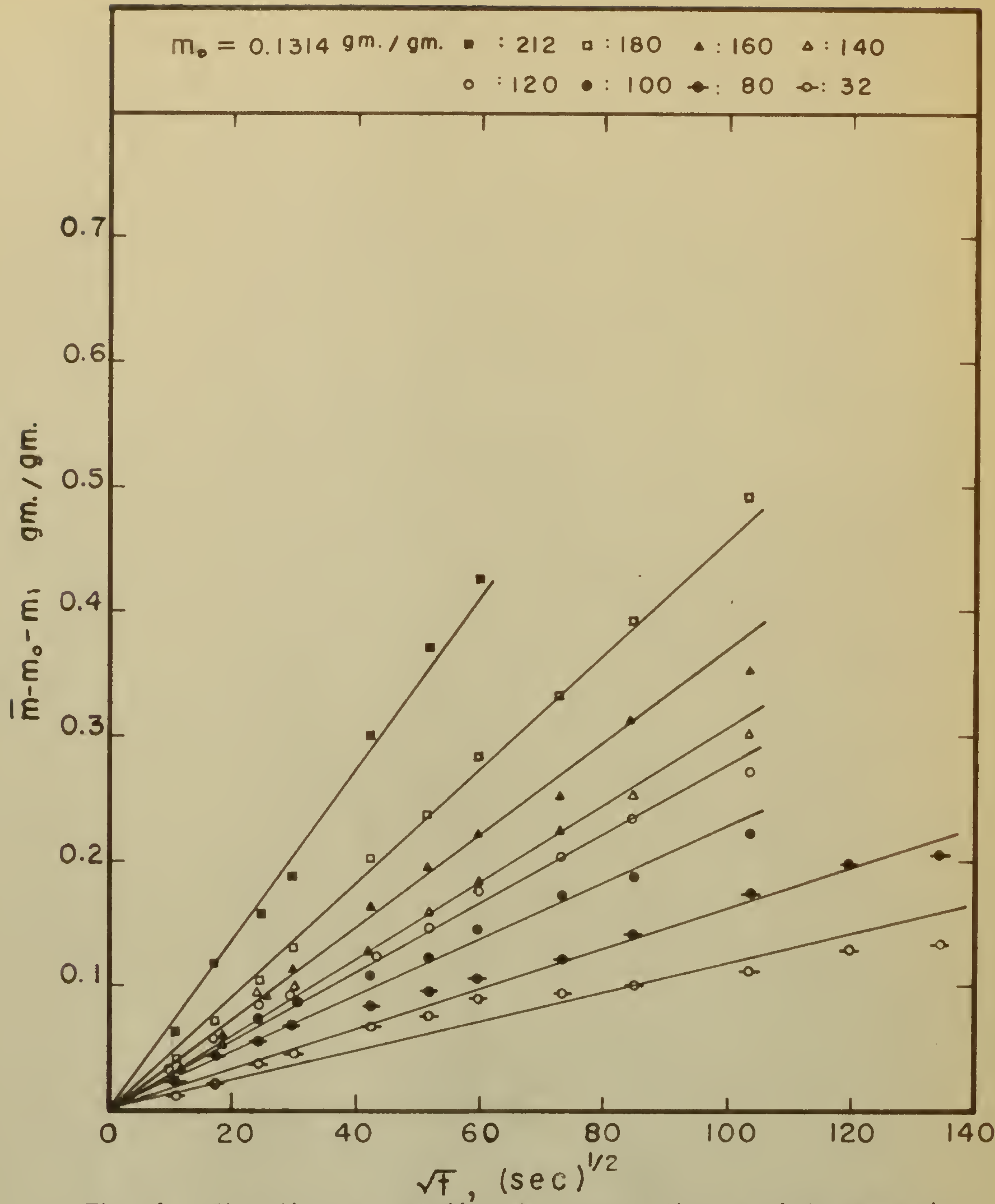


Fig. 4. The linear relation between the moisture gain and the square root of the absorption time for K-4 Hybrid pop corn.

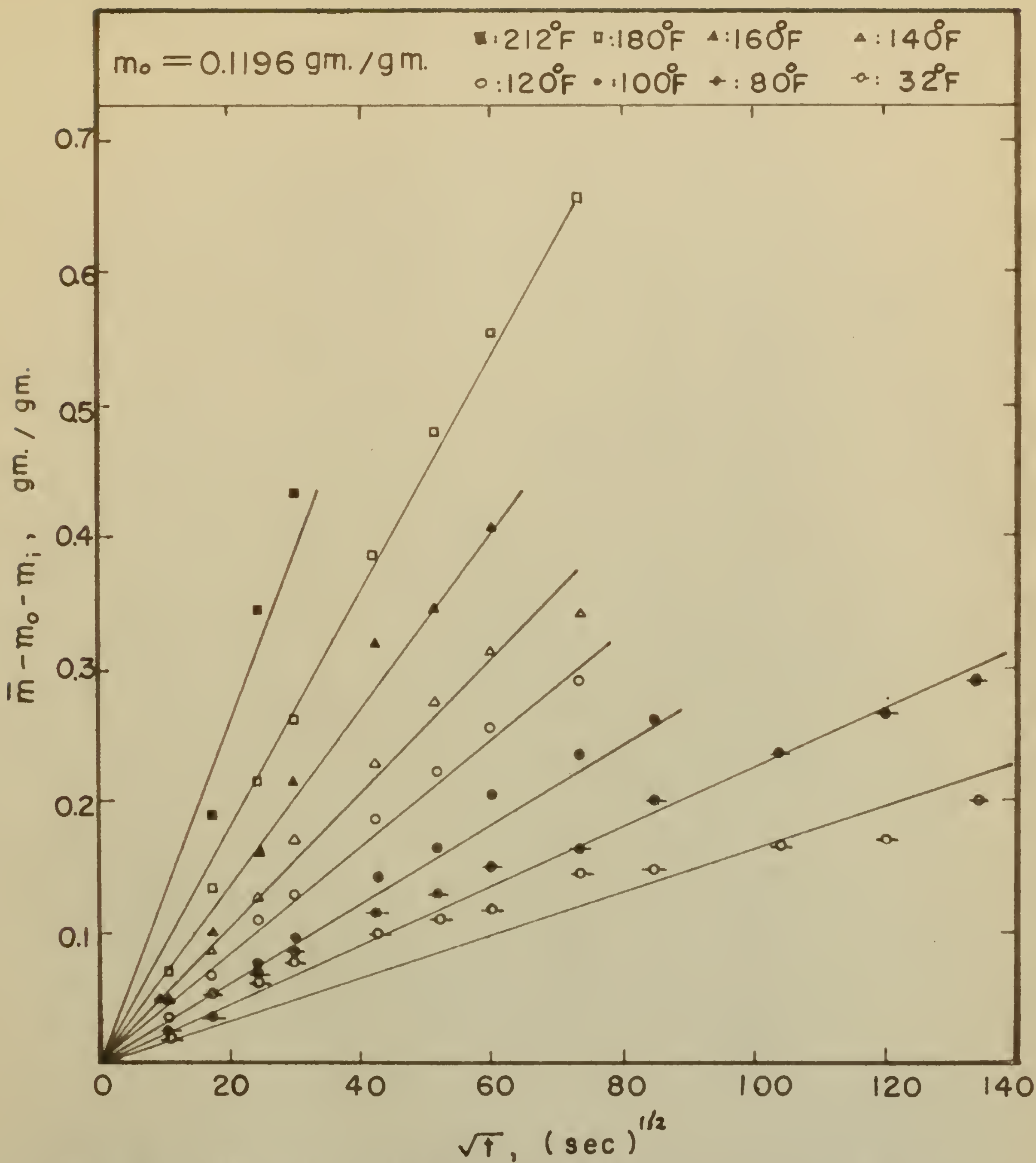


Fig. 5. The linear relation between the moisture gain and the square root of the absorption time for White Kafir (grain sorghum).

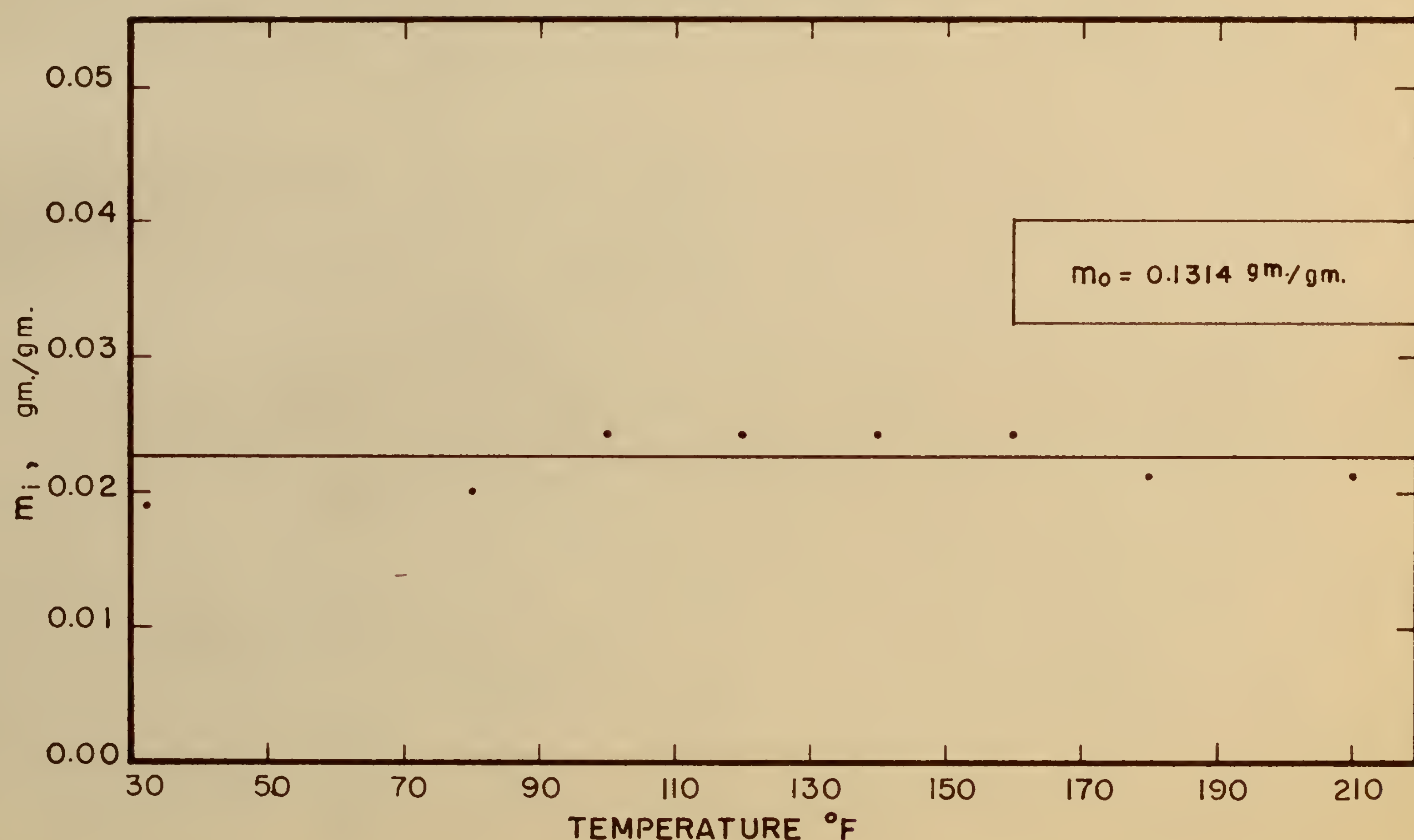


Fig. 6. The moisture gain due to capillary action versus temperature for the K-4 Hybrid pop corn.

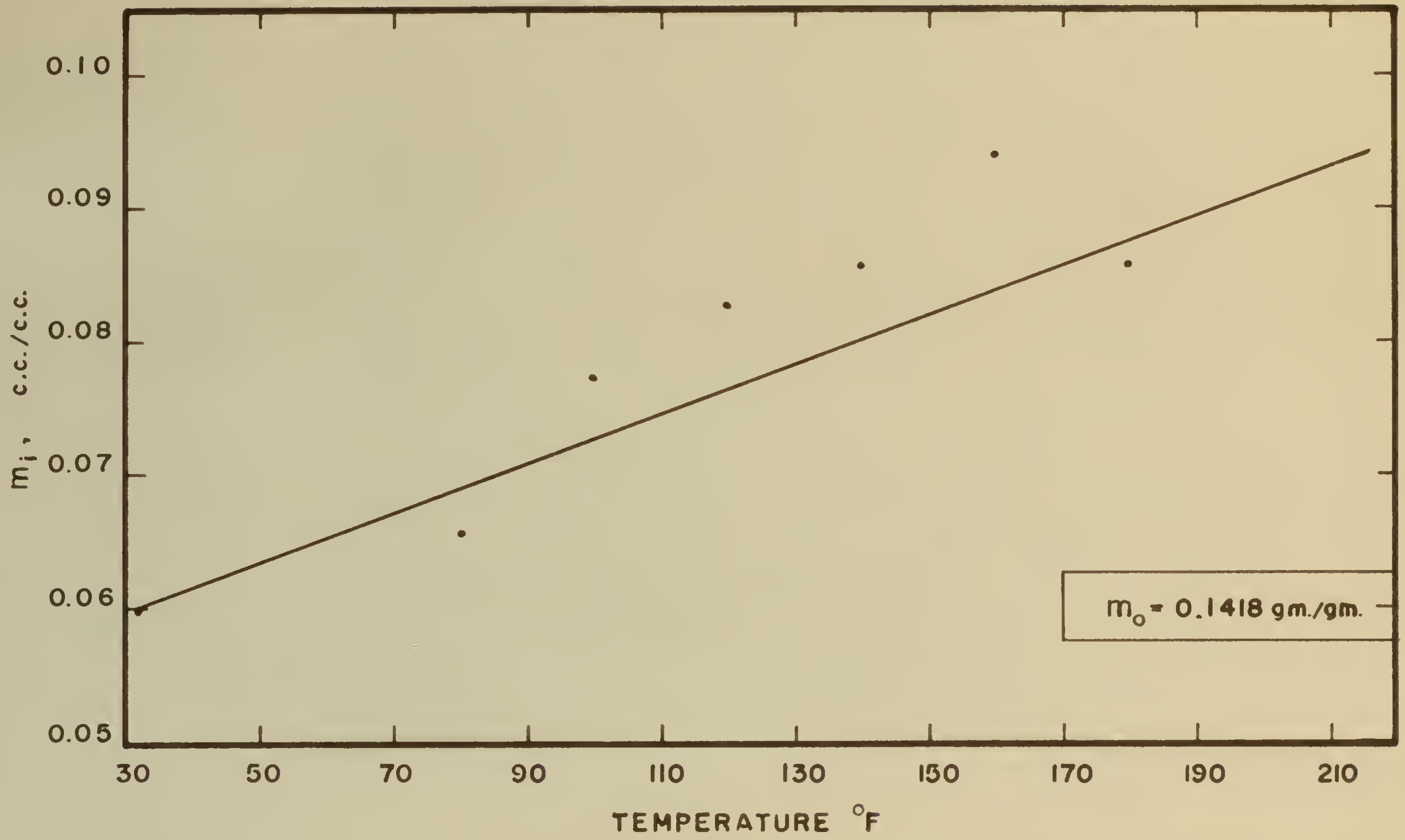


Fig. 7. The moisture gain due to capillary action versus temperature for the White Kafir (grain sorghum).

