Whole milk concentrate of 40 to 46% solids was chilled to below 50° F. Nitrogen was then dispersed in the concentrate to yield a foam of 0.4 gram per cc. density. The foam was applied in the form of ropes or slabs to the belt of a continuous, cross-circulation air dryer. Drying curves showed no detectable constant-rate period. The drying time between two given moisture contents varied as the square of the rope diameter or slab thickness, and the diffusion equation for mass transfer fits the drying data. Diffusivity of moisture correlated well with the inverse of absolute foam temperature in an Arrhenius-type plot. The activation energy for diffusion was calculated to be 14 kcal. per gram mole. Relative humidity had no effect on drying rate, but air velocity had some effect which was accounted for on the basis of its effect on the temperature of the foam.

A BROAD research program on dry whole milk is in progress at the Engineering and Development and Dairy Products Laboratories of the Eastern Utilization Research and Development Division, Agricultural Research Service, United States Department of Agriculture. Its objective is to develop an economically feasible process for preparing a beverage quality dry whole milk of rapid dispersibility and adequate shelf life. Techniques for drying whole milk foam under vacuum and in a spray dryer are being investigated as parts of the over-all program, and results from these studies have been reported (*1, 3–5, 9*).

In addition, cross-circulation drying of whole milk foam was begun at the Eastern Division in 1959 after Morgan *et al.* (*8*) of the Western Division had devised a new method which they called foam-mat drying. In the course of their work with a wide variety of foodstuffs, they prepared dry whole milk of good dispersibility. Their method involved addition of a stabilizing agent to milk concentrates, preparation of a foam by incorporating air or an inert gas, and application of this foam to a tray or a moving belt and exposing it to a hot air stream until dry. Since good dispersibility was one of the important goals of our work, a special dryer was built at the Eastern Division and a continuous unit was set up in order to study the mechanism of drying. This paper presents the results of the study.

Equipment

Figure 1 is a flow sheet of the pilot plant used in this work. Whole milk concentrate flows from the jacketed feed tank at a predetermined rate, while an appropriate amount of nitrogen gas is injected into it downstream from the metering pump. The mixture is then whipped by means of a gas-liquid mixer and passes to the dryer. Figure 2 is a schematic drawing of the dryer. The foam is laid in the form of ropes across the moving belt. The ropes pass successively through the two drying sections and are doctored off, passed through a screen, and collected in the receiver. The belt is glass fiber coated with Teflon, 1 foot wide and about 0.015 inch thick. The total drying length is 10 feet, divided equally between the two drying sections. The drying air is heated by steam coils and blown across the belt. Removable Plexiglas lids cover the feeding section, each drying zone, and the collecting section. Baffles suspended from cross-members separate each section.

Figure 3 is a drawing of the feeding mechanism. The foam passes through the vertical shaft and the horizontal tubes to the feed valves. When the cam depresses the cam wheel, the feed valve opens and the foam emerges. As the feeder rotates, an

