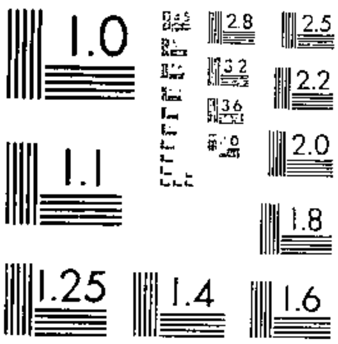
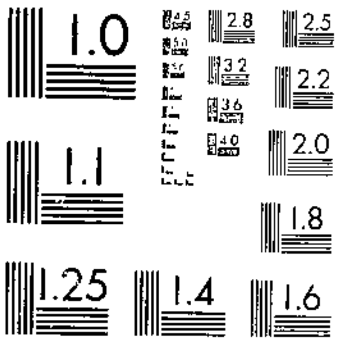
TB 592 (1937) USDA TECHNICAL BULLETINS UPDATA
FACTORS AFFECTING THE RATE OF DRYING OF KIEFFER PEARS
CULPEPPER, C W ; MOON, H H 1 OF 1

START



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

Technical Bulletin No. 592 — December 1937

UNITED STATES DEPARTMENT OF AGRICULTURE
WASHINGTON, D. C.

FACTORS AFFECTING THE RATE OF DRYING OF KIEFFER PEARS [1]

By C. W. Culpepper, *physiologist*, and H. H. Moon, *assistant pomologist*, *Division of Fruit and Vegetable Crops and Diseases, Bureau of Plant Industry*

CONTENTS

INTRODUCTION

For several years the Department of Agriculture has been carrying on investigations on the preservation and use of the Kieffer pear. The results of studies of the ripening, storage, canning, and preserving with sugar have already been reported (*7, 8, 10*).[2] There are still a number of other ways in which the fruit may be used immediately or be preserved for future use. The method of preserving many fruits by drying has long been employed, and it was suggested early in the course of these studies. It is the purpose of this report to deal particularly with the factors that influence the rate of drying. The general principles underlying the evaporation of water from moist products have long been understood (*1, 2, 3, 4, 5, 6, 13*). The purpose here is to show how these principles apply in the drying of Kieffer pears.

APPARATUS AND METHODS EMPLOYED

In these tests, use was made of a small steam-heated drier through which a large volume of air could be forced by means of a powerful fan (fig. 1). It was built in two sections, one of which provided for the heating of the air and the other for the space devoted to the drying proper. The first section was 4 feet long, 30 inches wide, and 22 inches high. It was provided with two radiators each having 65 square feet

[1] Received for publication Mar. 23, 1937.
[2] Italic numbers in parentheses refer to Literature Cited, p. 29.

of radiation which were separately connected to the steam supply so that either or both could be cut off or regulated as desired.

The drier proper was a "stack" type 6 feet high, 4 feet wide, and 30 inches deep, lined with asbestos, and covered with insulating board. It was provided with small steel rods extending through the drier for supporting trays of fruit in such fashion that they could be readily introduced or removed, and arranged in different ways to facilitate drying. Adjustable shelves or baffle plates could also be introduced in various positions so that the entire volume of air could be forced through a narrow tunnel, or air channel, producing an air current of high velocity, or through a large channel that gave a current of low velocity. The plates could also be placed so as to allow part of the air to pass directly through the drier without passing through any particular channel. Thus in figure 1, at *a* the air would have a high velocity, at *b* the velocity would be less, and at *c* it would be low as a result of progressive widening of the air channel. In this