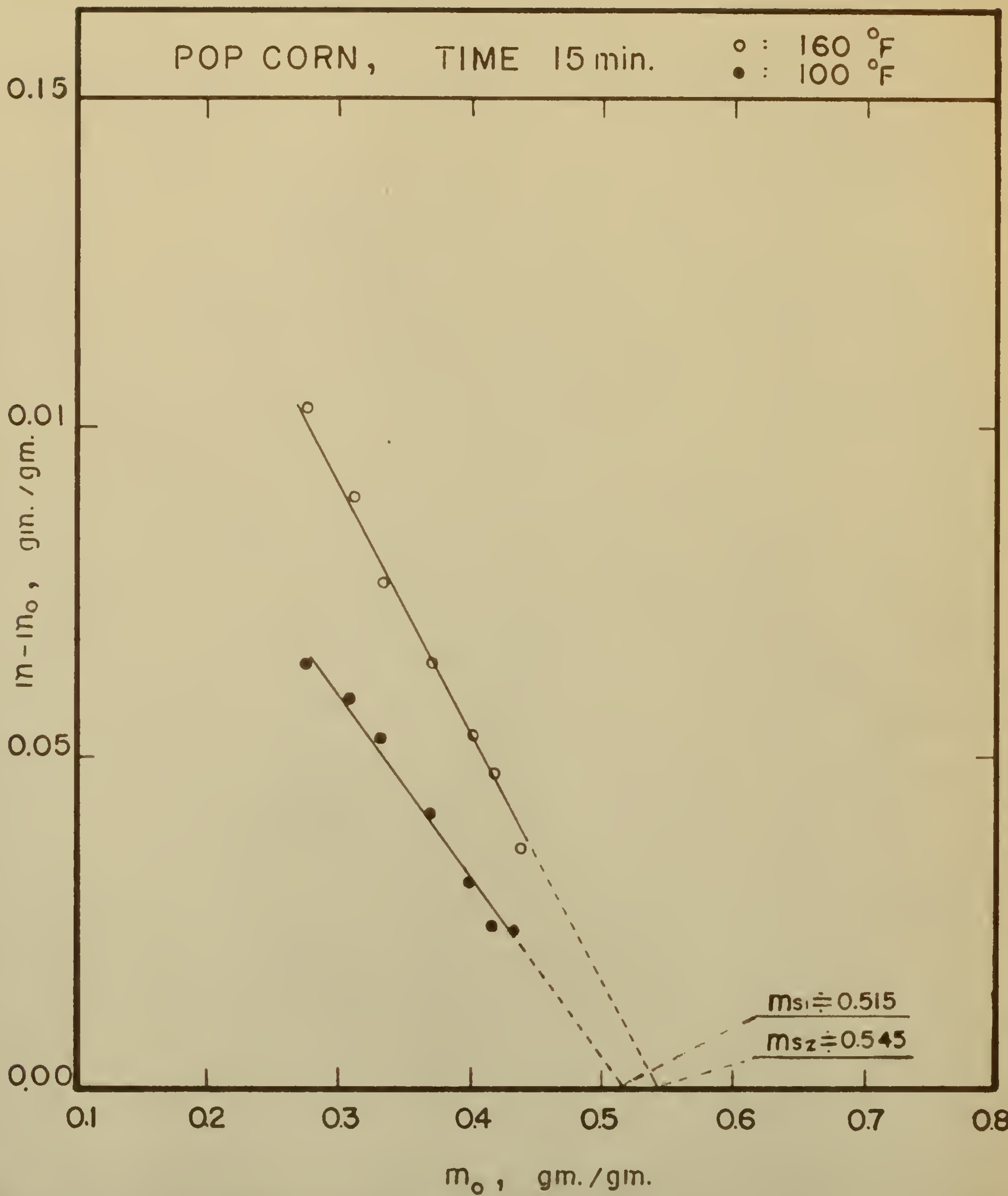


Fig. 8. Extrapolation of $m-m_o$ as function of m_o at different temperature to obtain the effective surface moisture content m_s for the K-4 Hybrid pop corn.

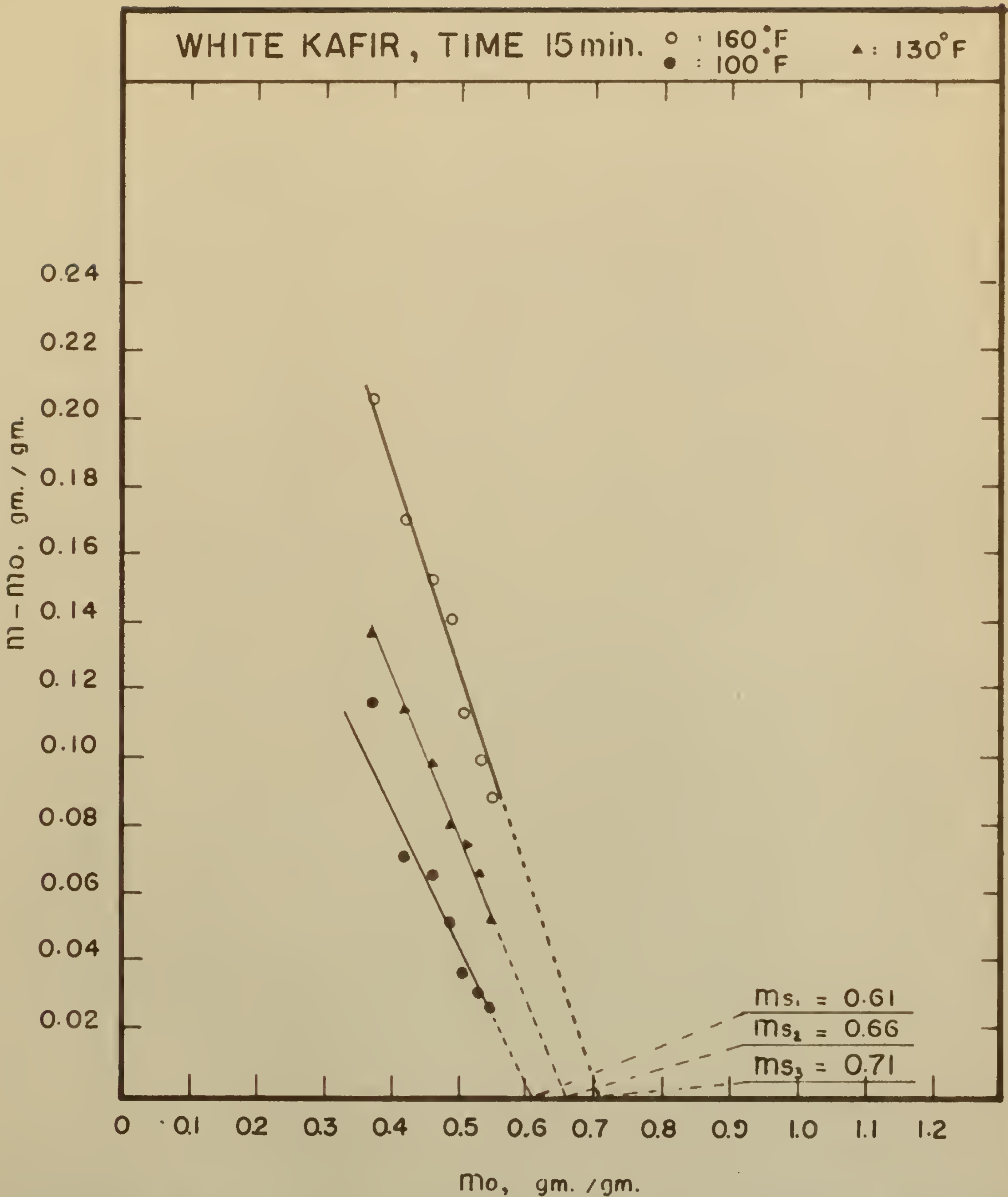


Fig. 9. Extrapolation of $m - m_o$ as a function of m_o at different temperature to obtain the effective surface moisture content m_s for White Kafir (grain sorghum).

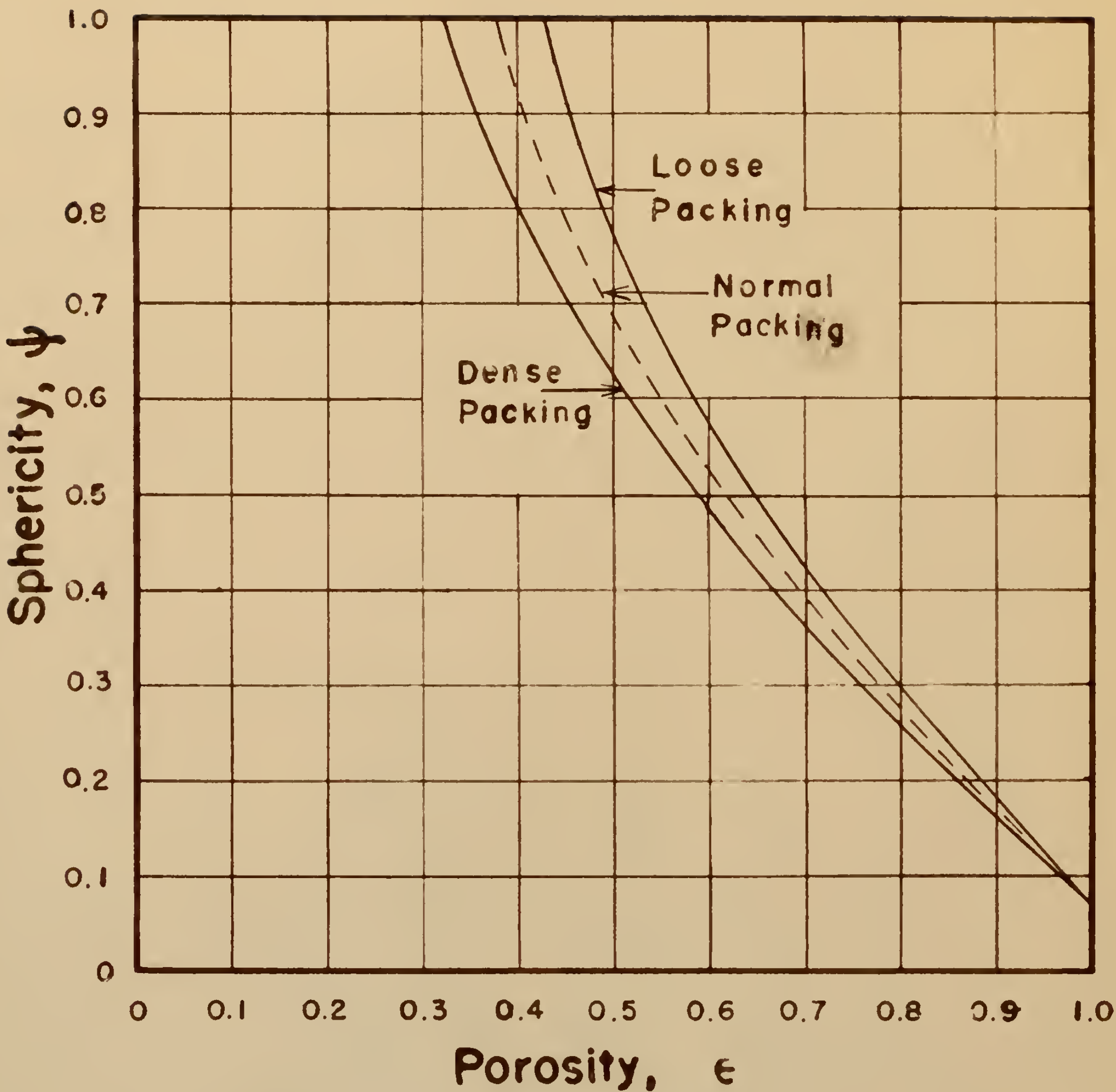


Fig. 10. Sphericity as a function of porosity for random-packed beds of uniform-sized particles. (4)

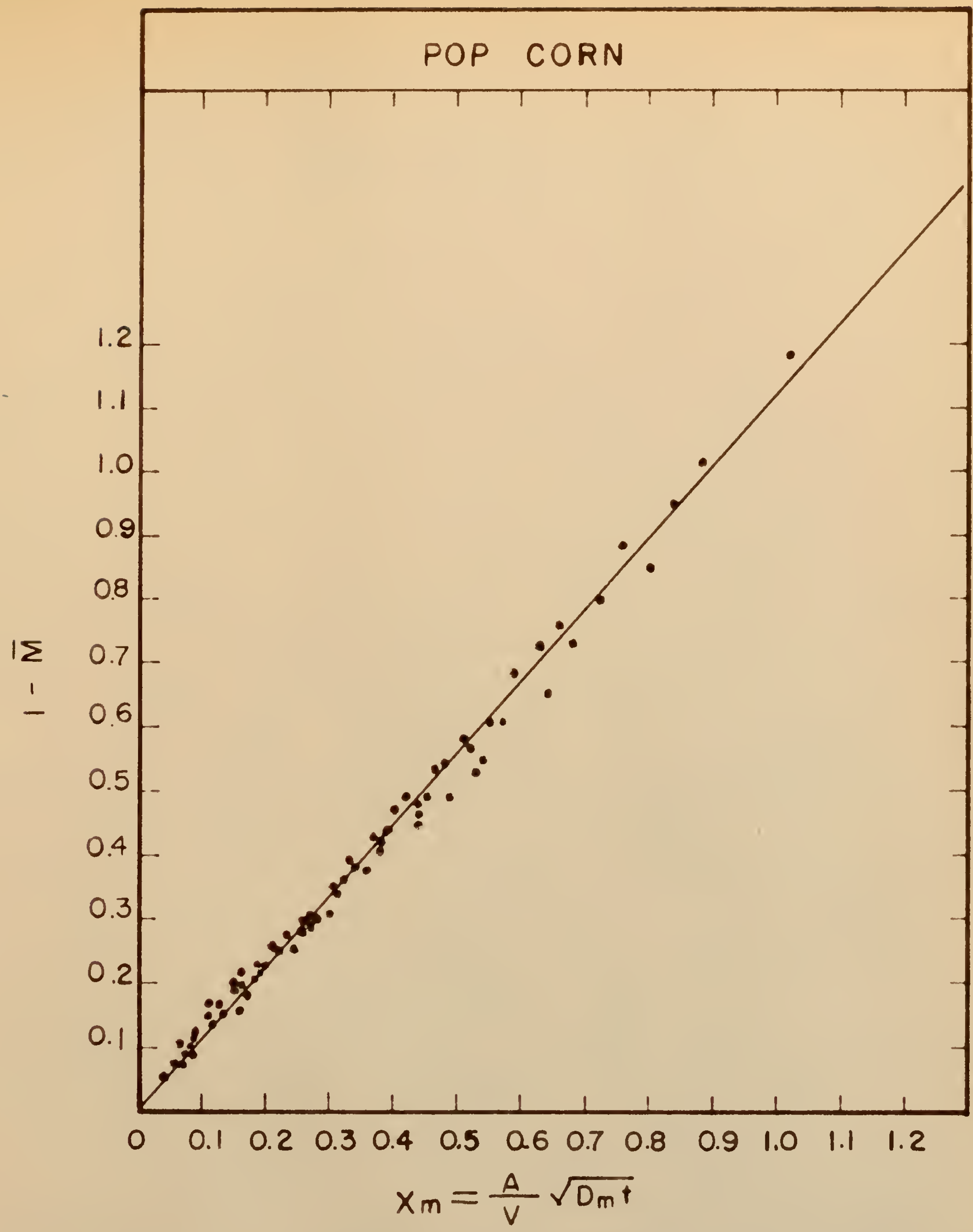


Fig. 11. Dimensionless correlation for the weight gain data of the K-4 Hybrid pop corn according to the first order approximation to diffusion equation.

