ON THE ABSORPTION OF LIQUID WATER BY THE WHEAT KERNEL[1]

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ABSTRACT

The absorption of liquid water by the wheat kernel proceeds by a heterogeneous mechanism. There is a very rapid initial absorption in which the pericarp is saturated by capillary imbibition. The average moisture gain due to this absorption is 0.045 g. per g., dry basis, at 22°C., but decreases with increasing temperature. Subsequent absorption is directly proportional to the square root of the period of immersion and is described by the diffusion equation

$$1 - \overline{M} = \frac{2}{\sqrt{\pi}} \frac{S}{V} \sqrt{Dt}$$

where $1 - \overline{M}$ is the relative moisture gain and S/V is the surface-to-volume ratio. The average diffusion coefficient is given by the Arrhenius relation
$$D = 30 \ \exp.(-12300/RT)$$
The activation energy, 12.3 kcal. per mole, is identical with that previously found for vacuum drying, but the diffusion coefficient itself is only one-fifth to one-third as large. The effective moisture content at the surface of an immersed wheat kernel is 0.75 g. per g. and is identical with the critical moisture content in drying.

Previous studies (3,4) dealt with the drying of wheat in a moisture-free atmosphere and were designed to elucidate the process of water diffusion in the wheat kernel under desorption conditions. The validity of these results under adsorption conditions is conjectural, however, for the water diffusion coefficients of polymers are often sensitive to the direction of changes in concentration. The present investigation was undertaken to obtain data on the absorption of water by wheat kernels fully immersed in liquid water. The present and previous studies describe the nature of water diffusion in the wheat kernel under opposite extremes of ambient conditions and thus define the limits of the behavior to be expected between them. The present study also provides information which is basic to the commercially important practice of tempering wheat.

Materials and Methods

Wheat. The Thatcher wheat was from the same lot used in a previous study (3) of the vacuum drying of wheat. Samples were prepared

with initial moisture contents[2] ranging from 7.1 to 50%, ~~dry~~ basis. The conditions of tempering and storage are described in the above-mentioned paper.

Methods. Samples for moisture determination were ground at the "medium" setting in a Hobart coffee mill; this produced a product which was granular rather than powdery. The time the sample remained within the mill appeared to be well under 1 second, and the product was received directly in the bottles used for further storage. In general, every precaution was taken to minimize moisture losses during handling of the samples destined for moisture assay.[3]

Moisture contents were determined by drying the ground samples for a period of 4 hours at 110°C. in an oven evacuated by an efficient vacuum pump. This method of moisture determination had previously been found to give excellent results (3).

The absorption of water by wheat was studied as a function of time, temperature, and initial moisture content. Samples were placed in wire gauze baskets and immersed in a stirred water bath controlled within 0.1°C. of the set temperature. At the end of the absorption period the samples were quickly removed and superficially dried by manual rolling of the kernels on a large filter paper until they lost the glistening appearance associated with the presence of a surface film of water. The filter paper was then quickly rolled into cylindrical shape, the wheat inside, and the wheat was thence transferred to a storage bottle in a total time (after cessation of drying) of roughly 5 seconds. Despite the speed of handling, it is still possible that significant losses of moisture occurred after surface drying at the higher temperatures because of evaporation.[4] The effect of such losses will be dis-

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[2] All moisture contents in this paper are expressed in g. per g., dry basis.

[3] It has been pointed out by a reviewer that the USDA prescribes a two-stage moisture method for cases where the initial moisture content is higher than 15% moisture content, dry basis (or 13%, wet basis) : namely, that wheat of high moisture content be equilibrated at ambient conditions to grinding. This is, in general, a sound criticism and will be heeded in future studies. Nevertheless, it is thought that moisture losses in grinding were not serious in the present case for the following reasons: 1) samples were reduced to a granular rather than a pulverized (floury) state so that, from the point of view of diffusion, residence times within the mill appear to have been safely short; 2) the evaporation of moisture within the mill would establish an equilibrium atmosphere (assuming negligible through-circulation of air), and the amount of vaporizable moisture would therefore be severely limited by the dearth of available gas volume; and 3) the samples ground were small (10 g.) so that heating of the grinding chamber was negligible, as ascertained by tactile examination of the grinding plates. It should be noted, in the latter connection, that fine grinding of dry samples produces vastly more heat than coarse grinding of rather moist samples.