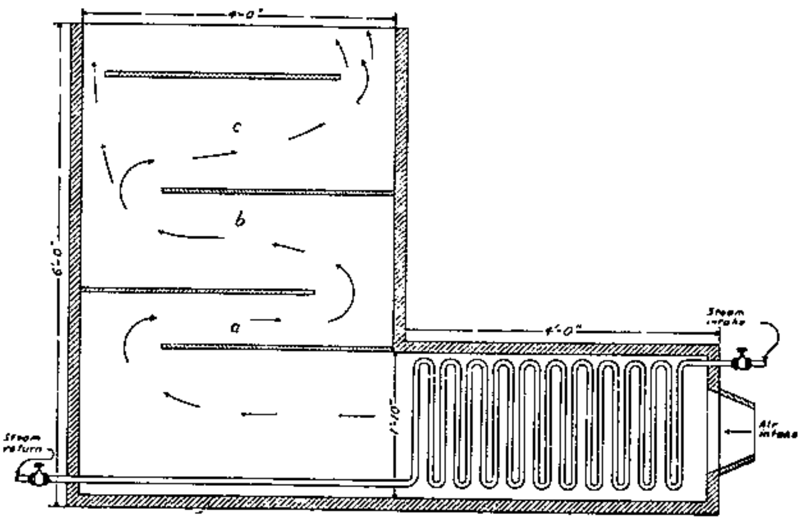


FIGURE 1.—Diagram of drier used in the study of the factors influencing the rate of drying in Kieffer pears: *a*, Air channel of high velocity; *b*, air channel of medium velocity; *c*, air channel of low velocity.

way air velocities from a fraction of a mile to more than 12 miles per hour could be readily obtained. Tests with two or more air velocities could be carried out simultaneously.

Steam was supplied by a high-pressure boiler and was reduced to any desired pressure (±1 pound) by a reducing valve. By using both radiators, or eliminating one and regulating the valves, almost any temperature between 30° and 70° C. could be obtained.

The air velocity was measured by a standard anemometer and thermometers were inserted through the side walls of the drier so that the temperature could be observed at all times.

There was no device for maintaining a definite constant humidity. Considerable variations in the humidity could be obtained by introducing steam into the air intake, or by allowing the air to pass directly over pans of water before entering the drying tunnel. This was an easy matter as the pans of water could be placed in one air channel before entering the next where the material for the test could be placed for observation. Thus for a particular set-up, the humidity would generally remain almost constant for a number of hours.

The chemical method of measuring the humidity was employed. This consisted of drawing a definite volume of air (2,000 to 12,000 cc) over phosphorus pentoxide and weighing the amount of water absorbed. The result obtained was the absolute humidity which was converted into relative humidity for the particular temperature employed.

The weighings were made upon a standard analytical balance. The removal of the sample from the drier, while being weighed, required at most only a few minutes, and since the drying process extended over a period from several hours to many days, the error thus introduced is obviously small.

PREPARATION OF FRUIT AND METHODS OF DRYING

The fruit for the tests was grown at Beltsville, Md. A large quantity was ripened in a constant-temperature room maintained at 60° F. After properly ripening, the fruit not needed for immediate use was stored at 32° until the tests could be made. Likewise, because all the tests upon the unripened fruit could not be made immediately after it was picked from the tree, a large quantity was put in storage at 32° to be used as convenient.

For most of the tests the fruit was peeled and cored as is usually done in canning. A guarded knife for peeling and a special looped knife for removing the cores were used, because smoother and more uniform surfaces could be obtained with these than with ordinary knives. The surface of the ripened peeled fruit appeared slightly smoother than that of similar unripened fruit. This is mentioned because it may possibly have some influence on the drying rates.

To facilitate the handling during weighing, a series of small wooden bases each 2 by 2 inches by one-fourth of an inch thick was employed to support the slices of fruit. From the center of each base extending upward was a pin 2 inches high upon the top of which the slices of fruit were impaled during the drying process. The segments of fruit were therefore not in contact with each other or with any other object, so that the entire surface was exposed to the drying action of the surrounding atmosphere. The fruit was thus 1 or 2 inches above the floor of the air channel which largely avoided the influence of the drag upon the air flow due to the resistance offered by the channel floor. The anemometer could be placed exactly beside the fruit so that the determinations of the air velocity applied precisely to the velocity of the air current passing the fruit under test. The bases served as a means of transferring the fruit to the analytical balance, thus avoiding the necessity of touching the fruit or disturbing the surface in any manner during the weighing process.

The peeled or unpeeled fruit was sliced longitudinally into segments of the desired size; each segment was then impaled upon the pin of the base so that the outer surface of the fruit was downward and the inner surface or margin was upward. The base, previously weighed, and the fruit were weighed together and the results were recorded. The segments, with their longitudinal dimensions parallel to the direction of the air flow and the stem end pointing into the wind, were then placed in the drier which had been previously set for the conditions desired. This seemed necessary for uniformity, especially with the smaller segments. The fruit was generally weighed at the end of 1 hour of drying and thereafter every 2 to 6 hours, depending upon the rate of drying. Rarely was the fruit allowed to remain in the drier until complete equilibrium was established or the weight became constant, because the final part of the drying process required many days, especially with the larger pieces or with the lower temperatures.