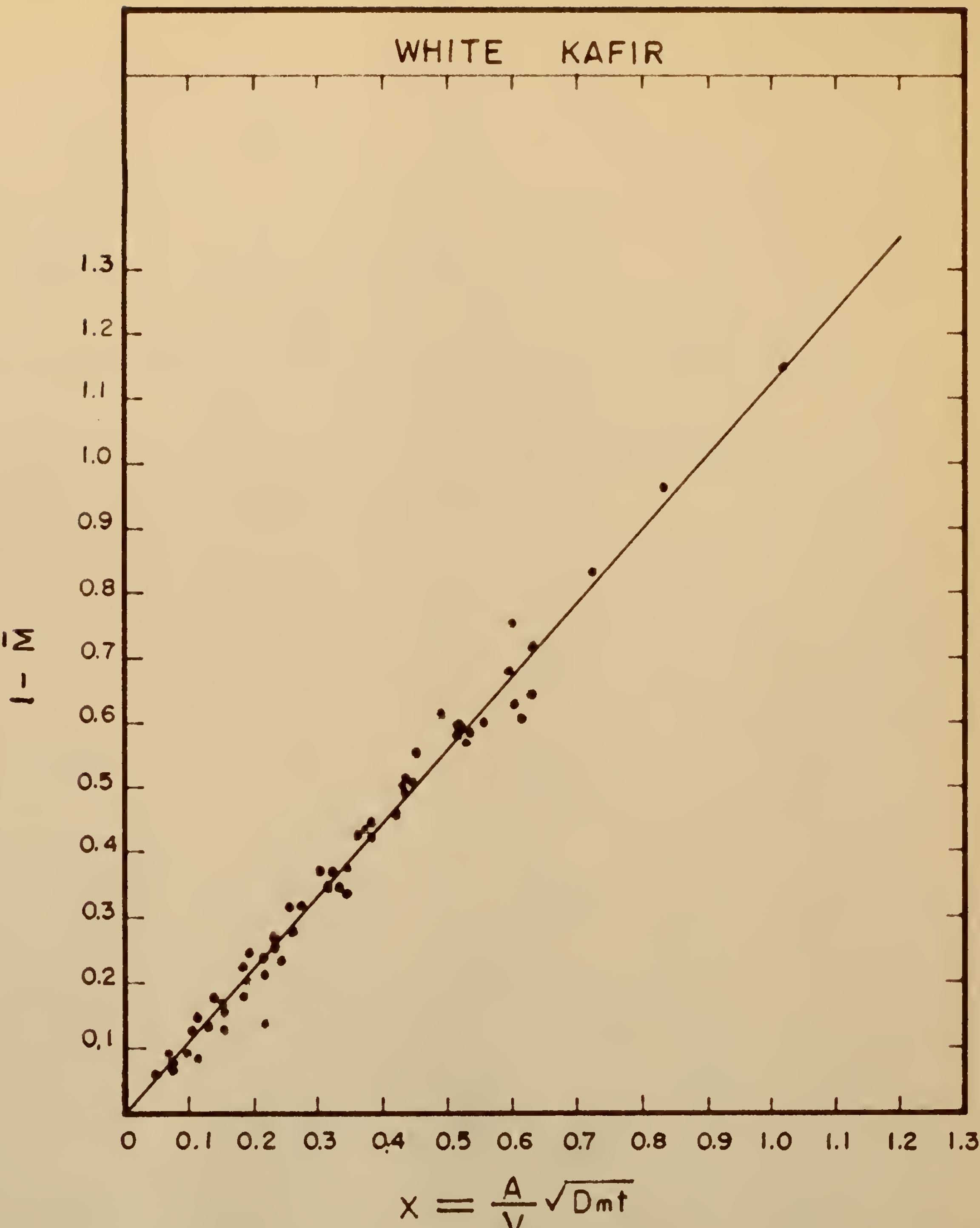


Fig. 12. Dimensionless correlation for the weight gain data of White Kafir (grain sorghum), according to the first order approximation to diffusion equation.

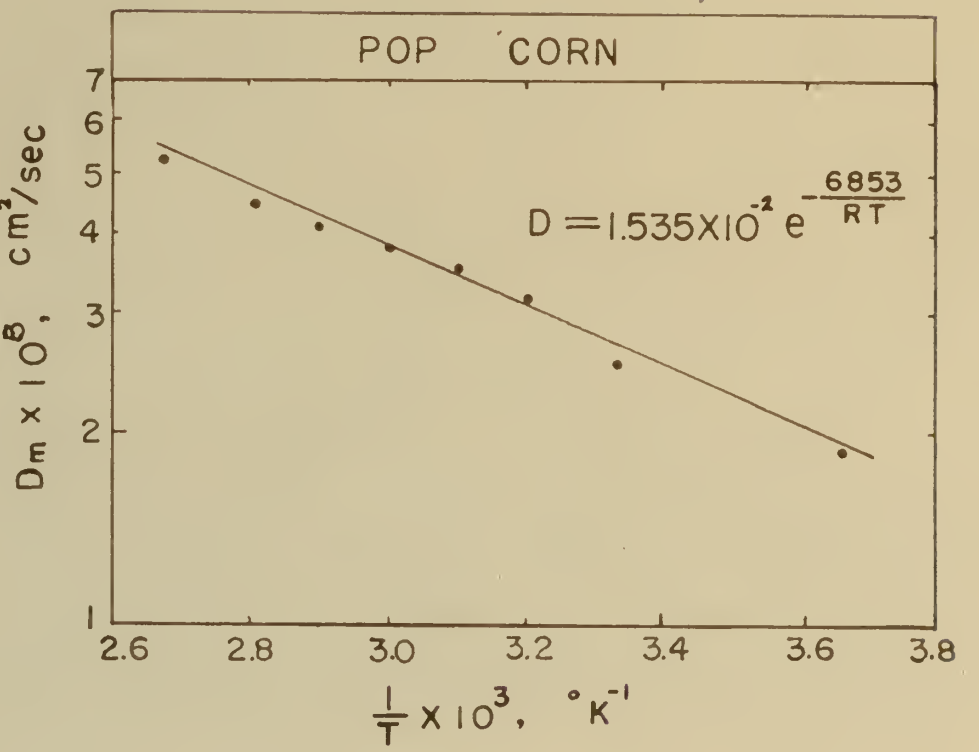


Fig. 13. The diffusion coefficient as a function of the reciprocal of absolute temperature for the K-4 Hybrid pop corn.

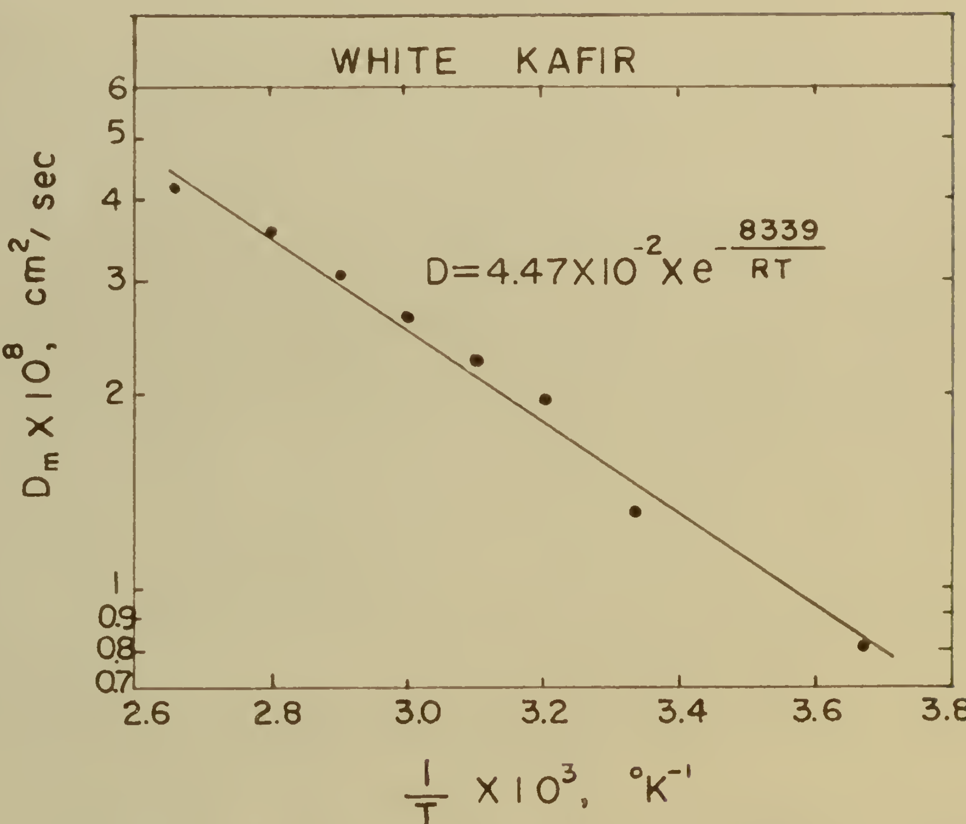


Fig. 14. The diffusion coefficient as a function of the reciprocal of absolute temperature for White Kafir (grain sorghum).

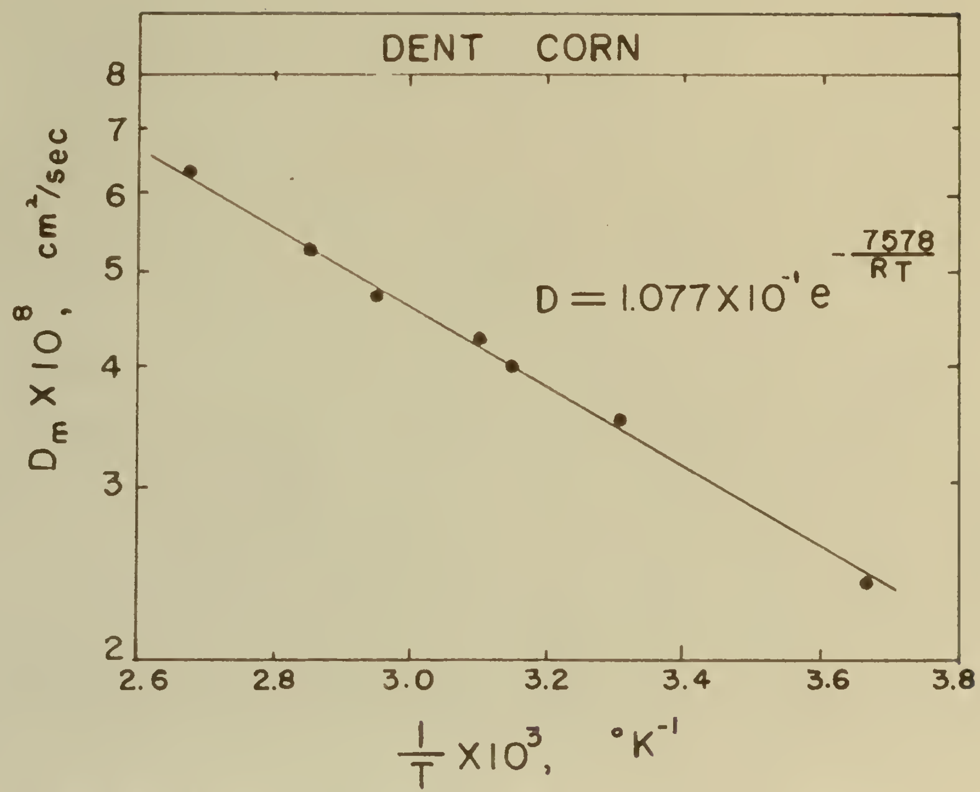


Fig. 15. The diffusion coefficient as a function of the reciprocal of absolute temperature for K1859 Hybrid corn (dent corn).

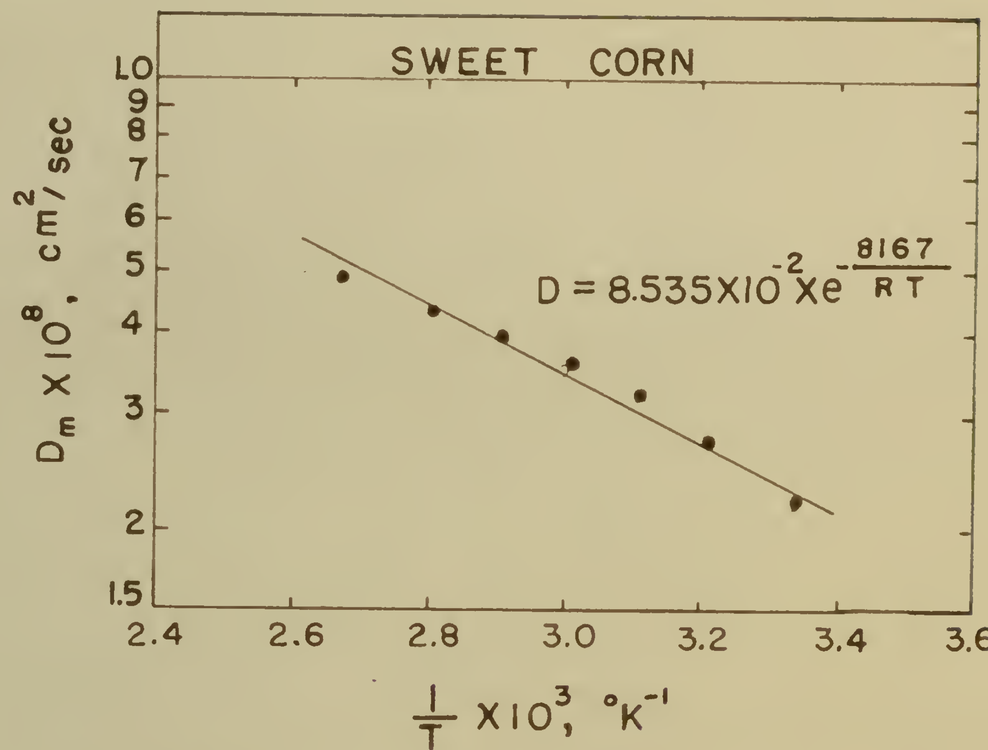


Fig. 16. The diffusion coefficient as a function of the reciprocal of absolute temperature for Gold Rash sweet corn.