An estimate of the maximum moisture loss possible during grinding is easily made, using the approximate diffusion equation $(\overline{m} - m_s)/(m_o - m_s) = (2/\sqrt{\pi})\ (S/V)\ (\sqrt{Dt})$. Assume, for the sake of argument, that the ground wheat particles are spherical, that the temperature is 30°C., and that the atmosphere surrounding a particle is perfectly dry (corresponding to high vacuum or to a high rate of ventilation with dry air). The diffusion coefficient is then 10^{-7} cm.^{2} per second (3), the surface moisture content is $m_s = 0.10$ g. per g. (3), and for the ratio S/V one can substitute $S/V = 6/D_v$, where D_v is the diameter of the particle. With these substitutions, the diffusion equation can be written $(\overline{m} - m_s)/(m_o - m_s) = 2.14 \times 10^{-3}\ \sqrt{t}/D_v$. Then, in 1 second the reduction in free moisture content (moisture above 0.10 g. per g.) is 2.14% for a particle 1 mm. in diameter, and 21.4% for a particle 0.1 mm. in diameter. The main weight fraction of ground wheat in the present study was in the half-millimeter range. At a moisture content of 0.30 g. per g. such a particle would lose 0.0086 g. per g. moisture in 1 second, and the loss would increase in proportion to the square root of the time.

[4] The maximum possible magnitude of the moisture loss after the completion of surface drying is

cussed at an appropriate point further on in the paper.

In a first series of experiments, the moisture gain during the absorption period was calculated from the initial and final moisture contents, both of which were determined by the vacuum-oven method. In the second series only the initial moisture content was determined, the size of the sample was reduced from 10 g. to 2 g., and the moisture gain was calculated from the gain in weight of the sample. Distinction between the two series is made because the absorption-time relations were slightly different. The second method of determining moisture gain is superior because it reduces handling of grain at high moistures. It should be noted that in series 1 the surface-moist wheat kernels obtained from the absorption experiments were allowed to equilibrate in sealed bottles for at least 3 to 4 hours prior to grinding.

Experiments were carried out at temperatures of 0° to 70°C., and absorption periods ranged from several minutes to 8 hours.

Mathematical analysis (3) of nonstationary-state diffusion in solids of arbitrary shape shows that at times in the neighborhood of zero and under the conditions

$$m = m_0 \text{ at } t = 0$$
$$m = m_s \text{ at the bounding surface at } t > 0$$
$$D = \text{constant}$$

the integral diffusion equations are of the general form

$$\overline{M} = 1 - \frac{2}{\sqrt{\pi}} X + BX^2 \tag{I}$$

where

$$M \equiv \frac{m_s - \overline{m}}{m_s - m_0}$$

$$X \equiv \frac{S}{V} \sqrt{Dt}$$

and

$m_0 =$ initial, uniform moisture content, dry basis, ... g/g

$\overline{m} =$ average moisture content at given absorption time, dry basis, ... g/g

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

t = absorption time .... sec
S = area of bounding surface .... cm^2
V = volume (e.g., of wheat kernel) .... cm^3
D = diffusion coefficient .... cm^2/sec
B = dimensionless constant

At small values of X this equation approximates to

$$1 - \overline{M} = \frac{2}{\sqrt{\pi}} X \qquad (2)$$

or, in terms of the experimental variables,

$$\overline{m} - m_o = k_o \sqrt{t} \qquad (3)$$

where

$$k_o \equiv \frac{2}{\sqrt{\pi}} (m_s - m_o) \left(\frac{S}{V} \right) \sqrt{D.}$$