COMPOSITION OF FRUIT

Lutz, Culpepper, Moon, and Meyers (*8*) have reported upon the composition of the ripened and unripened fruit at different stages of maturity. Since seasonal conditions might cause some variation it was thought advisable to take samples of the peeled and unpeeled fruit, both ripened and unripened, under study. Ten representative fruits from each lot were selected and analyses made upon duplicate samples. The results are shown in table 1. It may be noted that there were only small differences between the ripened and unripened fruits, as well as between the peeled and unpeeled fruit. The soluble solids were slightly higher and the insoluble solids slightly lower in the ripened than in the unripened fruit. The dry matter or total solids was nearly the same in the ripened and in the unripened fruit and the moisture averaged 86.5 percent. The insoluble solids were slightly higher in both the ripened and the unripened unpeeled fruits. From the practical standpoint the differences in composition appear too small to be of much importance. It is noted that the Kieffer pear has a rather high percentage of soluble materials—three to four times the amount of the insoluble. The solubles, consisting of sugars, acids, tannins, and other undetermined materials with a high water-absorbing capacity, influence the physical characteristics of the dried material as well as the rate of drying. The significance of these influences will be pointed out subsequently.

The tests were necessarily conducted upon individual fruits because the different fruits varied somewhat in their behavior in drying. In order to minimize the effects of these individual variations and make the tests as comparable as possible, each test was generally repeated several times. Further details regarding this will be given in the discussion.

TABLE 1.—*Composition of the Kieffer pear before and after ripening and before and after peeling*

[Expressed as percentage of the fresh material]

Treatment	Soluble solids	Insoluble solids	Total solids	Reducing sugar	Nonreducing sugar	Total sugar	Acidity as citric	Total astringency
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Ripened, peeled	11.06	2.44	13.50	7.16	0.30	7.46	0.26	0.146
Ripened, unpeeled	10.56	3.04	13.60	7.57	.31	7.88	.24	.180
Unripened, peeled	10.55	2.98	13.53	6.64	.39	7.03	.20	.160
Unripened, unpeeled	10.17	3.20	13.37	6.85	.33	7.18	.29	.185

The purpose of the drying tests to be described has been (1) to determine whether or not there are differences in the ripened and the unripened fruit that affect drying behavior; (2) to determine what differences factors other than stage of maturity inherent in the history of the fruit previous to drying, such as size, make in drying behavior; (3) to determine the effect the different methods of preparation, such as peeling and size of pieces, have upon drying; and

(4) to gain information on the rate of drying at different periods during the process and on the effects of the temperature, and rate of movement and humidity of the drying air.

EXPERIMENTAL RESULTS

EFFECT OF SUBDIVIDING FRUIT INTO SEGMENTS OF DIFFERENT SIZES

For the tests on the effect of segments of different sizes the fruit was weighed, peeled, and sliced longitudinally to give a series of sections consisting of pieces one-half, one-fourth, one-eighth, one-sixteenth, and one thirty-second of the entire fruit. The slicing was always parallel to the longitudinal axis of the fruit so that the pieces consisted of radial segments corresponding to the above-stated sizes. It was obvious that there was some error in slicing the fruit, for the segments were not geometrically perfect. To compensate for this error as much as possible the tests were repeated eight times. Fruit in one half of the tests was ripened; in the other half, unripened. The difference in the ripened and unripened fruit was small and by combining the groups, using the larger number of tests, smoother curves and more reliable results were obtained. The fruits for each of these tests also varied somewhat in size. The mean weights for each series of segments were: Halves, 76.30 g; quarters, 38.61 g; eighths, 19.65 g; sixteenths, 10.18 g; and thirty-seconds, 4.97 g. It is noted that even the average values are not quite correct for a perfectly subdivided fruit; however, they are close enough to those of a fruit theoretically perfectly divided to give an approximate idea of the variations in the rate of drying of pieces of different sizes.