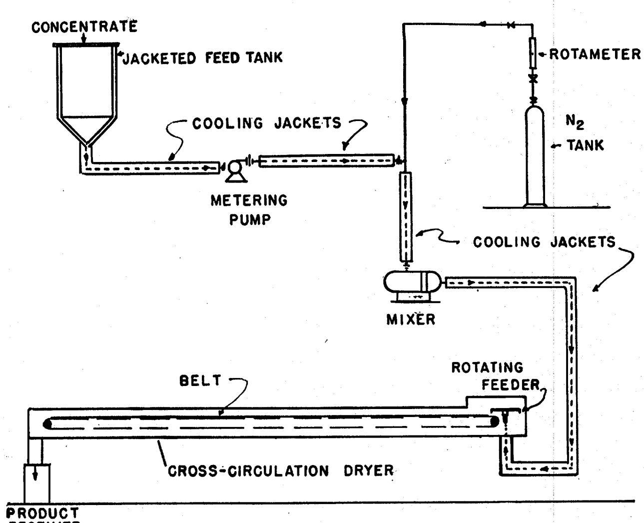

Figure 1. Flow sheet of pilot plant

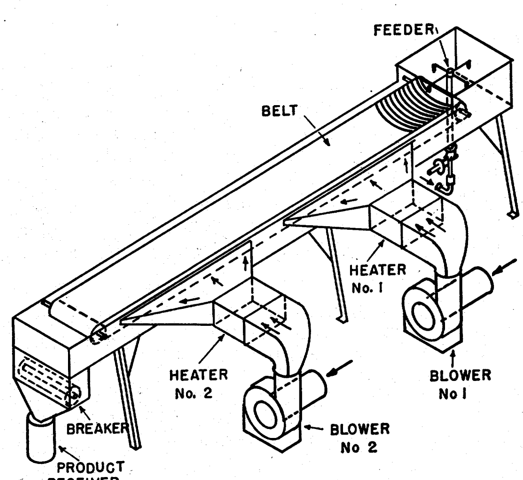

Figure 2. Cross-circulation dryer

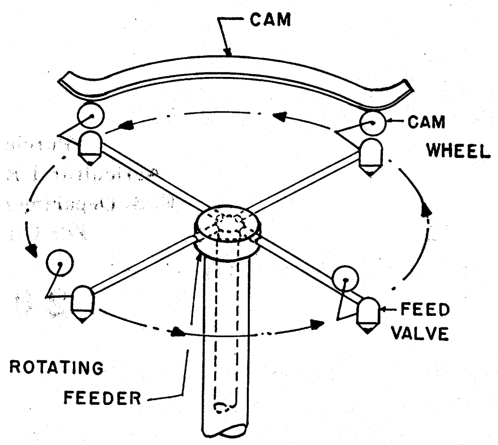

Figure 3. Feeding mechanism

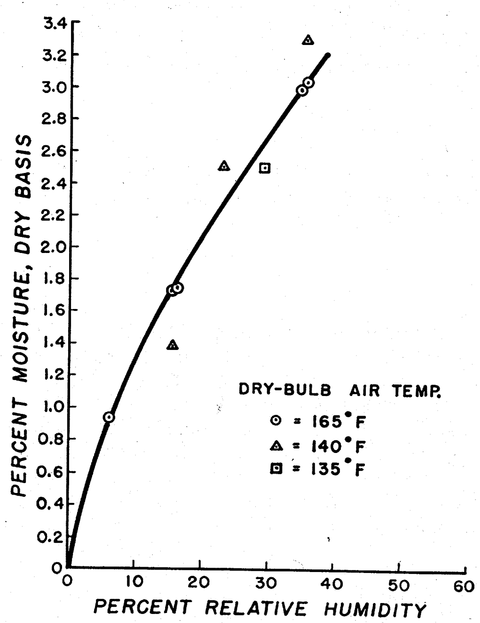

Figure 4. Equilibrium moisture content of atmospheric foam-dried milk

arclike rope of foam is applied across the belt. When the cam wheel disengages from the cam, the feed valve closes. Meanwhile another cam wheel has reached the cam, and the cycle is repeated.

Procedure

Rope diameters ranging from 0.05 to 0.10 inch were studied. By rope diameter is meant the diameter of the cylinder of foam extruded from the nozzle opening. Once on the belt, the ropes acquired a semi-elliptical cross section, the ratio of the smaller axis to the larger being about 0.43. By varying the speed of the belt or the feed rate it was possible to lay the foam on the belt in the form of slabs of uniform thickness. The slab thicknesses ranged between 0.05 and 0.15 inch. The following air conditions were studied:

Dry-bulb temperatures from 112° to 232° F.
Air velocities from 240 to 710 feet per minute
Relative humidities from 1 to 24%

Samples for drying curves were obtained by removing the Plexiglas covers and sampling at various points along the belt. Values for the equilibrium moisture content at various humidities were determined by spreading ropes of dry whole milk prepared in the cross-circulation dryer onto a perforated tray and drying them further in a small through-circulation dryer at set conditions of temperature and humidity until analyses showed that equilibrium had been attained. These data are plotted in Figure 4.