Therefore, at small values of X, the moisture gain of a wheat sample immersed in water should be approximately proportional to the square root of the absorption time, if the diffusion equation is applicable. Figure 1, which shows typical data from series 2, shows that such a relation is indeed obeyed. However, the curves do not extrapolate to
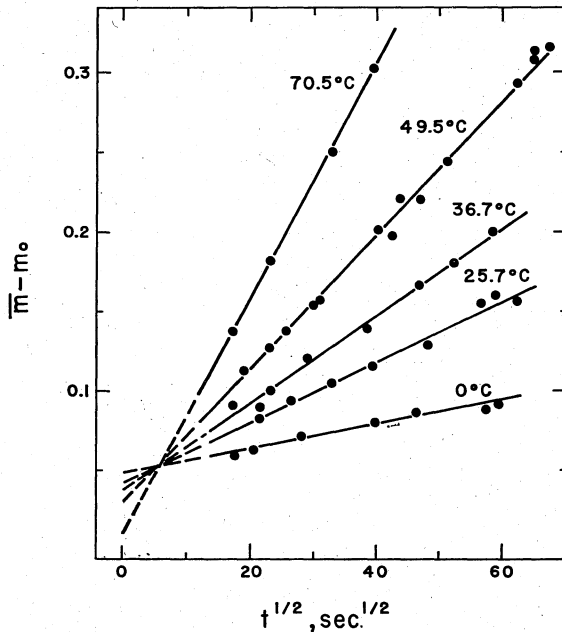

Fig. 1. Data from series 2 for an initial moisture content of 0.25 g. per g., showing the linear relation between the moisture gain and the square root of the absorption time.

zero moisture gain at time zero, but to an intercept $\Delta \overline{m}_i$. The experimental data were therefore analyzed statistically to obtain the slopes, k_o, and the intercepts, $\Delta \overline{m}_i$, of the linear regression of the moisture gain on the square root of the absorption time.

The Initial Moisture Gain, $\Delta \overline{m}_i$. If the linear relation between the moisture gain and the square root of the absorption time indeed signifies obedience to Fick's Law with a constant diffusion coefficient, then the occurrence of the nonzero intercept $\Delta \overline{m}_i$ means that there is a very rapid initial absorption of water which is due to another phenomenon than slow diffusion into the interior of the kernel. The nature of this phenomenon is evident from the structure of the wheat kernel, for the outermost layer, the pericarp, is highly porous and should quickly become saturated by capillary imbibition. (Jones (10) appears to have been the first to distinguish this aspect of liquid water absorption by wheat.) It therefore appears that the intercept $\Delta \overline{m}_i$ is a measure of the amount of water required for saturation of the pericarp. The pericarp constitutes approximately 4.8% of the dry weight of the wheat kernel (15), and so its moisture content at saturation is (dry basis)

$$m_p = m_o + \Delta \overline{m}_i / (0.048), \tag{4}$$

assuming that the initial moisture distribution is uniform. Figure 2 shows that saturation moistures so calculated from the experimental data were in the range 1.0 to 1.2 g. per g. at room temperature and decreased markedly with increasing temperature. The values appear to be independent of initial moisture content at levels above 0.14 g.
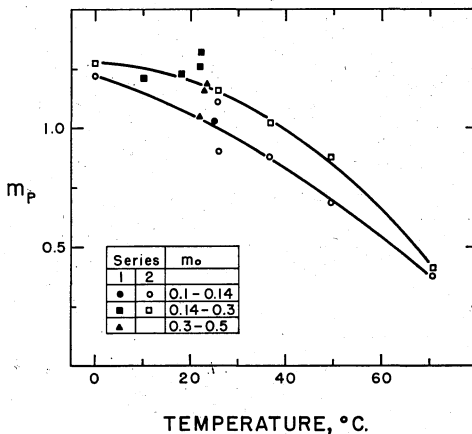

Fig. 2. The saturation moisture of the pericarp as a function of temperature and initial moisture content.

per g. but are significantly lower at moistures of 0.11 and 0.14 g. per g. One would expect the saturation moistures to be practically independent of the initial moisture level, but the reason for their strong dependence on temperature is not wholly clear. While evaporative moisture losses during handling of the grain after surface drying on filter paper may have been partly responsible, it seems likely that the effect is largely due to drainage of the grosser capillary structure of the pericarp by the filter paper itself, this process being promoted by the lowering of the surface tension of water with increasing temperature. The presence of air bubbles (whose volume would increase with rising temperature) in the pericarp may also have been a contributing factor.