The segments were placed in the drier, side by side, so that the drying conditions were identical.[3] The weighings were made at intervals of from 1 to 6 hours, depending upon the size of the piece or the rate of drying. The difference in the weight of the fruit at the beginning and at any subsequent time represents the actual water evaporated. The results appear more satisfactory, however, if expressed as percentage of moisture that the material contains at different times during the drying process. This was done on the basis that the fruit contained 13.5 percent solid matter at the beginning, as the chemical analysis had shown (table 1). The results, expressed as percentages of residual moisture, are given in table 2 and illustrated in figure 2.

TABLE 2.—*The moisture content of Kieffer pears cut into different sized segments after drying for various lengths of time*

Length of drying period (hours)	Moisture content [1] in—					Length of drying period (hours)	Moisture content [1] in—				
	Halves	Quarters	Eighths	Sixteenths	Thirty-seconds		Halves	Quarters	Eighths	Sixteenths	Thirty-seconds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1				82.47	78.7	24	66.2	45.3	30.0	14.6	13.3
2	84.4	83.5	82.0	78.3	69.1	32	43.1	31.5	20.2	12.5	11.5
4	82.3	80.3	77.7	70.3	46.6	40	32.2	22.3	15.6	12.0	
6	79.9	77.3	73.5	60.8	33.1	48	24.6	16.9	13.2	11.8	
8	77.6	74.4	68.8	50.2	26.1	56	19.8	14.5	12.3	11.5	
10	75.2	70.9	64.3	39.3	22.2	68	15.4	12.9	11.7		
14	70.2	64.0	54.5	27.1	18.3	80	12.9	12.3	11.5	10.7	10.5
18	64.6	56.7	44.5	20.1	15.8						

[1] Original moisture content was 86.5 percent.

[3] Unless otherwise stated the temperature of the drying air in all tests was 35° C., its velocity 5.72 miles per hour, and its relative humidity 16.2 percent.

RATE OF CHANGES IN MOISTURE CONTENT WITH PROGRESS OF DRYING

It may be noted from figure 2 that the rate of change in the moisture content is not constant throughout the drying process. There is a large amount of difference at the beginning and toward the end of the process and a decided difference in the large and the small segments. The curves have a characteristic form, sloping downward abruptly at first, but increasing this downward trend until toward the middle of the process, when they begin to flatten out decidedly. The form of the curves is quite similar for all sizes of the fruit pieces; the curve for the smallest segment slopes downward much more abruptly than that for the largest.

These changes may perhaps be better understood by studying them directly. The rates of change in moisture content were obtained