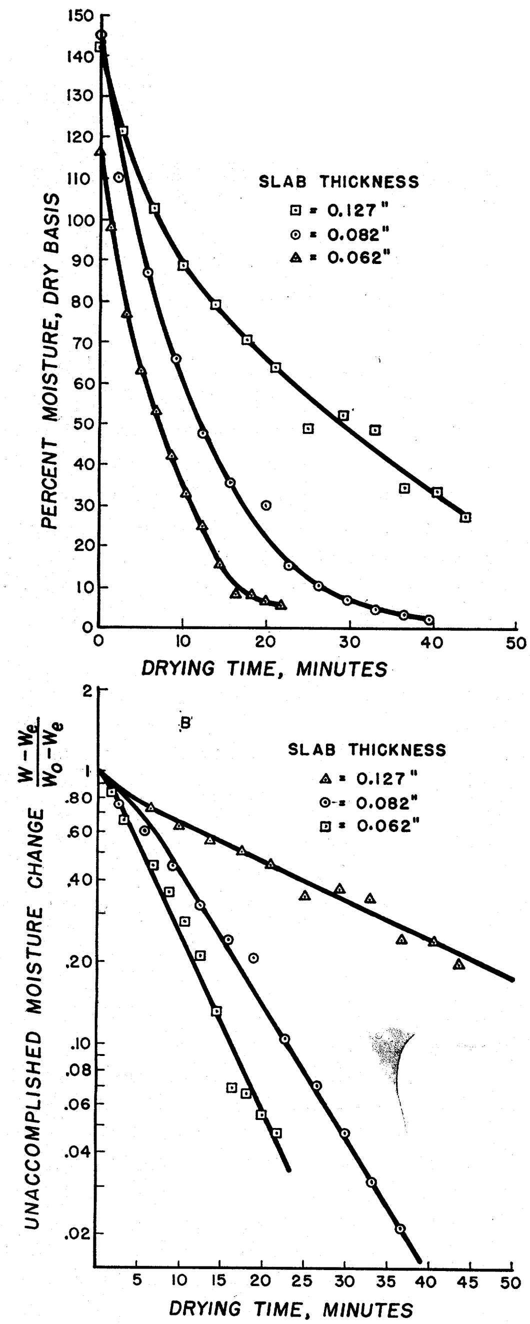

Figure 5. Effect of slab thickness on drying rate

Results

Preparation of Foam. The first phase of the study was the preparation of a foam that would be stable during drying and yield a dry product of good dispersibility. It was found that satisfactory whole milk foams can be produced without stabilizers in commercially available gas-liquid mixing devices if the temperature is kept below 50° F. prior to drying, the solids content is between 40 and 46%, and the foam density is between 0.35 and 0.5 gram per cc. When prepared at a higher temperature the foam contains large gas bubbles and tends to collapse readily. Foams containing less than 40% solids drain very readily and are unstable to heat, whereas foams containing more than 46% solids yield dry products of poor dispersing properties. Foams of density lower than 0.35 or higher than 0.5 gram per cc. are unstable. Consequently, solids content of the foam in all drying runs reported here was within the range given, and density was about 0.4 gram per cc.

Drying of Whole Milk Concentrate Foams. EFFECT OF FOAM THICKNESS. Figure 5, *A*, shows three runs in which slabs 0.062, 0.082, and 0.127 inch thick were exposed to an air stream with a velocity of 468 feet per minute, a dry-bulb temperature of 174° F., and a relative humidity of 2.1%. This figure presents typical drying curves of moisture content (pounds of water per pound of dry solids) *vs.* drying time. Although a constant drying rate period was probably present at the very beginning of each drying run, it was so short that it could not be detected. Thus, only a falling-rate period was considered to be present.

In Figure 5, *B*, the same data are replotted as log $\frac{W - W_e}{W_o - W_e}$ *vs.* drying time, yielding straight lines following initial curvature. The time required to reach a given moisture content varies as the square of the ratio of the thickness of the slabs. Similar results were obtained in drying ropes of whole milk foam, as can be seen from Figure 6, *A* and *B*. In this example ropes of 0.099-inch and 0.053-inch diameter were extruded onto the belt and dried at 143° F. dry-bulb temperature, and 11% relative humidity, in air with a velocity of 710 feet per minute. Comparison of the drying times of the two curves (Figure 6, *B*) at any ordinate shows a constant ratio of 3.4, which is also the square of the ratio of thickness. These results showed that the appropriate integrated form of the diffusion equation could be used to describe the drying process.

For slabs where drying is from one face, the approximate equation is:

$$\frac{W - W_e}{W_o - W_e} = \frac{8}{\pi^2} e^{-D\,\theta\,(\pi/2L)^2}$$

EFFECT OF FOAM TEMPERATURE. A series of six runs was carried out to correlate the effective diffusion coefficient with foam temperature. Fine thermocouples were placed in the centers of slabs of foam and made to travel along the full length of the belt during drying. The temperatures of the foam and the air were recorded at various positions.