The presence of unexpelled air was illustrated by a number of experiments in which wheat with an initial moisture content of 0.147 g. per g. was soaked in water at the point of incipient boiling (under vacuum) at 25°C. It was observed that bubbles were liberated at the surfaces of the kernels in the first 2 minutes of exposure. The value found for the saturation moisture of the pericarp in these experiments was 1.60 g. per g., an increase of 0.5 g. per g. over the value of atmospheric pressure. The slope, k_o, of the linear relation between the moisture gain and the square root of the absorption time, however, was unaffected by this variation in total pressure, in further proof that this relation indeed reflects a diffusion-controlled mechanism.

Figure 3 shows that the initial moisture gains $\Delta \bar{m}_i$ in the rather narrow range of initial moistures, 0.1 to 0.25 g. per g., of ordinary practical interest were not significantly dependent on the initial moisture
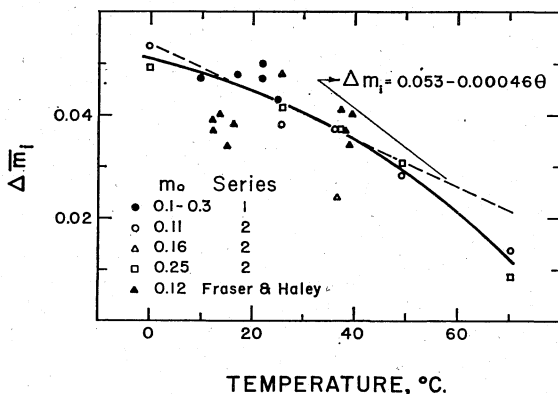

Fig. 3. The initial moisture gain as a function of temperature and initial moisture content for the practically important range of initial moisture 0.10 to 0.25 g. per g.

level. The data for temperatures in the range 10° to 50°C. are represented with fair accuracy by the relation

$$\Delta \overline{m}_i = 0.053 - 0.00046 \ \theta \tag{5}$$

where θ is the temperature in °C. Also shown are values of $\Delta \overline{m}_i$ calculated from the early data of Fraser and Haley (7). These are in good agreement with the present results at 40°C. but show no trend with temperature and so are somewhat lower at 15°C.

In general, it is evident that the experimental value of the initial moisture gain is more or less dependent on the treatment of the wheat kernels following emersion from the water bath. Removal of the adhering film of liquid water by rolling the kernels on a filter paper, as in the present study, gives results of high precision. However, it is desirable that $\Delta \overline{m}_i$ should, in some future study, be determined under conditions simulating more closely those prevailing in commercial tempering.

Although the rapidity of saturation of the pericarp is clearly ascribable to capillary imbibition, it does not follow that the water imbibed ($\Delta \overline{m}_i$ or m_p) is held solely by weak capillary forces. It can hardly be doubted that a part of it swiftly diffuses into the thin cell walls (the substance of the pericarp) and is held there by adsorptive forces. Hence m_p consists of two fractions: a capillary-held, free-water fraction, and an adsorbed, bound-water fraction. The two are probably of comparable magnitude, the critical moisture content of cellulose (the moisture content above which a surface film of free water appears) being approximately 0.3 g. per g. The capillary-held fraction appears to be the one which was strongly dependent on temperature in the present study.

Relating to the section which follows, the critical moisture content of the pericarp material appears to be considerably lower than that with respect to the entire kernel, which will be shown to be approximately 0.75 g. per g.