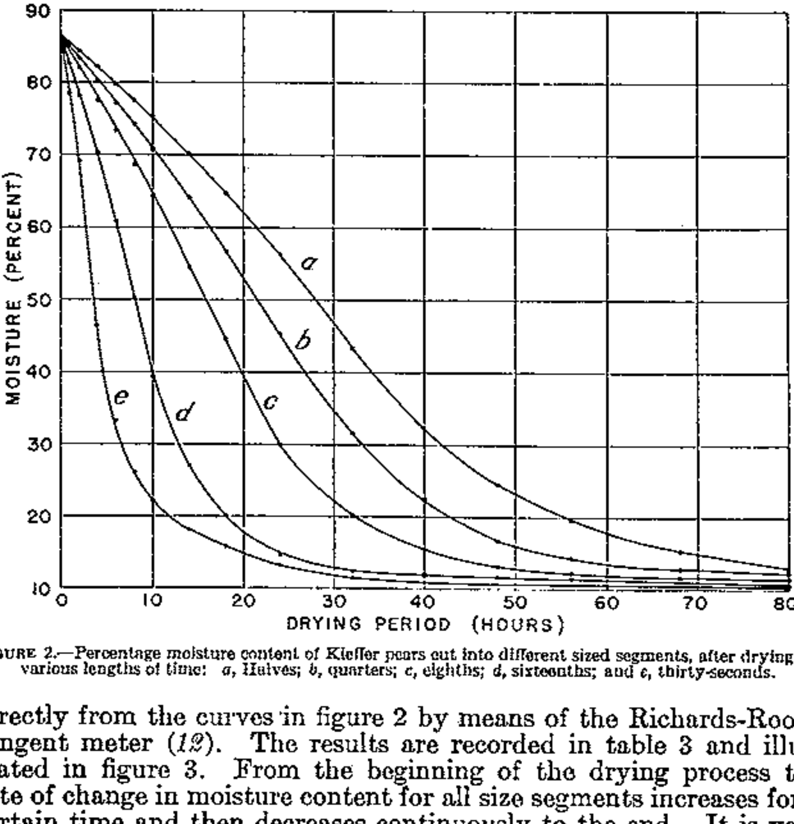


FIGURE 2.—Percentage moisture content of Kieffer pears cut into different sized segments, after drying for various lengths of time: *a*, Halves; *b*, quarters; *c*, eighths; *d*, sixteenths; and *e*, thirty-seconds.

directly from the curves in figure 2 by means of the Richards-Roope tangent meter (*12*). The results are recorded in table 3 and illustrated in figure 3. From the beginning of the drying process the rate of change in moisture content for all size segments increases for a certain time and then decreases continuously to the end. It is very much greater in the smaller segments during the first part of the drying process, although the rate of change in all segments approaches zero toward the end of the process. The rate begins to slow down very much in the thirty-second segments before the maximum is reached in the halves, the maximum rate in the former being six and one-half times the value of that in the halves. The maximum was reached at the end of 3 hours in the thirty-second segments and at the end of 30 hours in the halves. In the intermediate-size segments the maximum rate of change occurred at various intermediate times.

TABLE 3.—*Rate of change in moisture content during the drying of Kieffer pears when sliced into segments of different sizes*

Length of drying period (hours)	Change in moisture content per hour, in—					Length of drying period (hours)	Change in moisture content per hour, in—				
	Halves	Quarters	Eighths	Sixteenths	Thirty-seconds		Halves	Quarters	Eighths	Sixteenths	Thirty-seconds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
2			2.000	4.003	10.000	15				1.938	0.625
3					12.500	20	1.400	1.870	2.000	1.040	.469
4					11.400	30	1.600	1.670	.950	.340	.162
5	1.125	1.540	2.175	4.588		40	1.150	.844	.421	.037	
6				5.000		50		.406	.137		
8				5.620	4.000	60	.418	.152	.054		
10	1.200	1.740	2.350	4.063	2.070	70	.219	.050	.026		

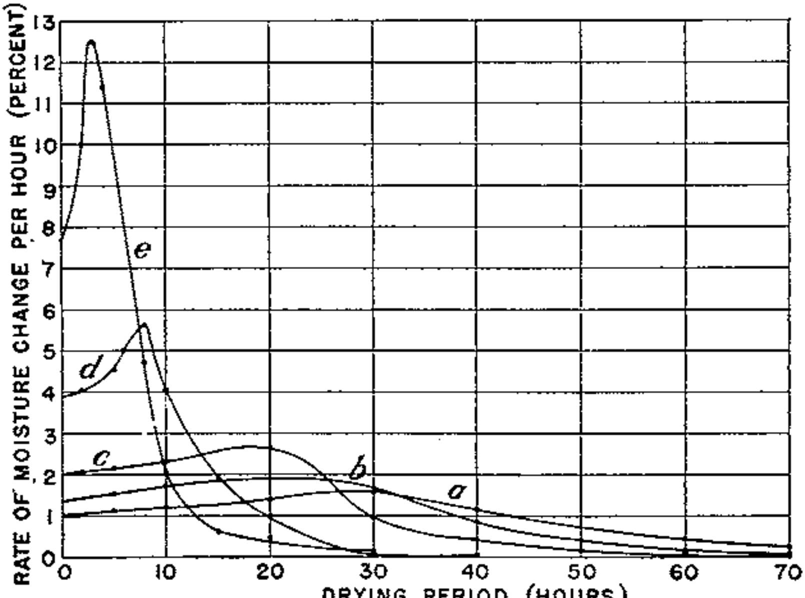


FIGURE 3.—Rate of change in the moisture content of Kieffer pears during the drying process for *a*, halves; *b*, quarters; *c*, eighths; *d*, sixteenths; and *e*, thirty-seconds.