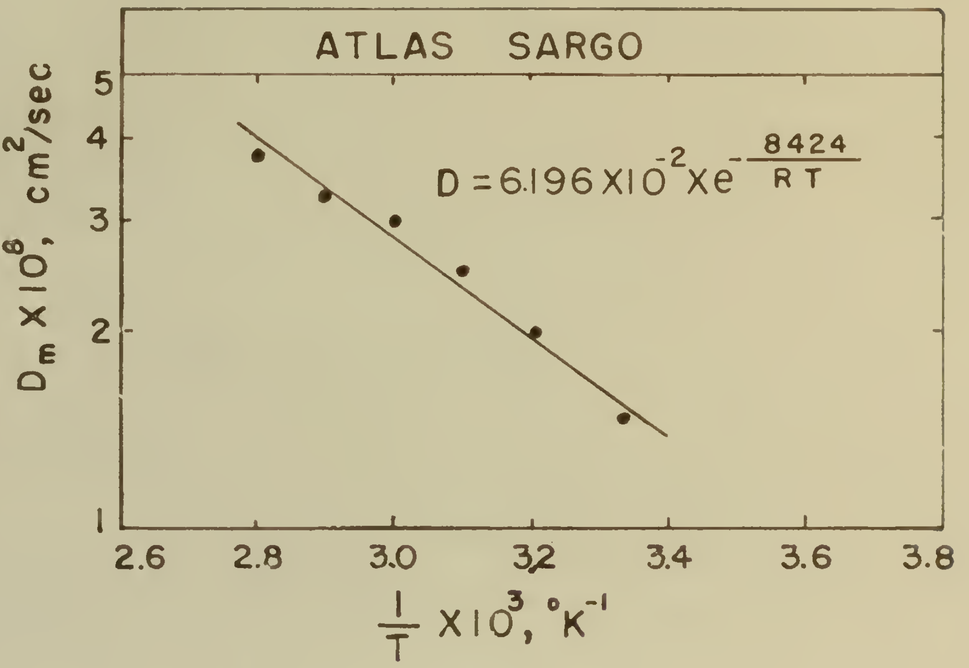


Fig. 17. The diffusion coefficient as a function of the reciprocal of absolute temperature for Atlas sargo.

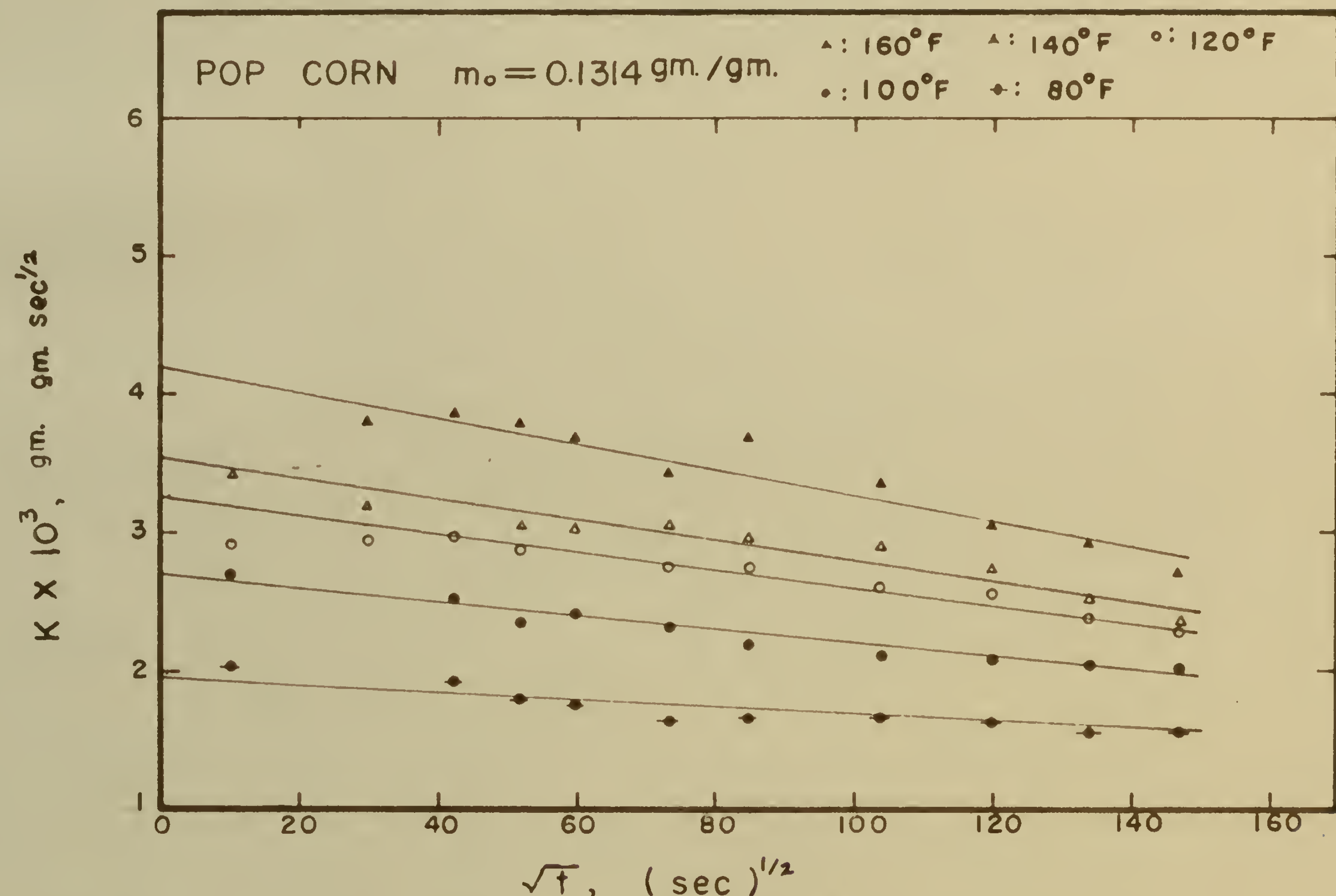


Fig. 18. $K = \bar{m} - m_o / \sqrt{t}$ as a function of square root of time at different temperature for the steeping data of the K-4 Hybrid pop corn.

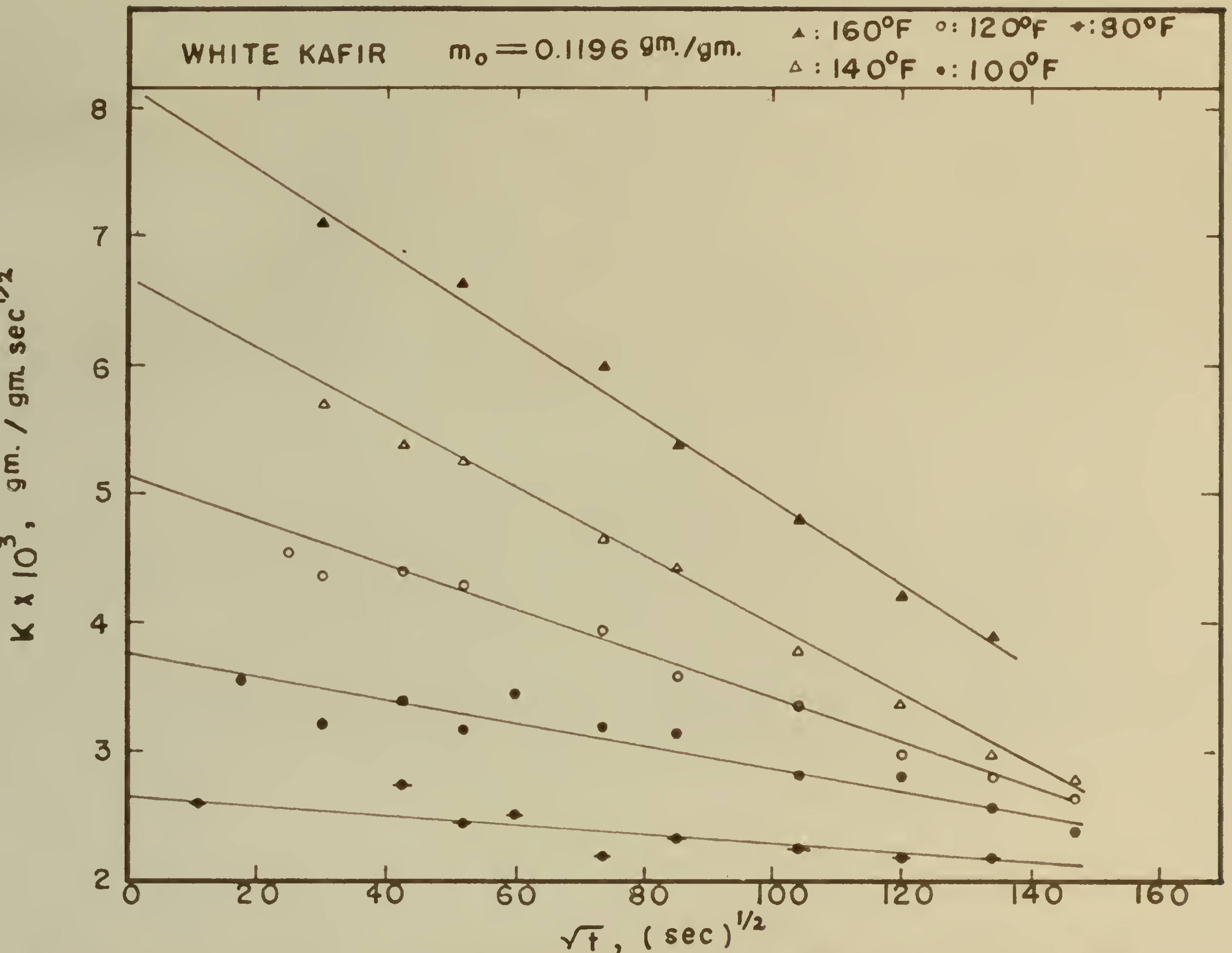


Fig. 19. $K = m - m_o / \sqrt{t}$ as a function of square root of time at different temperature for the steeping data of White Kafir (grain sorghum).

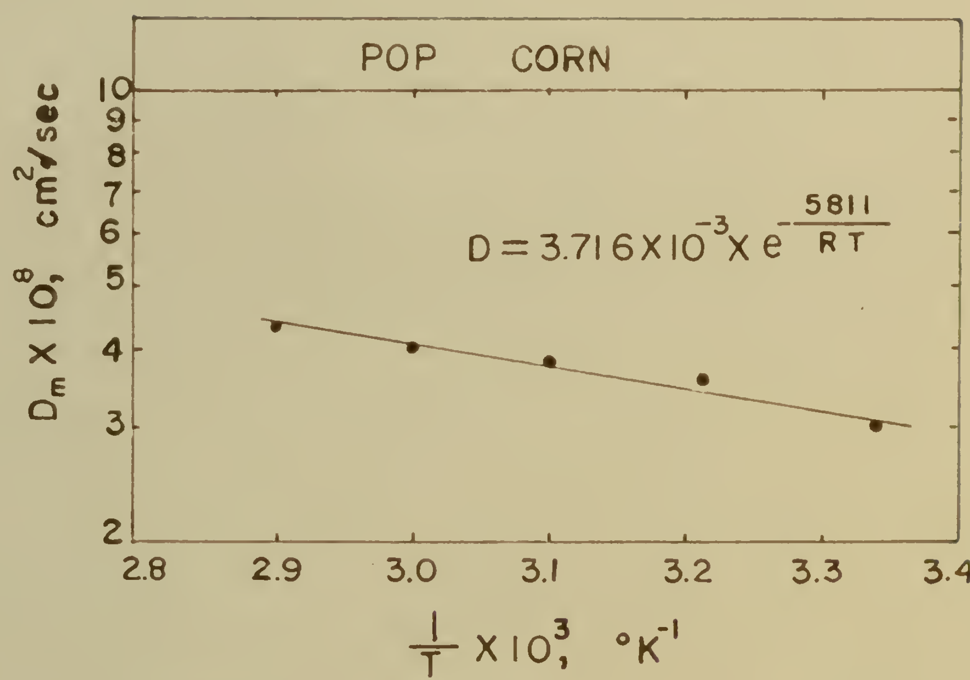


Fig. 20. The diffusion coefficient calculated from equation (57), as a function of reciprocal of temperature for the K-4 Hybrid pop corn.

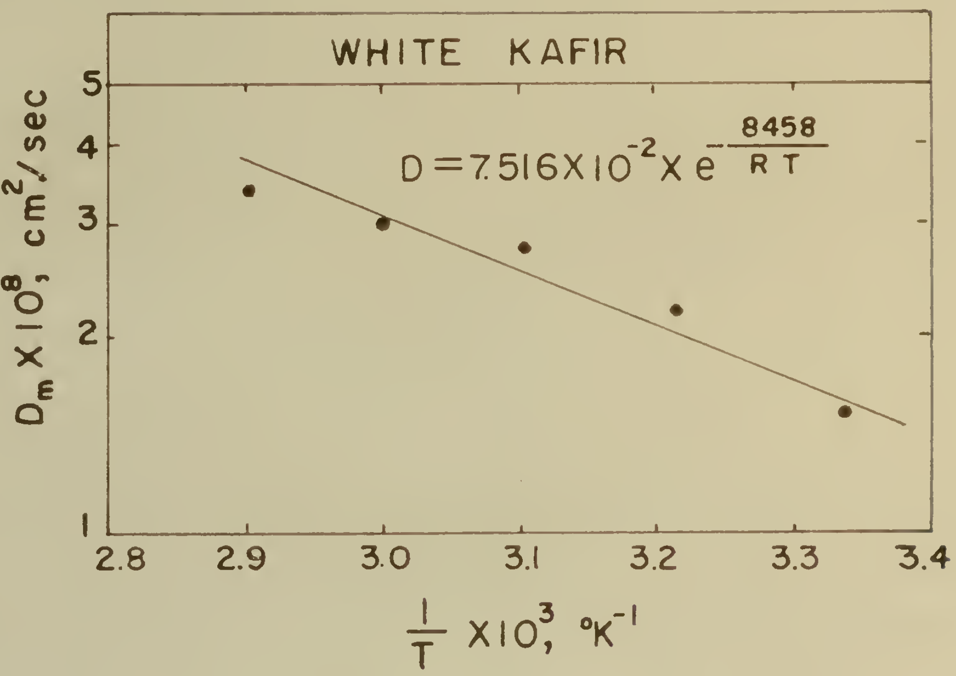


Fig. 21. The diffusion coefficient calculated from equation(57), as a function of reciprocal of temperature for White Kafir (grain sorghum).