The Effective Surface Moisture Content, m_s. Equations 2 and 3 show that if the diffusion coefficient is independent of moisture content in the range studied, the product of the slope k_o and the kernel volume-to-surface ratio V/S should be a linear function of the initial moisture content and should extrapolate to an intercept $m_o = m_s$ at $k_o V/S = 0$, where m_s is the effective moisture content at the bounding surface. Figure 4 shows that the data fulfill this expectation reasonably well and indicates that the effective moisture content at the surface of a wheat kernel immersed in liquid water is approximately 0.75 g. per g. The volume-to-surface ratio was in each case evaluated at the initial
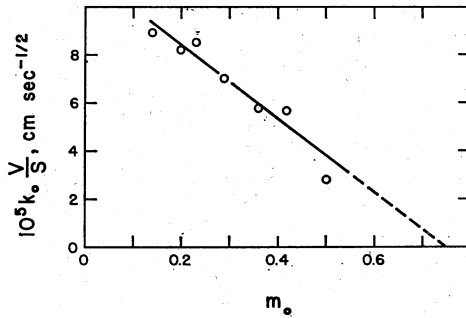
Fig. 4. The product $k_o V/S$ as a function of the initial moisture content at 22°C., showing the regression on an effective surface moisture content of 0.75 g. per g.

moisture content,[5] using the formula previously given (formula 5): $V/S = 0.91\ r_v/3$, where r_v is the radius of a sphere with volume equal to that of the wheat kernel. The volume-to-surface ratio at a moisture content of 0.10 g. per g. was 0.0515 cm. and increased with increasing moisture content in proportion to $(0.69 + m_o)^{1/3}$, where 0.69 cm.[3] per g. is the specific volume of moisture-free wheat (3).

The moisture gain at 22°C. and at a constant absorption time of 15 minutes was determined at a large number of initial moisture contents and is shown as a function thereof in Fig. 5. As might be expected, the relation is very similar to that in Fig. 4, and the intercept is again approximately $m_o = m_s = 0.75$ g. per g.
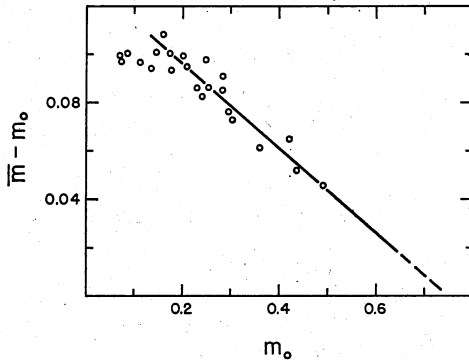

Fig. 5. The moisture gain in an absorption time of 15 minutes as a function of initial moisture content at 22°C., showing the regression on an effective surface moisture content of 0.75 g. per g.

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[5] In vacuum drying (3) V/S was evaluated at a moisture content of 0.10 g. per g. The present work, however, embraced a much wider range of initial moistures, and consequently did not permit treatment of V/S as a constant. The volume-to-surface ratio was therefore based on the initial moisture content, in order to account at least partially for the effects of appreciable variation of kernel volume with the moisture content.

The effective surface moisture content with respect to diffusion when wheat is immersed in *liquid* water appears to be practically identical with the critical moisture content in drying (i.e., the moisture content above which drying is controlled by evaporation from the free-water surface which then envelops the kernel). Simmonds *et al.* (16) found the critical moisture content of wheat to be in the range 0.7 to 0.8 g. per g., and 0.75 is an acceptable average value of their results. This identity with the critical moisture content is plausible theoretically and attaches a concrete significance to the surface moisture level prevailing under conditions of *liquid* water absorption.

The Diffusion Coefficient, D. The diffusion coefficient D is given directly by equations 2 and 3 once the effective surface moisture content is known. Figure 6 shows diffusion coefficients calculated from the
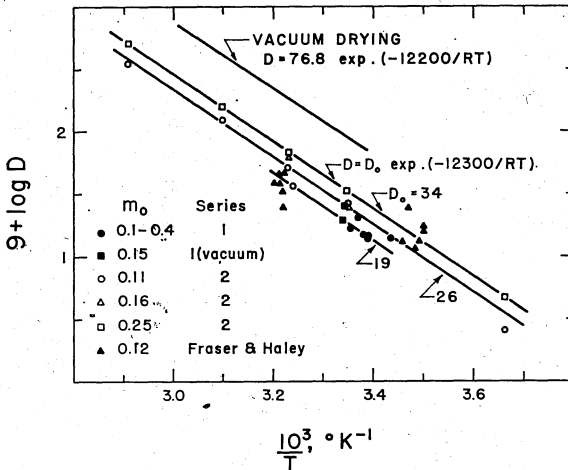