Since the moisture content, and hence the total solids, varies with the time of drying and the rate of change in moisture varies with the time of drying, there must be a relationship between the rate of change in moisture and the percentage of solids present. Table 4 gives the percentages of solids and the corresponding values of the rate of change in moisture content. In figure 4 the values for the rates are plotted against the corresponding percentages of solids present. The maximum rate of change occurs when the fruit has a total solids content of 50 to 60 percent for all size pieces. This suggests that the maximum should be at a definite moisture content for pieces of all sizes and that the variations here present are due to differences in the shape of the pieces, or errors in averaging and drawing the curves. This method appears to be an interesting and useful way to study the effect of various factors on the drying process.

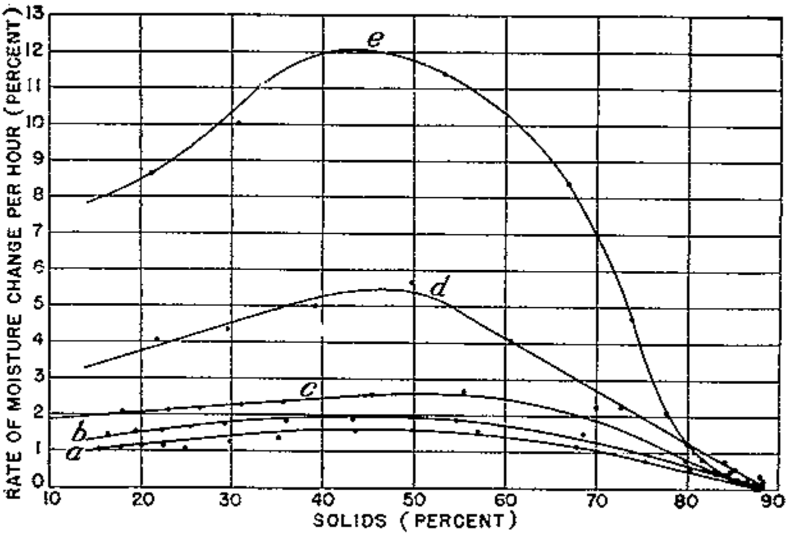


FIGURE 4.—Rate of change of moisture percentage during the drying of Kieffer pears when the solids or dry matter have reached different percentages. The values for the rates of change of moisture percentage were obtained directly from the curves in figure 2 by means of the Richards-Roope tangent meter: *a*, Halves; *b*, quarters; *c*, eighths; *d*, sixteenths; and *e*, thirty-seconds.

TABLE 4.—*Rate of change in moisture content during the drying of Kieffer pears when the solids or dry matter have reached different percentages*

Halves		Quarters		Eighths		Sixteenths		Thirty-seconds	
Dry matter	Change in moisture per hour	Dry matter	Change in moisture per hour	Dry matter	Change in moisture per hour	Dry matter	Change in moisture per hour	Dry matter	Change in moisture per hour
Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
15.5	1.08	10.5	1.43	18.0	2.09	21.7	4.06	21.3	8.64
17.7	1.10	19.7	1.61	23.0	2.13	29.7	4.35	30.9	10.00
20.1	1.13	22.7	1.59	20.6	2.19	39.2	5.00	42.5	12.50
22.4	1.10	25.6	1.67	31.2	2.26	49.8	5.62	53.4	11.40
24.8	1.20	29.1	1.74	35.7	2.35	60.0	4.06	66.9	8.35
20.8	1.27	36.0	1.82	45.5	2.52	72.9	2.25	73.9	4.69
35.2	1.36	43.3	1.89	55.5	2.66	79.9	1.27	77.8	2.07
43.8	1.53	54.7	1.88	70.0	2.22	85.2	.54	81.7	.80
56.9	1.55	68.5	1.60	70.8	.78	87.5	.18	84.2	.42
67.8	1.15	77.7	.84	84.4	.42	88.0	.037	86.7	.23
75.4	.78	83.1	.44	88.2	.20			88.5	.10
80.2	.52	85.5	.23	88.5	.06				
84.6	.20	87.1	.06						

DRYING PROCESS IN TERMS OF WATER LOSS

It is sometimes advantageous to consider the drying process from the standpoint of the amount of water evaporated. The results from the foregoing tests upon the rate of drying at different intervals of time during the drying process have been calculated in terms of water evaporated or water loss (table 5 and fig. 5), and it is observed that the drying process gives a somewhat different picture. There is a very large difference in the percentage of water lost in a given time, from fruit sliced into segments of different sizes. The halves, after being dried for 4 hours, lost 23.75 percent of the fresh weight of the fruit, whereas in the fruit sliced into thirty-seconds, 74.72 percent was lost. The curves showing the relationship between the drying time in hours and the percentage of water lost for the different size segments have a similar form; they pass rapidly upward at first and then gradually become more nearly horizontal toward the end of the process.