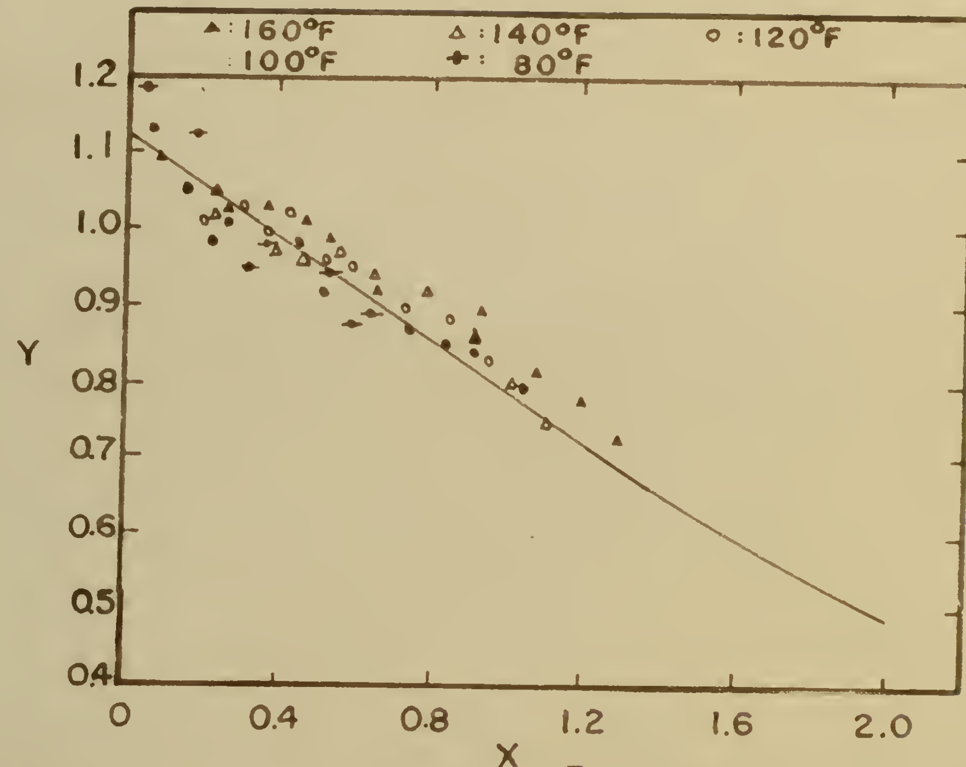


Fig. 22. Comparison of $Y = \frac{1-\bar{C}}{X}$ as a function of X for the theoretical curve with the experimental steeping data of the K-4 Hybrid pop corn.

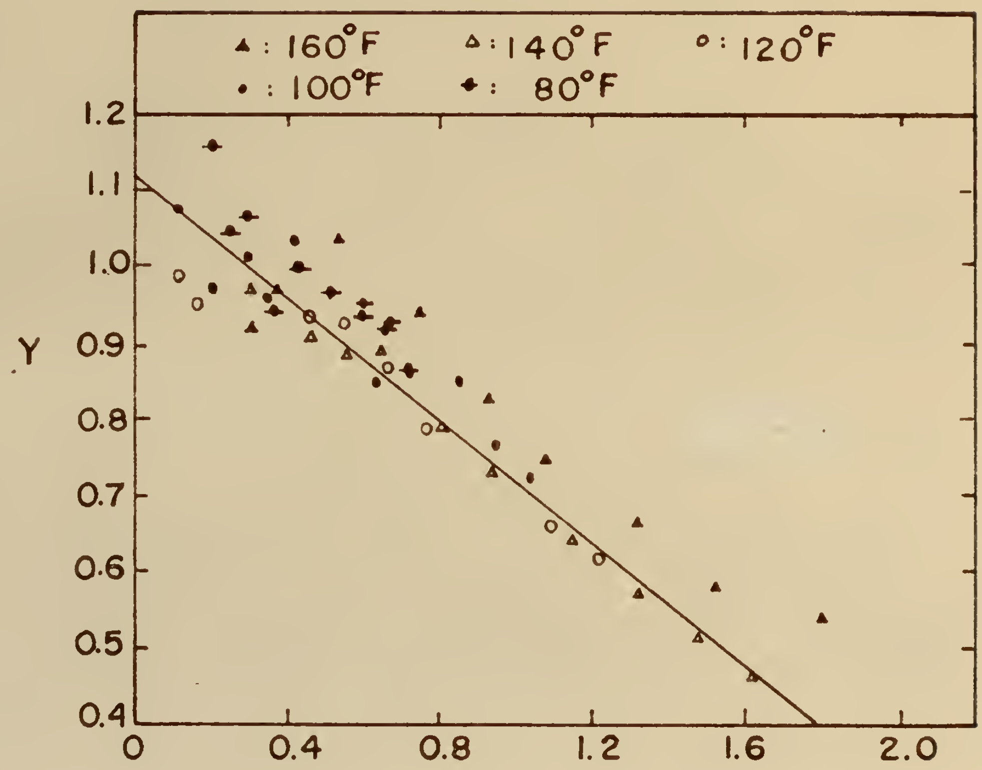


Fig. 23. Correlation of $Y = \frac{\frac{X}{1-\bar{C}}}{X}$ as a function of X for the experimental steeping data of White Kafir (grain sorghum).

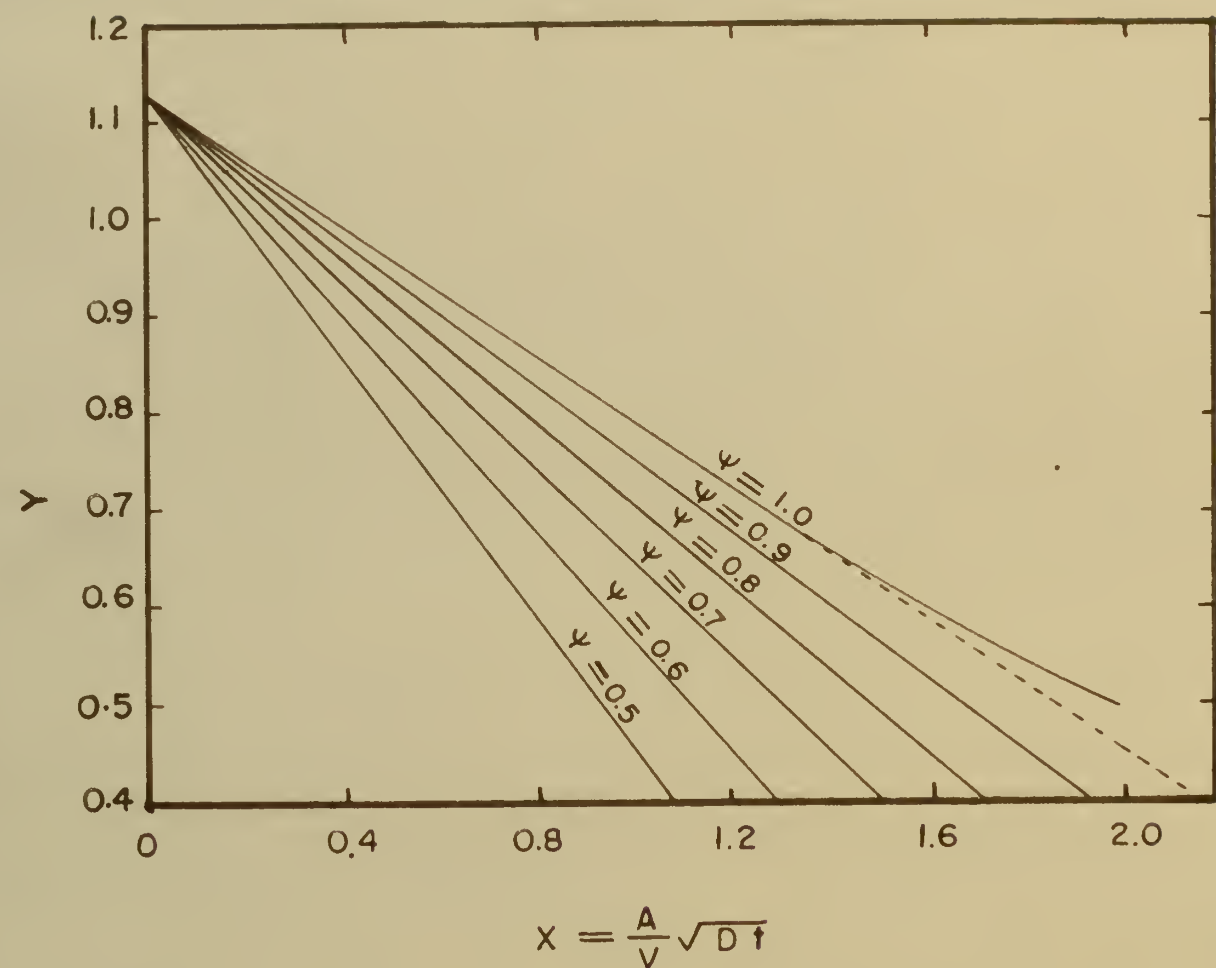


Fig. 24. $Y = \frac{1-\bar{C}}{X}$ as a function of X and sphericity.

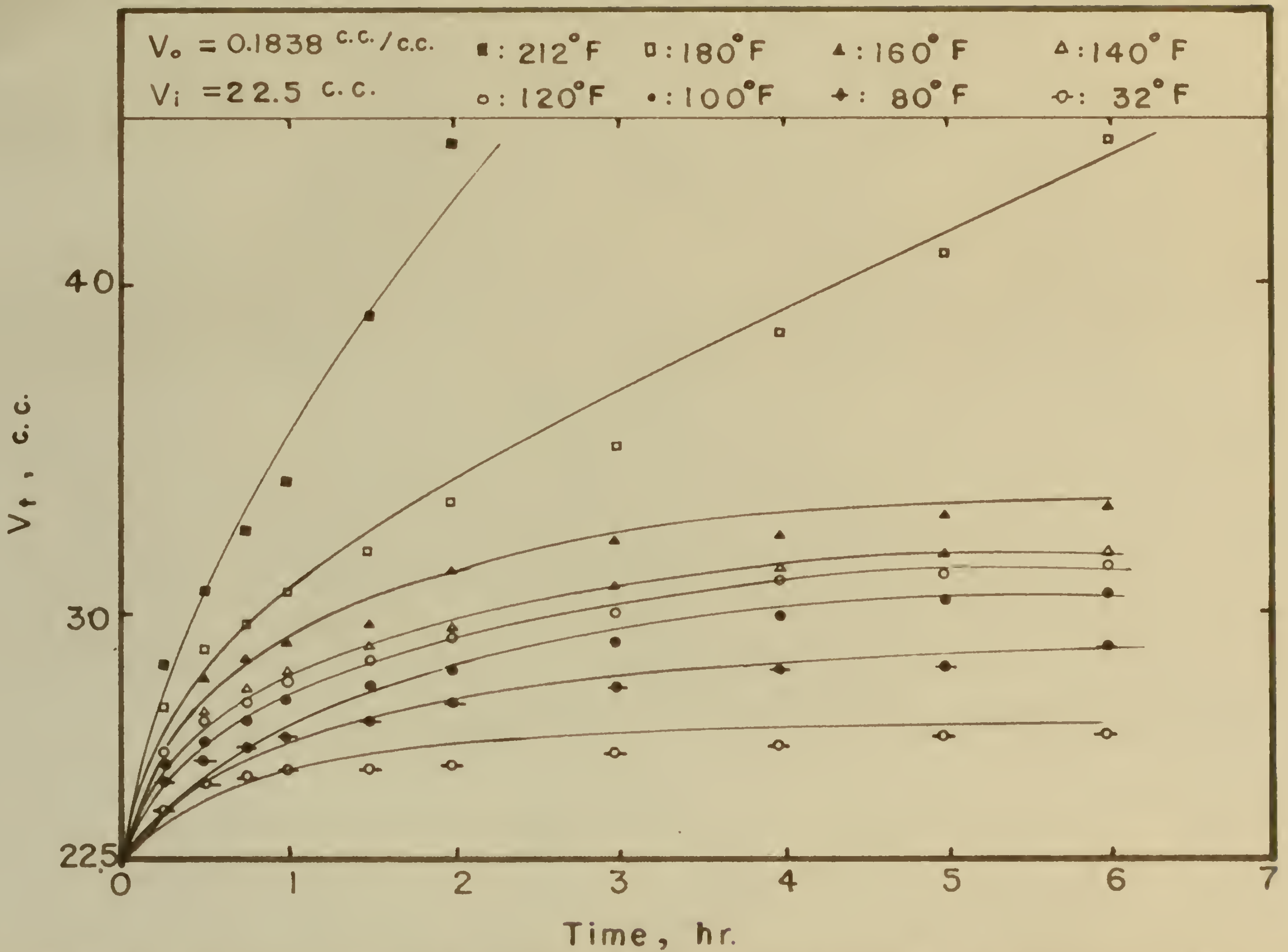


Fig. 25. Volume of the K-4 Hybrid pop corn as a function of absorption time.

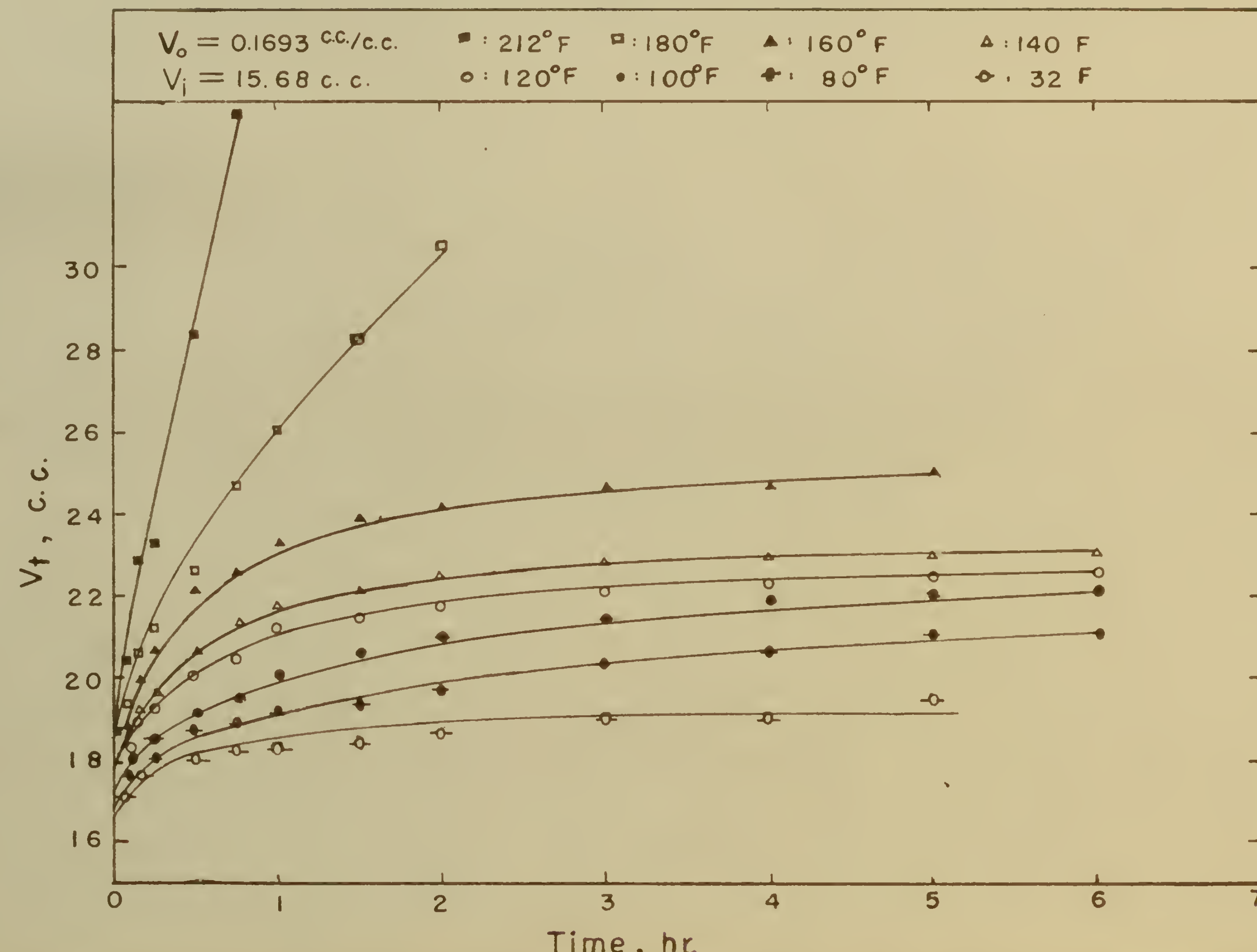


Fig. 26. Volume of White Kafir (grain sorghum) as a function of absorption time.