Fig. 6. The diffusion coefficient as a function of the reciprocal of the absolute temperature, showing obedience to Arrhenius's relation.

present data and those of Fraser and Haley (7), as a function of the reciprocal of the absolute temperature, $°K^{-1}$. The data for series 2, which covered a wide range of temperatures, give for the energy of activation in the Arrhenius relation

$$D = D_0 e^{-E/RT} \tag{6}$$

the value E = 12.3 kcal. per mole. This is in close agreement with the value E = 12.2 kcal. per mole previously found in vacuum-drying experiments (3) in which the initial moistures ranged from 0.13 to 0.25 g. per g. It therefore appears that the activation energy of the diffusion process is independent of the direction of changes in moisture level.

However, the coefficient for the diffusive part of liquid water absorption is appreciably smaller than the coefficient for vacuum drying; the value of D_o in the Arrhenius relation for an energy of activation of *12.2* kcal. per mole is 16 to 29 cm.^{2} per second, compared with 76.8 cm.^{2} per second in vacuum drying. (It is emphasized that this comparison is based on an energy of activation of *12.2* kcal. per mole, not *12.3*, and that the values quoted for D_o are for this reason different from those in Fig. 6.)

The diffusion coefficients calculated from Fraser's and Haley's data (7)[6] fall within the range enclosed by series 1 and 2 (Fig. 6 and Table

TABLE I

DIFFUSION OF WATER INTO THE WHEAT KERNEL

PRESENT DATA	$10^8 \, D_{25^\circ}$	E
	cm^2/sec	kcal/mole
Thatcher, series 1	2.4–3.1	12.3
series 2	1.8	
Fraser and Haley		
Marquis	2.1	7.4
Turkey	3.3	5.1
Baart	2.1	2.3
Hard Federation	2.8	7.6
Club	1.9	8.7
Red Russian	1.8	4.9

I), but the energies of activation are considerably lower (Table I), being in the range 5 to 9 kcal. per mole.

Practical Applications of the Data. Figure 7 shows a general relation of all the data for temperatures in the range 10° to 50°C. and initial moistures in the range 0.10 to 0.30 g. per g., *dry basis.* The parameters were calculated from the experimental relations

$$1 - \overline{M} = \frac{\overline{m} - m_o - \Delta\overline{m}_i}{m_s - m_o}$$

$$D = 30 \; exp \, (-12300/RT) \tag{6'}$$

$$m_s = 0.75$$

$$\Delta\overline{m}_i = 0.053 - 0.00046 \, \theta \tag{5}$$

These relations, combined with equation 2, can also be used for practical prediction of the moisture gain as a function of the independent variables. Figure 7 therefore gives an indication of the accuracy with which such predictions can be made. It is seen that the only data which

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[6] Fraser and Haley gave no data on kernel size or weight; so a value of V/S of 0.052 cm. was assumed.
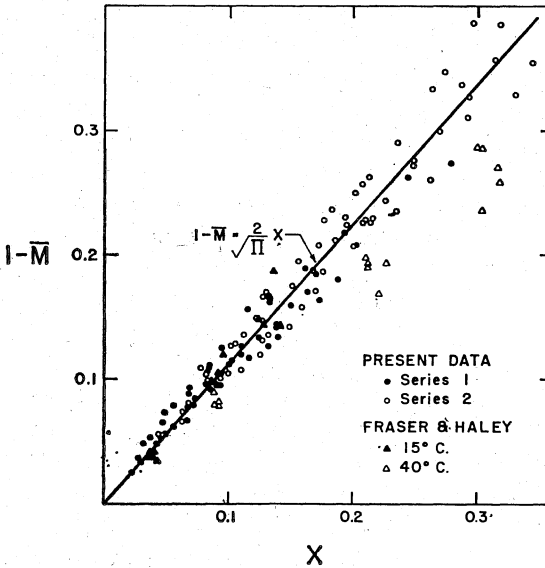
Fig. 7. Generalized correlation of the data, using empirical relations for the diffusion coefficient and the initial moisture gain.