The results from one of these runs are shown in Figure 7. The dry-bulb temperature was found to vary with the position in the dryer. The temperature of the foam reproduced the variations of the air temperature very closely at all positions of the dryer, but did not vary over as wide a range, permitting calculation of a meaningful average value for the temperature of the foam. The foam temperature was higher than the average wet-bulb air temperature, but lower than the dry-bulb. A different foam temperature was obtained for each of the six runs by using a different dry-bulb temperature.

The effective diffusivity of moisture during each drying run was calculated by applying the "method of slopes" suggested by Marshall and Friedman (7) as follows: The experimental drying data for each run were plotted as log $\frac{W - W_e}{W_o - W_e}$ *vs.* time and a straight line was passed through the points by the method of least squares. The effective diffusivity of moisture was then determined for each run by calculating the ratio of the slope of the experimental plot to the slope of the theoretical plot of the diffusion equation and equating this ratio to D/L^2. Log D *vs.* $1/T$ from all of the six runs were then plotted together and a straight line was passed through the points by least squares. The resulting Arrhenius-type plot is presented in Figure 8. The activation energy for diffusion was calculated to be E = 14 kcal. per gram mole.

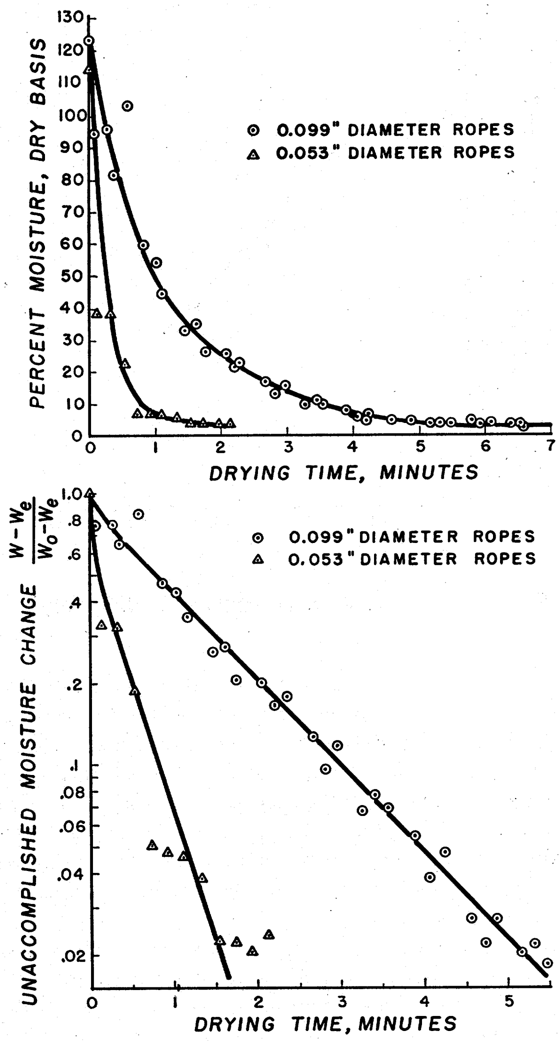

Figure 6. Effect of rope thickness on drying rate

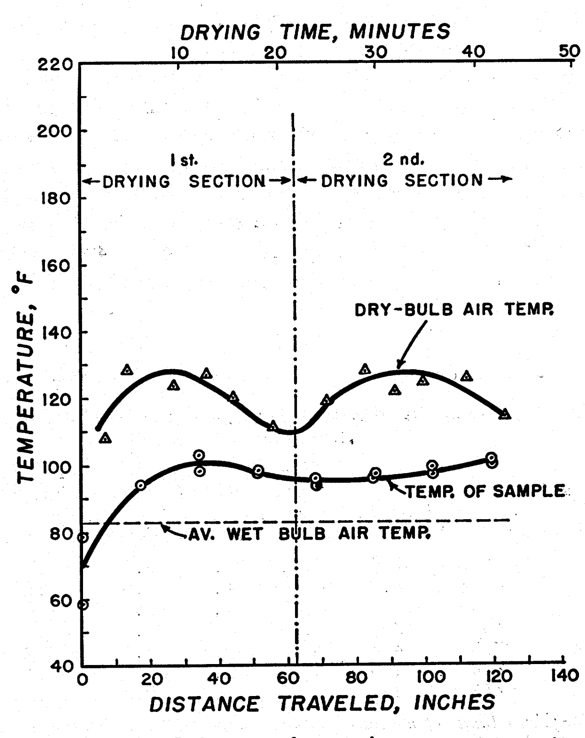

Figure 7. Relation of sample temperature to air temperature

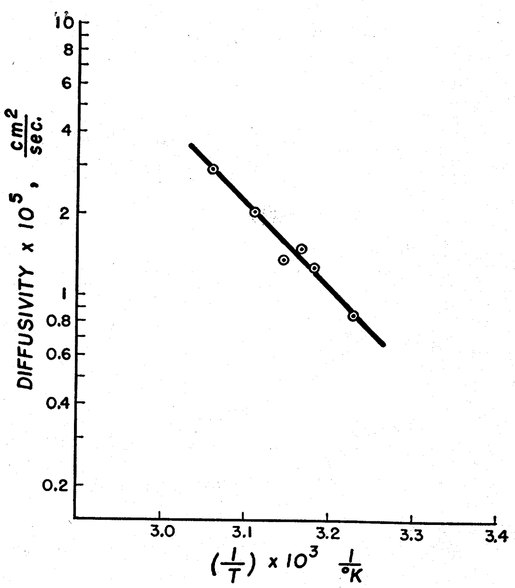