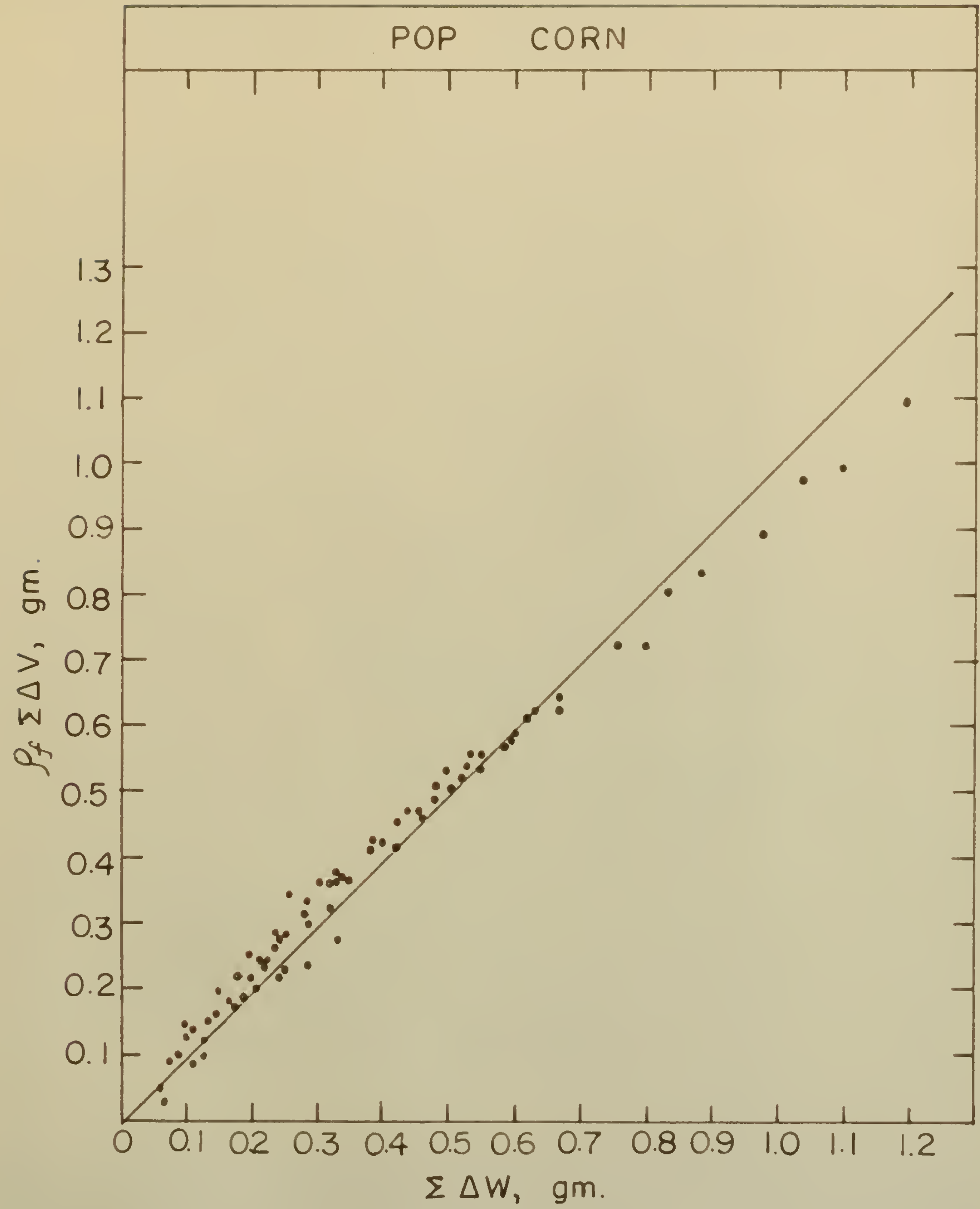


Fig. 27. The product of the volume increase of the K-4 Hybrid pop corn and the density of water as a function of the weight increase.

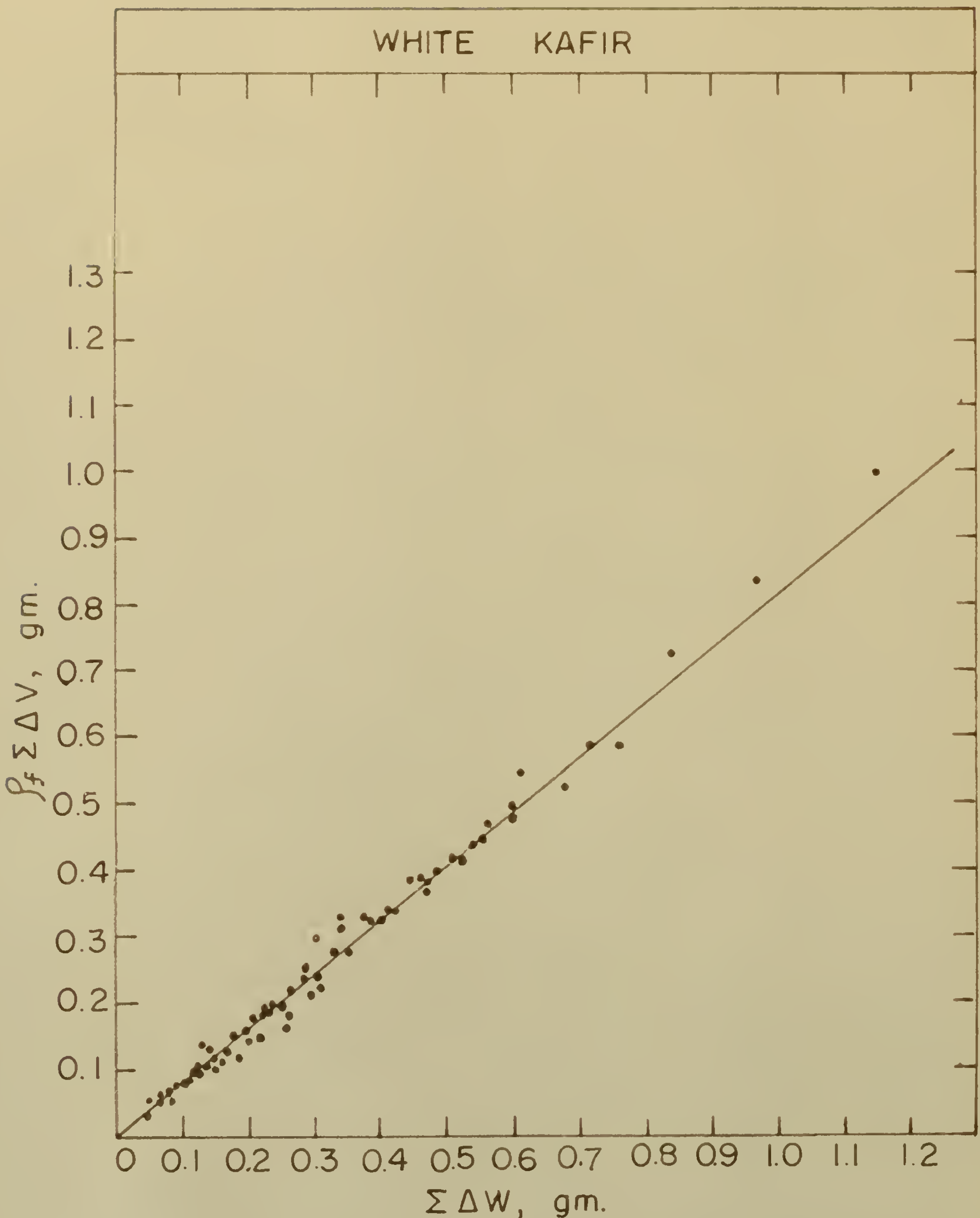


Fig. 28. The product of the volume increase of White Kafir (grain sorghum) and the density of water as a function of the weight increase.

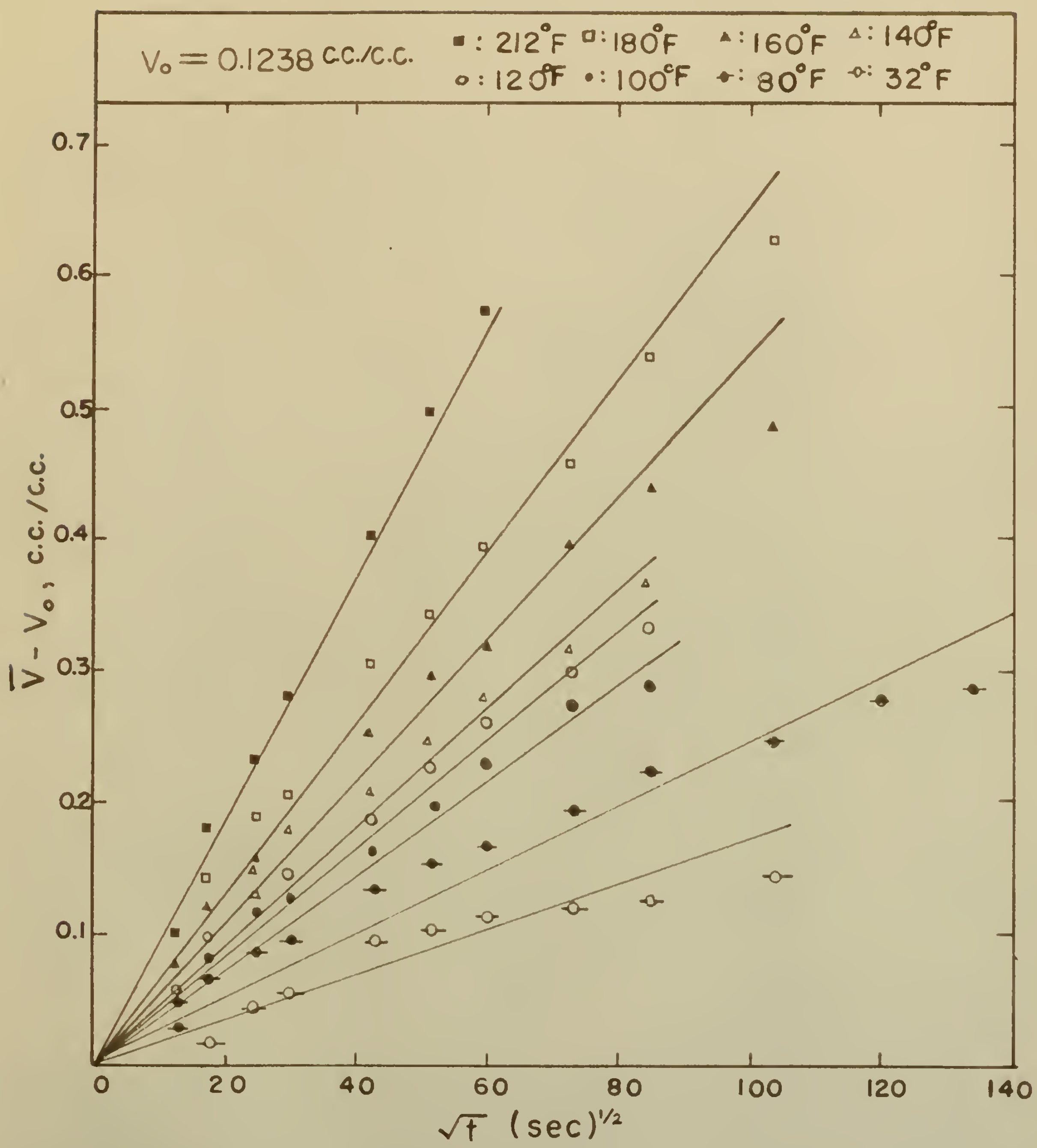


Fig.29. The linear relation between the volume gain and the square root of the absorption time for the K-4 Hybrid pop corn.

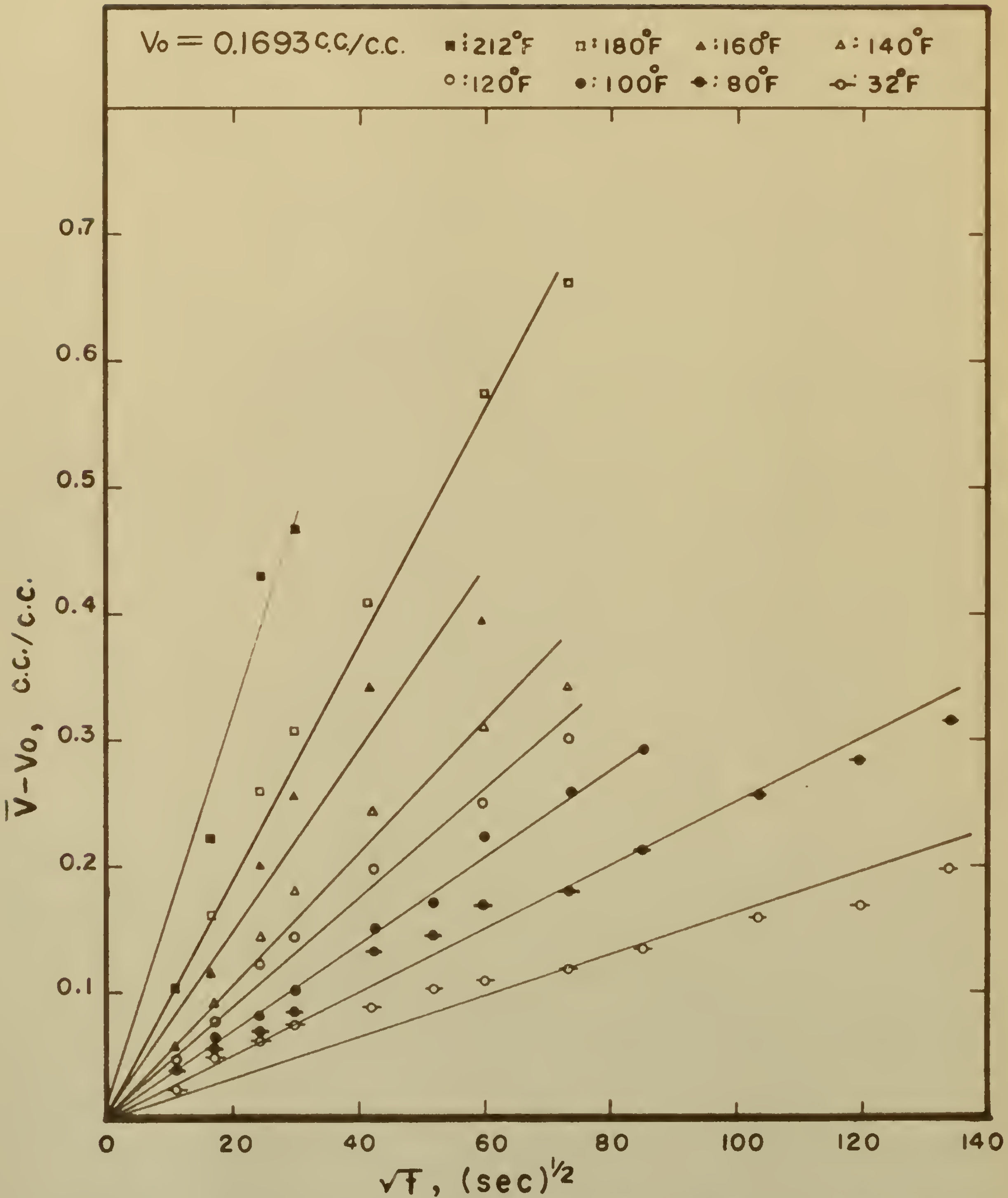


Fig. 30. The linear relation between the volume gain and the square root of absorption time for White Kafir (grain sorghum).