deviate remarkably from equation 2 with the above values of D, m_s and Δm_i are those of Fraser and Haley (7) for 40°C., which are approximately 20% low in the value of $1 - \bar{M}$. However, since their data for 15°C. are in excellent agreement with the present results, it is not unlikely that those for 40°C. are in error, owing to variation of grain temperature during the absorption period, to loss of moisture in handling, or to other causes. Such effects would almost certainly be more pronounced at the higher temperature. Moreover, the fact that the energies of activation for diffusion calculated from their data are so much lower than the present value and are in such poor agreement among themselves (Table I), makes the data for 40°C. doubly doubtful. The effects of variety, protein content, and other relevant constitutional factors on the absorption of liquid water by wheat should therefore be reinvestigated before any firm conclusions about their influence are made. It is noteworthy that these factors have no apparent effect on the drying of wheat (3).

It appears from Fig. 7 that the differences in the calculated diffusion coefficient between series 1 and 2 are more artificial than real. The data of series 1 generally gave the higher values of the initial moisture gain $\Delta \bar{m}_i$ (Fig. 3), but the lower values of the slope k_o (and, hence, of the diffusion coefficient, Fig. 6). Cancellation of these opposing effects pro-

duced the good agreement between the two series seen in Fig. 7; in fact, there was no practical difference between the total moisture gains at given values of time, temperature, and initial moisture content. However, the data of series 2 are the more reliable as to the values of the initial moisture gain and the diffusion coefficient because of the superior method used to determine the total moisture gain.

It should be noted, finally, that the applicability of equation 2 over the entire range of experimentation is partly due to the *a priori* assumption of its validity, made to define a basis for treatment of the data. Therefore, because the analysis was prejudiced in its favor, equation 2 should be regarded as an imperfect, though highly expedient, approximation to a more nearly correct general solution. A subtler approach, such as that previously applied to the vacuum drying of wheat (3), was not possible here, owing to the heterogeneity of the absorption mechanism.

Discussion

Hinton (9) found that removal of the testa, the botanical layer directly beneath the pericarp or outermost bran layer, approximately tripled the rate of liquid water absorption from a capillary tube, 0.35 mm. inside diameter, held to the surface of a wheat kernel. His work corrected an earlier notion that the hyaline layer, which lies directly beneath the testa, is a layer of exceptionally low water permeability (8, 10). In consequence of Hinton's and of the earlier work, it has often been suggested that the resistance to water penetration into the wheat kernel resides chiefly in one or the other of these outer layers, and it has even been generalized that the hyaline layer should control the drying of wheat (13). However, these theories disregard the possibility of changes in mechanism when the outer layers are removed, and the following, alternative explanation seems to give a more forceful interpretation of the facts.

The basic process by which gradients in the chemical potential of moisture in wheat are removed, in liquid water absorption as in drying, is diffusion. However, in liquid water absorption, the gross process of diffusion may be materially accelerated by the agency of natural capillaries and of structural flaws and cracks. It appears that these channels can facilitate the conduction of liquid water into the interior of the wheat kernel. From them it diffuses into the substance of the kernel, and its flow in them is maintained by the draining action of this diffusion. The rate of liquid water absorption is therefore controlled by the rate at which water can diffuse into the substance of the kernel, and the energy of activation of this process should be practical-

ly the same as in drying (as actually found in the present study). However, the gross value of the diffusion coefficient is increased, for the appearance of sources of liquid water within the kernel is equivalent to subdivision of the kernel into shapes of smaller size and greater total surface area.

The testa appears to be impervious only in the sense that it lacks an appropriate capillary structure and so seals the capillary channels by which liquid water might be conducted into the interior of the kernel. The only part of the kernel not so sheathed is the germ end, and the rate of absorption is abnormally high in this region (8,17); but, because the germ area is small, the effect of this on the total rate of absorption cannot be large.