Figure 8. Effect of temperature on diffusivity

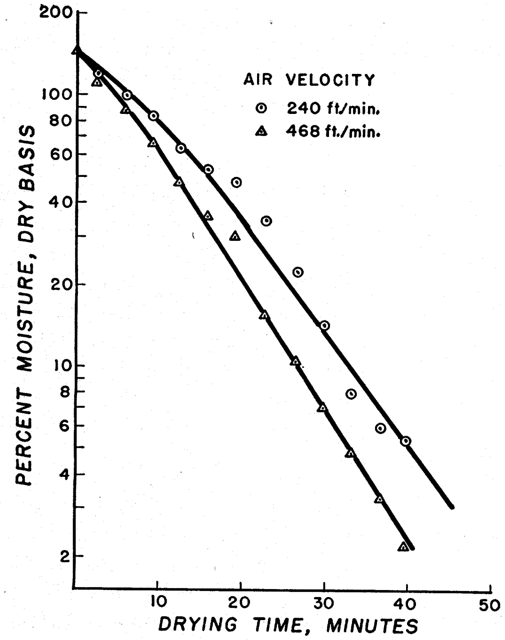

Figure 9. Effect of air velocity on drying rate

EFFECTS OF AIR VELOCITY AND RELATIVE HUMIDITY. Experiments designed to show the effects of air velocity and relative humidity on drying time were conducted. Figure 9 represents data obtained with slabs of 0.082-inch thickness for two runs at 174° F. dry-bulb air temperature and 2.1% relative humidity, in which the air velocity was set at 468 and 240 feet per minute. These experiments demonstrate that air velocity has a relatively small effect on drying rate when compared to the effect of foam thickness.

The continuous dryer used in this work did not allow a wide variation of humidity. Therefore, experiments were carried out in a batch-type cross-circulation dryer that did. Slabs of foam $^1/_8$ inch thick on glass plates were dried at relative humidities of 3 and 24% while the dry-bulb air temperature was maintained at 150° F., and the air velocity at 550 feet per minute. Results from these experiments are given in Figure 10. The humidity is of importance only in so far as it controls the equilibrium moisture content.

DRYER CAPACITY. The foregoing shows that highest dryer capacity will result when ropes of the thinnest diameter are dried at the highest dry bulb temperature consistent with good product quality. Results obtained in drying the thinnest ropes used in this work are given in Table I. Mechanical limitations precluded the use of ropes thinner than 0.05-inch diameter and limited the belt area covered to 40% when forming the ropes. Thus, the capacities cited are for 40% belt coverage.