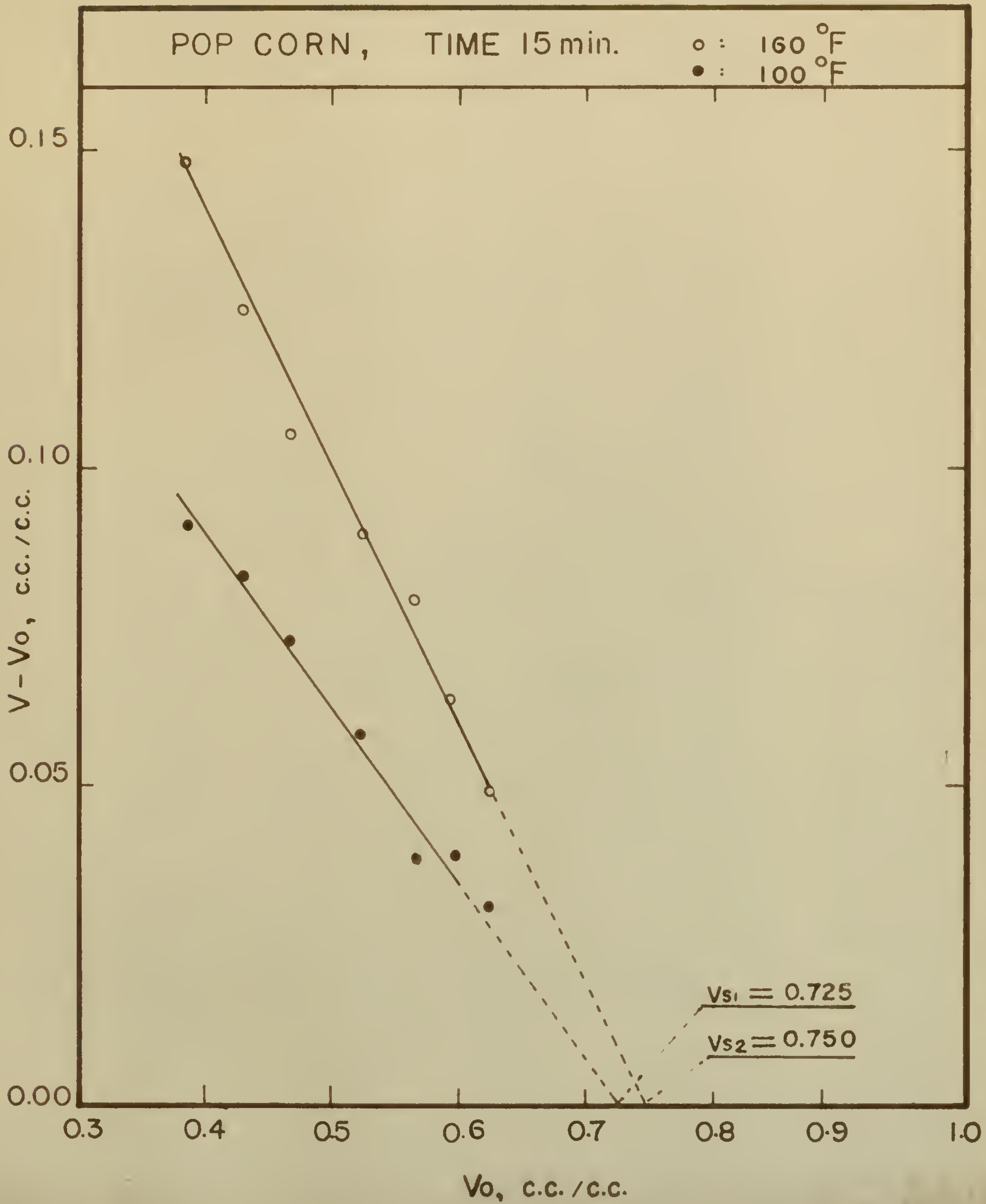


Fig. 31. Extrapolation of V-Vo as a function of Vo at different temperature to obtain the effective surface volume expansion V_s for the K-4 Hybrid pop corn.

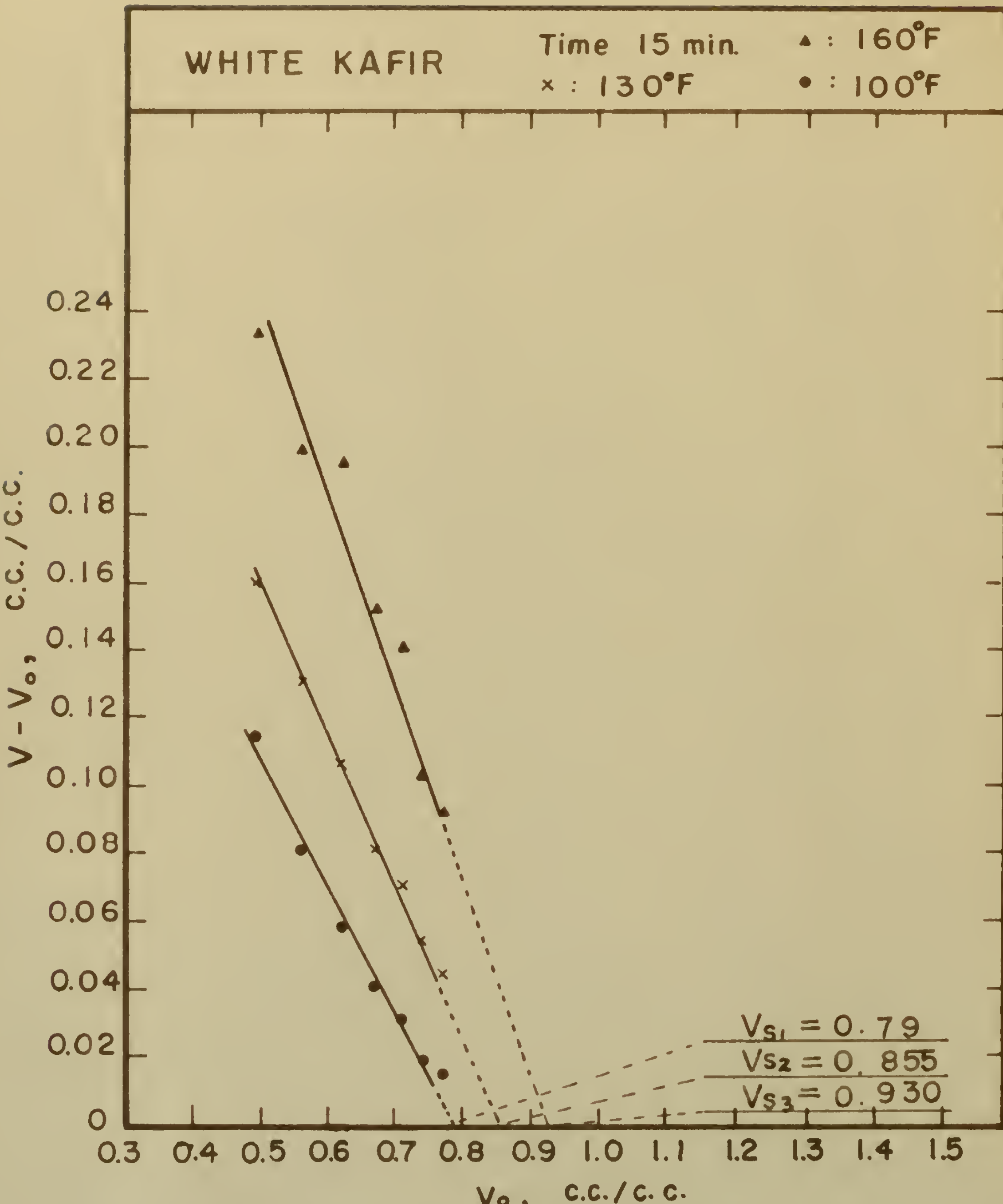


Fig. 32. Extrapolation of $V-V_o$ as a function of V_o at different temperature to obtain the effective surface volume expansion V_s for White Kafir (grain sorghum).

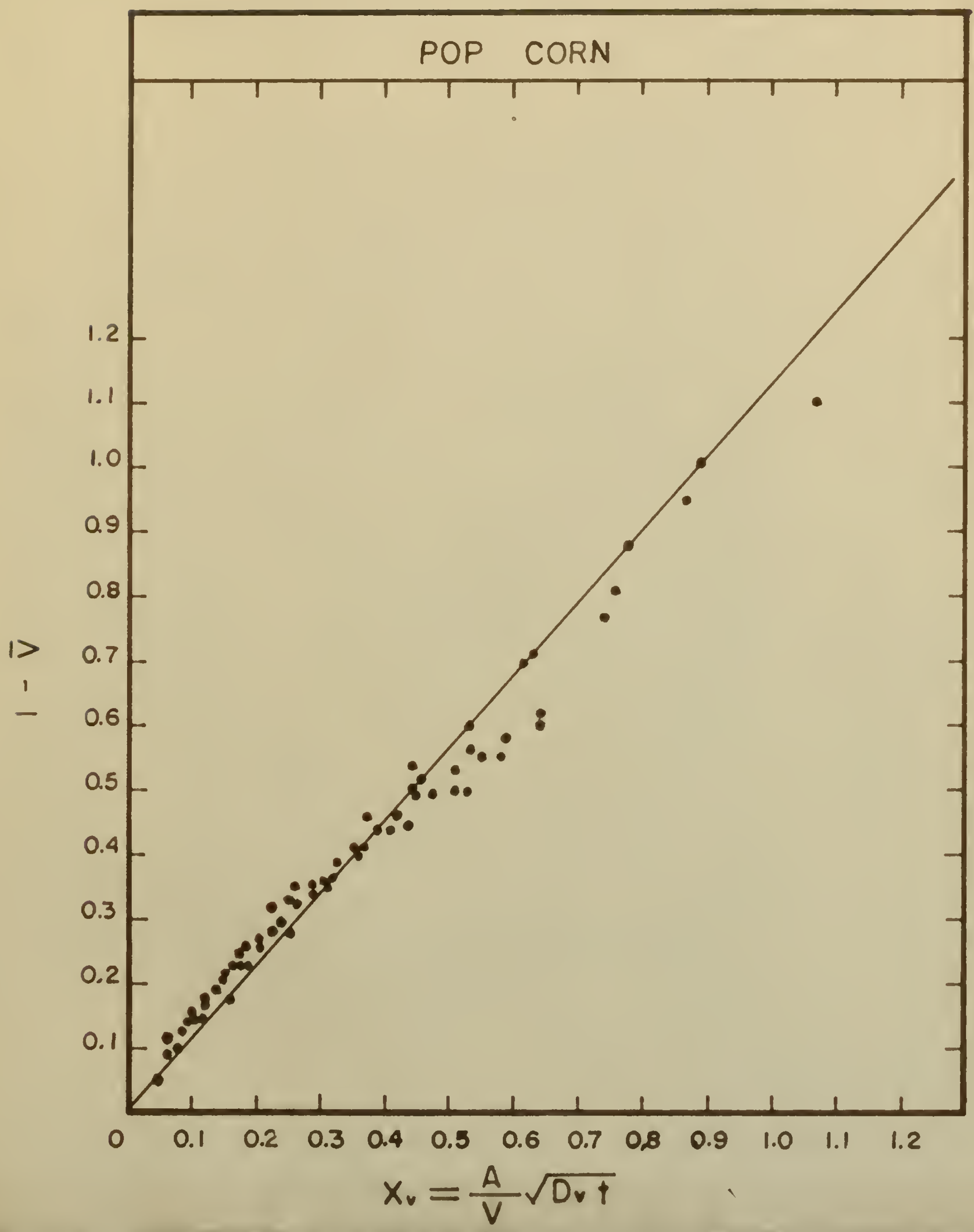


Fig. 33. Dimensionless correlation for the volume gain data of the K-4 Hybrid pop corn, according to the first order approximation to diffusion equation.

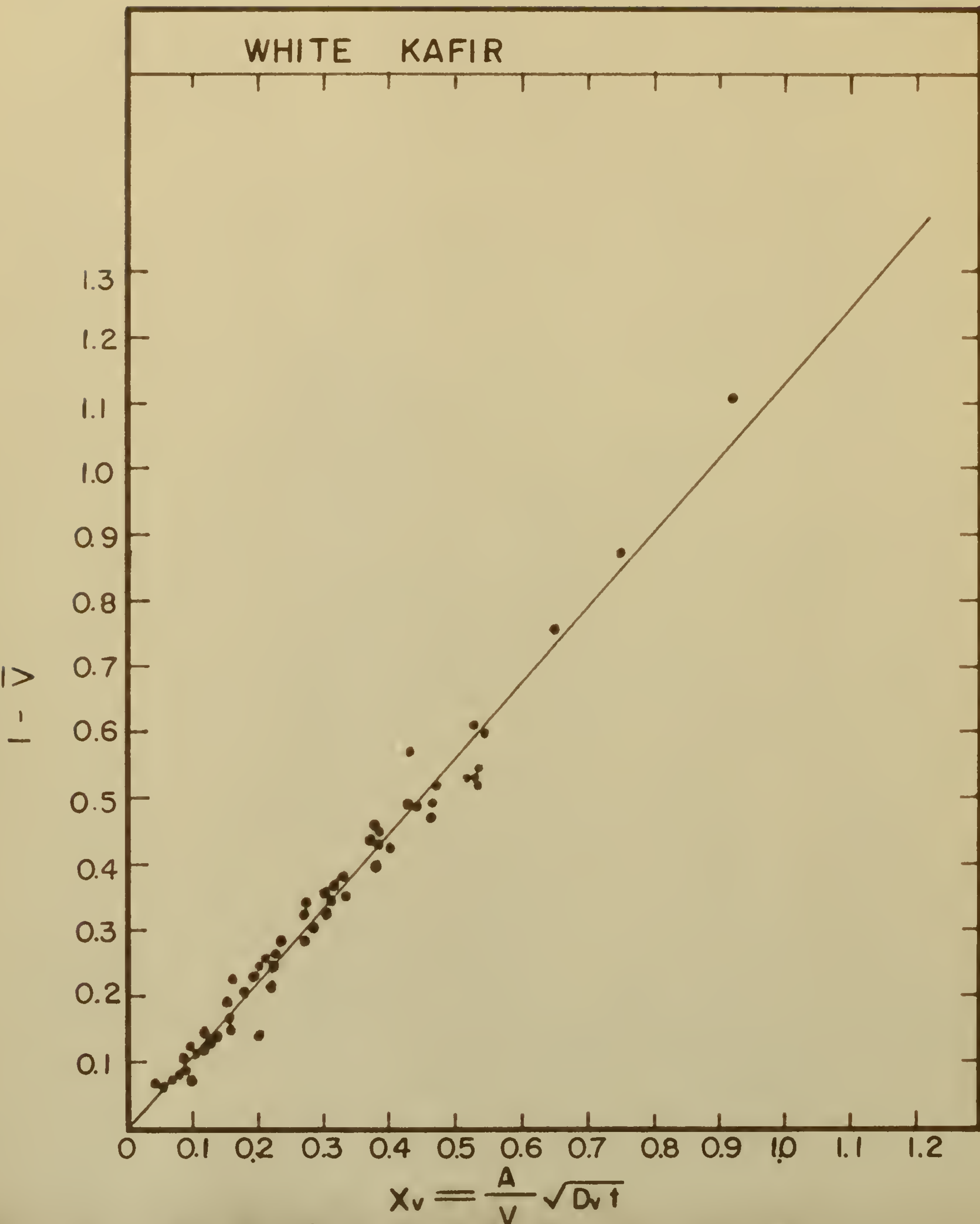


Fig. 34. Dimensionless correlation for the volume gain data of White Kafir (grain sorghum) according to the first order approximation to diffusion equation.