The effect of the testa, it thus appears, is to prevent direct access of liquid water to the interior of the kernel. Presumably, any water then entering does so by diffusion alone, except, of course, in the germ area. There is no reason, be it noted, for assuming that the testa importantly limits a process of pure diffusion. The water diffusion coefficient for the testa may well be lower than that for the interior of the kernel, but it would have to be many orders of magnitude lower if this thin layer were to constitute a controlling resistance.

If the foregoing reasoning is correct, the diffusion coefficients based on total kernel size should be nearly normal and directly comparable with those determined from drying experiments. Indeed, the problem is to explain why the calculated diffusion coefficients for liquid water absorption are only one-fifth to one-third as large as those previously found for vacuum drying, and not why they are larger. It is unlikely that there is any difference in the process of diffusion under these different conditions, for the identity of the energies of activation (12.3 and 12.2 kcal. per mole for water absorption and for drying, respectively) indicates that the mechanism is the same. Thermodynamic factors should therefore be chiefly responsible; it is generally held that the motivating force in diffusion is the chemical potential and that the Fickian diffusion coefficient can therefore be expressed as (12,14)

$$D = ukT \frac{\partial \ln f}{\partial \ln c} \tag{7}$$

where u, f, and c are, respectively, the mobility, relative vapor pressure, and concentration of the diffusing species, and k is Boltzmann's constant. Because of the very appreciable hysteresis in the adsorption-desorption equilibria of water with wheat or its constituents (1,6), the factor $\partial \ln f / \partial \ln c$ is considerably larger in desorption than in adsorption, at least in the range of moistures presently concerned. This, then,

explains a part, and perhaps nearly all, of the observed difference in the diffusion coefficients. A small part (at most, 20%) may be due to the inexactness of the mathematical method used to evaluate the diffusion coefficient in the present study. Consideration of the entropy of activation as a responsible agency appears to be irrelevant here, for changes in the entropy of activation for diffusion in polymers are quite generally accompanied by proportional changes in the energy of activation (2), and such a change did not occur.

The foregoing is, of course, not the only possible explanation of the observed phenomena, but it appears to the author to be the simplest one and, indeed, the only one that accounts for all the salient features of the absorption-time-temperature relation without encountering serious, invalidating contradictions.

It has often been suggested that the penetration of water into the endosperm involves a capillary mechanism, and, in favor of this, the fact has been quoted that the wheat kernel indeed possesses an appropriate capillary structure. However, the mere existence of a capillary structure does not mean that the *rate* must be capillary-controlled. The basic conclusion of the present investigation in this regard, that the rate of penetration is diffusion-controlled, has no plausible alternative; for the capillary mechanism, compounded of a surface-tension driving force and a viscous resistance, is inflexible as to temperature dependency and cannot possibly explain an energy of activation of 12.3 kcal. per mole.

The possible role of the capillary system is thus narrowed to the potentially important one suggested earlier; i.e., the capillaries may conduct liquid water into the interior of the wheat kernel and so accelerate the process of diffusion into the *substance* of the kernel by effectively increasing the exposed surface area. Although this possibility has been discounted in the preceding argument, the question is by no means closed.

An important obstacle to capillary flow remains to be mentioned: If the capillaries are initially filled with air, they will tend to become vapor-bound when liquid water enters their termini. The present work has shown that this effect is important even in the relatively exposed pericarp. On the other hand, if cracking of the kernel takes place before an advancing front of moisture, such cracks may well fill with water and may then serve to accelerate the process of diffusion.

As to the role of the testa, Hinton (9) has expressed a viewpoint similar to that advanced here: In the concluding sentences of his highly relevant paper he states, "Thus, though the rate of movement is three to six times faster through the [bare] endosperm than through

the testa, the distances involved in the endosperm make it of prime importance in establishing the time required for complete conditioning of wheat. The practical significance of the resistance of the testa is that it limits the water taken up by wheat during washing to that which can be absorbed by the pericarp."

It may be concluded that while the hypotheses underlying the present interpretation of water absorption by the wheat kernel are certainly oversimplified with regard to the exact state of affairs inside the kernel, they are fruitful in yielding the mathematical form of the law governing absorption and bring to the surface new facts which must be considered in any more detailed investigation.

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