Table I. Results Obtained in Drying Ropes of 0.05-Inch Diameter

Dry-Bulb Temp., ° F.	*Air Velocity, Ft./Min.*	*Relative Humidity, %*	*Final Moisture[a] (Exptl.), %*	*Drying Time, Min. Exptl.*	*Drying Time, Min. Adjusted[b]*	*Dryer Capacity (Adjusted),[b] Lb./Hr.*
112	710	19.0	5.00	4.6	5.5	1.2
121	468	8.6	4.24	4.0	4.3	1.5
143	710	11.0	3.89	2.6	2.7	2.4
174	468	2.0	3.43	2.4	2.4	2.7
174	710	4.3	3.47	2.1	2.1	3.1
209	468	1.9	4.91	1.1	1.2	5.4
232	468	1.2	3.32	0.9	0.9	7.2

[a] *Confidence limits of moisture analyses ($p = 0.05$) = ±0.5% moisture.* [b] *Adjusted to common basis of 3.5% moisture content.*

Discussion

The appropriate integrated form of the diffusion equation can be used to describe the cross-circulation drying of whole milk foam. Furthermore, the effective diffusivity of moisture has been shown to correlate with foam temperature according to the Arrhenius function. Thus, the chief variables influencing drying time are the thickness and temperature of the foam. Relative to these, air velocity has little effect on the drying time, even though some effect was observed as shown in Figure 9. Such effect as it has can be explained on the basis of the effect of air velocity on heat transfer. The greater velocity would be expected to increase the rate of heat transfer, which would in turn cause a higher foam temperature, a larger diffusivity value, and a shorter drying time. Calculations based on the data of Figure 9 reveal that the diffusivities for the higher and lower air velocities are 3.36×10^{-5} and 2.78×10^{-5} sq. cm. per second, respectively, and from Figure 8, foam temperatures of 133° and 127° F., respectively, may be calculated. The dry- and wet-bulb temperatures for the runs of Figure 9 were identical (174° and 85° F., respectively).

Jason (*6*) in his study of the drying of fish muscle found two distinct phases in the falling-rate period, each of which could be characterized by an effective diffusion coefficient. The value of the coefficient for the first phase was considerably greater than that for the second. Only one phase was detected in this work, possibly because in most of the drying runs the moisture content of the foam was reduced to only 3.5% or above. Jason suggested that the transition between phases may have been associated with the uncovering of the monomolecular water layer covering the protein molecules. In other work at this laboratory (*2*) the value of the monolayer for whole milk foam dried under vacuum was found to be about 3.7% moisture. For these reasons, extrapolation of the data at moistures below 3.5% may not be reliable.

No literature reference could be found that treated the drying of foams from a quantitative standpoint, so that other results were not available for comparison. Nevertheless, the authors believe that the drying mechanism found valid for whole milk foams will be valid for drying stable foams of many other materials.

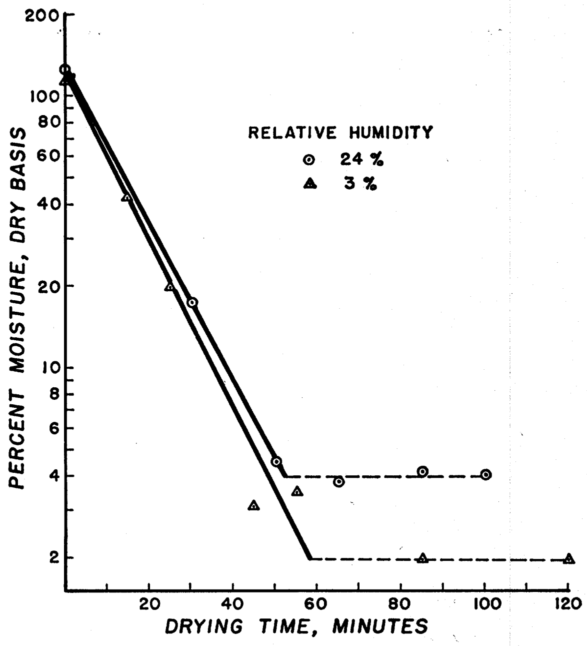

Figure 10. Effect of humidity on drying rate

Although this work confirmed the finding of Morgan (*8*) that a dry whole milk of ready dispersibility can be prepared by cross-circulation air drying of whole milk foams, taste panel evaluation of the products showed them to possess an objectionable oxidized flavor under all conditions of drying employed here. Heat treatment of the milk, commonly employed in the spray-drying process to avoid oxidized flavor, was not used here, as it is known to impart a cooked flavor and to impair dispersibility. This oxidized flavor might be avoided by use of an inert drying gas. The drying mechanism discussed here would still apply.

Acknowledgment

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Nomenclature

D = effective diffusion coefficient, sq. cm./sec.
L = slab thickness, cm.
W = moisture content at any time, lb. water/lb. dry solids
W_e = equilibrium moisture content, lb. water/lb. dry solids
W_o = initial moisture content, lb. water/lb. dry solids
θ = drying time, sec.

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