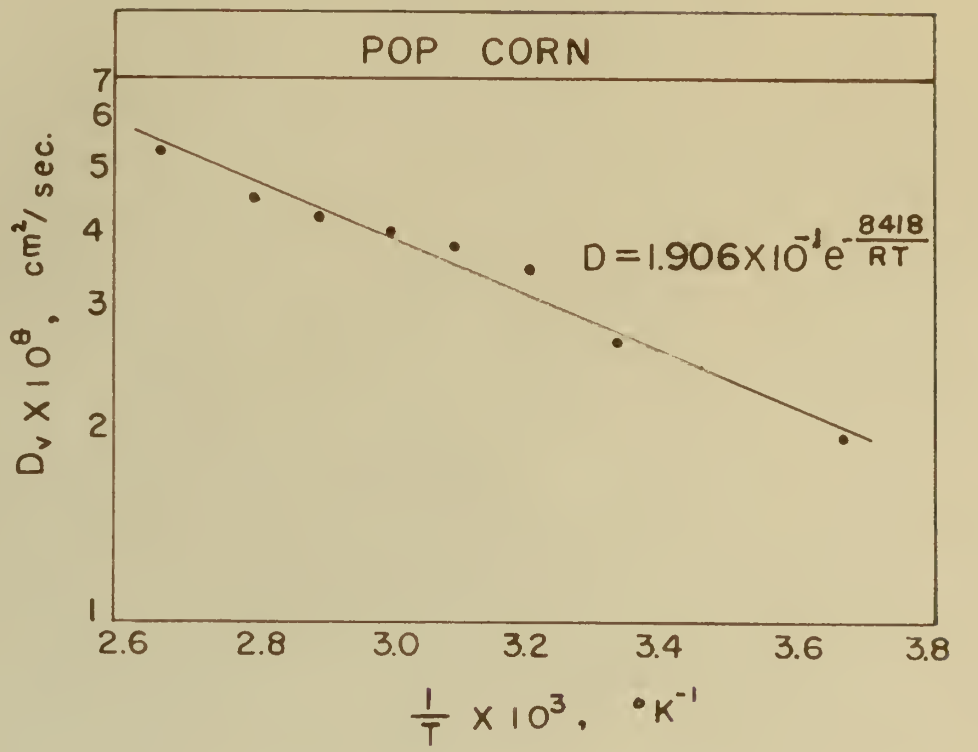


Fig. 35. The volume expansion coefficient as a function of the reciprocal of absolute temperature for the K-4 Hybrid pop corn.

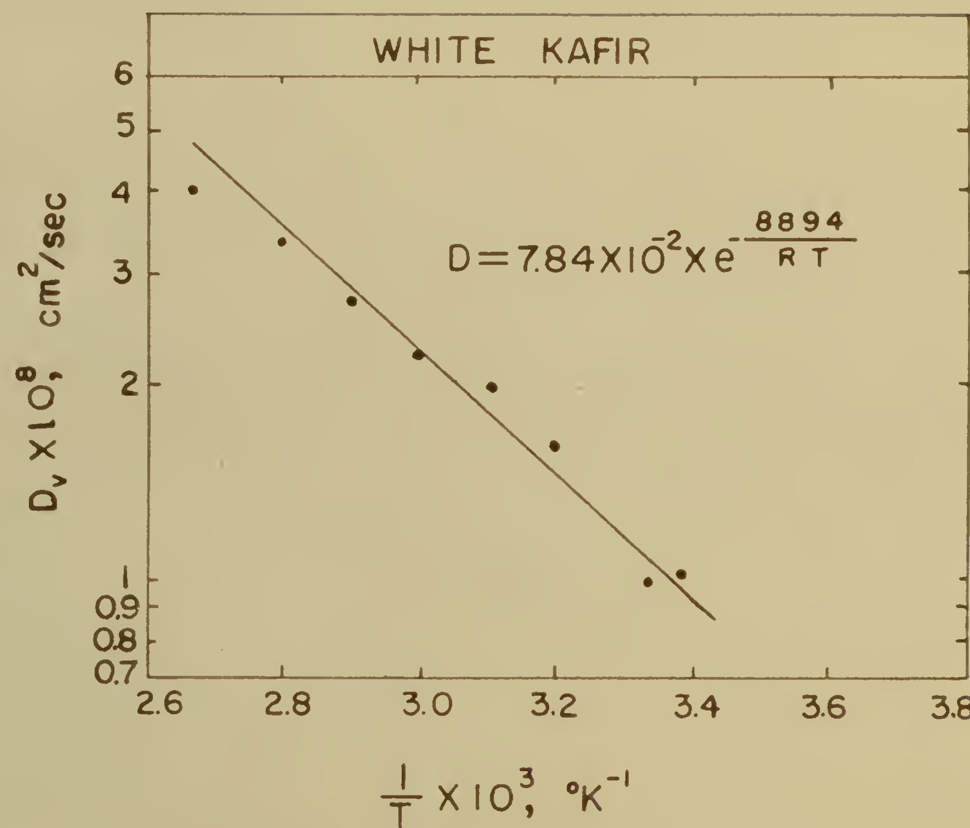


Fig. 36. The volume expansion coefficient as a function of the reciprocal of absolute temperature for White Kafir (grain sorghum.

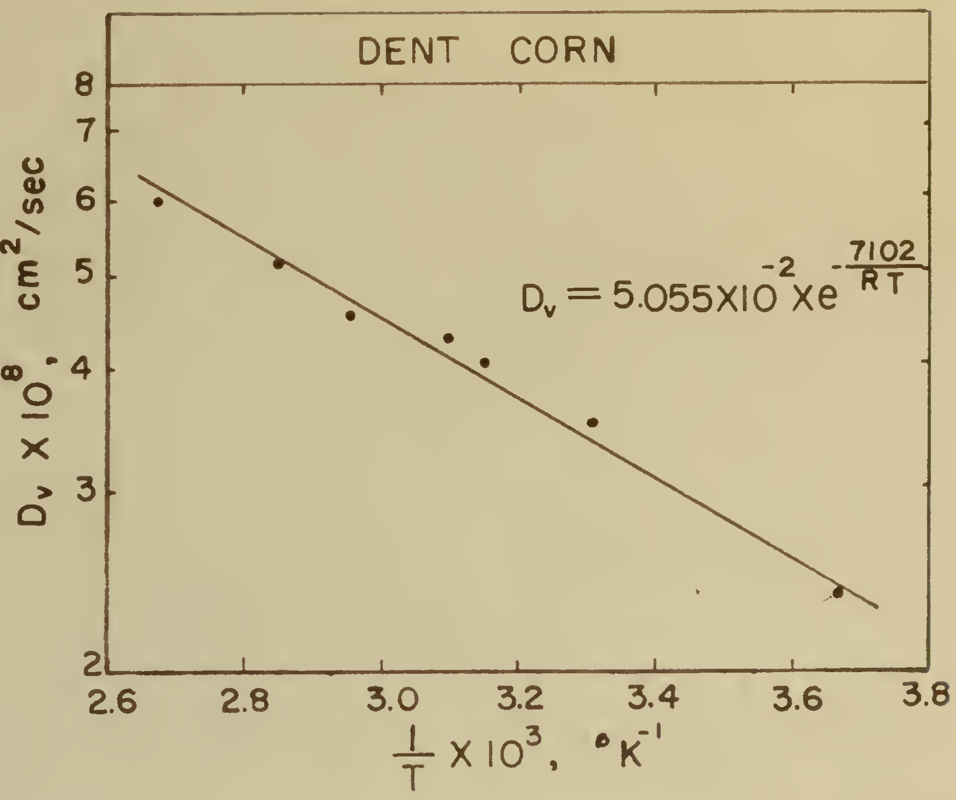


Fig. 37. The volume expansion coefficient as a function of the reciprocal of absolute temperature for K 1859 Hybrid corn (dent corn).

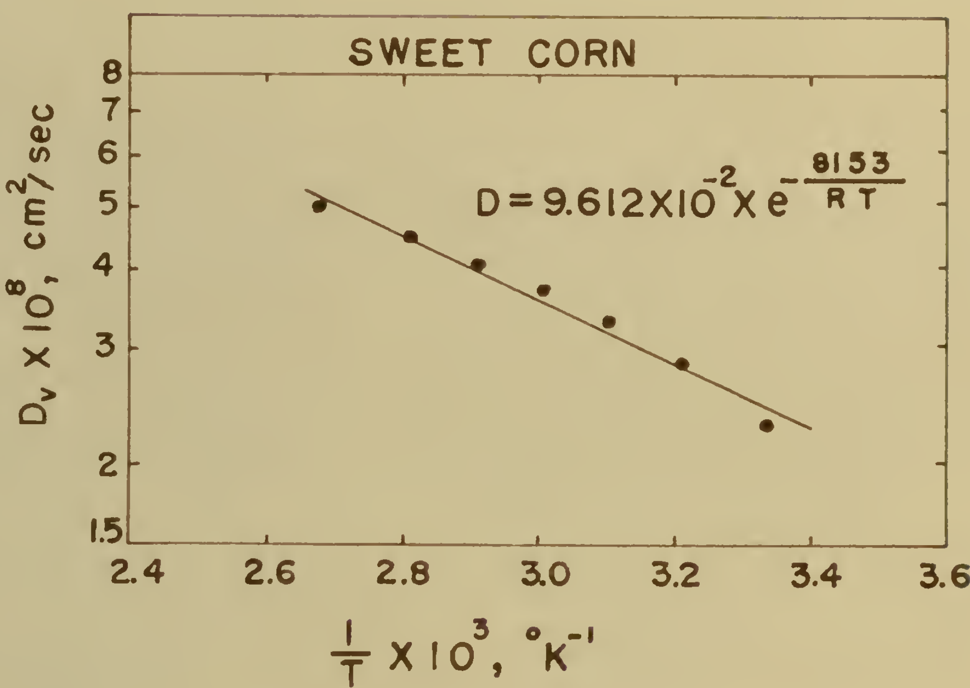


Fig. 38. The volume expansion coefficient as a function of the reciprocal of absolute temperature for Gold Rash sweet corn.

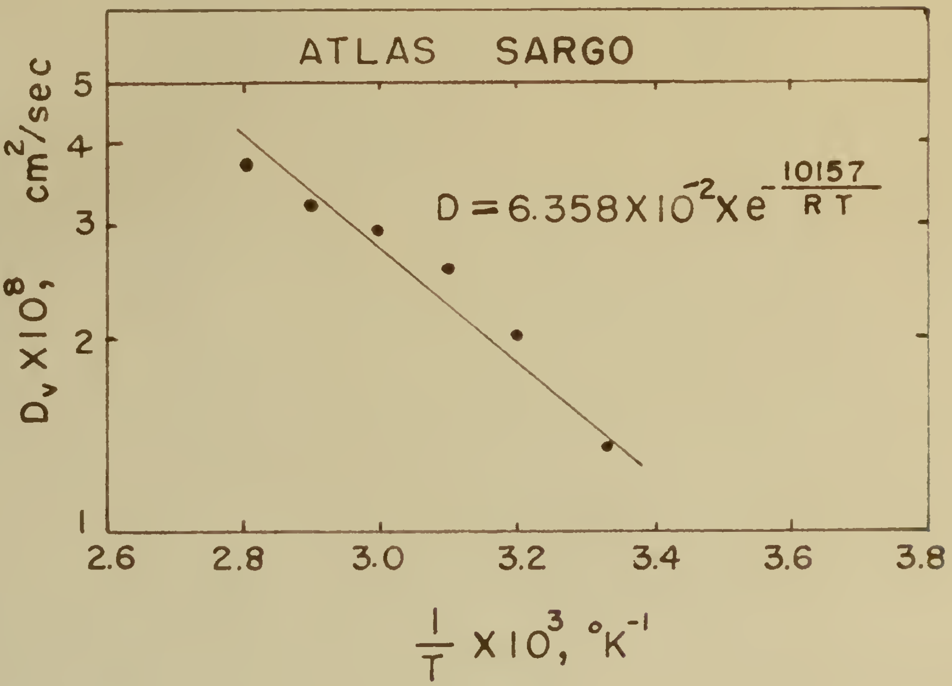


Fig. 39. The volume expansion coefficient as a function of the reciprocal of absolute temperature for Atlas Sargo.

DIFFUSION OF WATER IN KERNELS OF CORNS AND SORGHUMS

by

PU-SHIANG CHU

B.S., National Taiwan University, China, 1955

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

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Manhattan, Kansas

1962

Diffusion of water into five different cereal grains K-4 Hybrid pop corn, Gold Rash sweet corn, K1859 Hybrid corn, white kafir (grain sorghum) and Atlas Sorgo was investigated quantitatively. Experiments were carried out over a temperature range from 32°F to 212°F to measure the increases of both weight and volume during steeping. In the case of the weight increase, the correlation equation obtained by the first order approximation of the diffusion equation was:

$$1 - \overline{M} = \frac{2}{\sqrt{\pi}} X_m$$

where $\overline{M} = \dfrac{m_s - \overline{m}}{m_s - m_o}$, and $X_m = \dfrac{A}{V} \sqrt{D_m t}.$

The equation obtained by the second order approximation was

$$\frac{1 - \overline{M}}{X_m} = \frac{2}{\sqrt{\pi}} - 0.34 X_m$$ for the nearly spherical

grains such as K-4 Hybrid pop corn, and

$$\frac{1 - \overline{M}}{X_m} = \frac{2}{\sqrt{\pi}} - 0.4206 X_m$$ for a non-spherical grain

such as white kafir. For the volume increase, the equation obtained by the first order approximation was:

$$1 - \overline{V} = \frac{2}{\sqrt{\pi}} X_v$$

where $\overline{V} = \dfrac{v_s - \overline{v}}{v_s - v_o}$, and $X_v == \dfrac{A}{V} \sqrt{D_v t}$

The diffusion coefficient, D_m, and the volume expansion coefficient D_v, were evaluated from these equations. Plots of these coefficients versus the reciprocal of the absolute temperature show that an Arrhenius-type equation relates the coefficients to temperature.