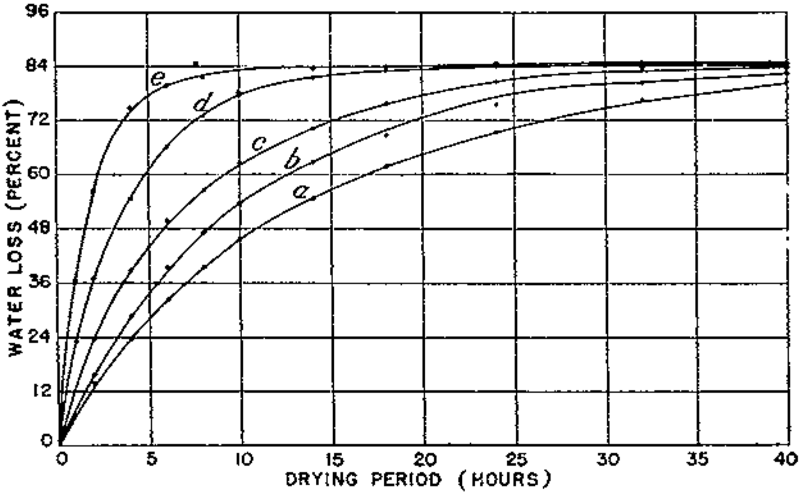


FIGURE 5.—Amount of water loss expressed in percentage of the initial fresh weight from Kieffer pears during the drying process when the fruit was sliced into different size segments: *a*, Halves; *b*, quarters; *c*, eighths; *d*, sixteenths; and *e*, thirty-seconds.

TABLE 5.—*Amount of water lost from Kieffer pears during the drying process when the fruit was sliced into different size segments*

Length of drying period (hours)	Water lost [1]					Length of drying period (hours)	Water lost [1]				
	Halves	Quarters	Eighths	Sixteenths	Thirty-seconds		Halves	Quarters	Eighths	Sixteenths	Thirty-seconds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	-------	-------	-------	23.00	36.61	24	69.18	75.32	80.71	84.15	84.43
2	13.47	15.15	23.75	37.00	56.31	32	75.15	80.29	83.08	84.57	84.75
4	23.75	28.75	38.75	54.55	74.72	40	80.09	82.63	84.00	84.60	-------
6	32.15	39.25	49.00	66.00	79.82	48	82.10	83.75	84.45	84.69	-------
8	39.74	47.27	56.73	72.89	81.73	56	83.1	84.21	84.61	84.75	-------
10	45.57	53.77	62.18	77.76	82.65	68	84.04	84.50	84.71	-------	-------
14	54.70	62.50	70.33	81.48	83.48	80	84.50	84.61	84.75	84.88	84.92
18	61.65	68.82	75.68	83.10	83.97						

[1] Values are expressed in percentage of the initial fresh weight.

TABLE 6.—*Rate of loss of water from Kieffer pears sliced into different size segments during the drying process* [1]

Length of drying period (hours)	Loss of water per hour [1] by—					Length of drying period (hours)	Loss of water per hour [1] by—				
	Halves	Quarters	Eighths	Sixteenths	Thirty-seconds		Halves	Quarters	Eighths	Sixteenths	Thirty-seconds
	Percent	*Percent*	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	7.00	7.70	11.80	17.20	26.00	10	2.57	2.78	2.44	1.60	0.30
2	5.90	7.28	10.00	11.80	16.00	15	1.96	1.80	1.44	.40	.004
3	-------	-------	-------	8.88	8.00	20	1.24	1.36	.88	-------	-------
4	-------	5.80	6.50	7.00	4.40	25	1.05	.66	-------	-------	-------
5	4.20	5.60	5.20	5.60	2.72	30	.76	.28	.172	-------	-------
7	-------	-------	-------	-------	.92	35	.44	.24	-------	-------	-------
8	-------	-------	-------	2.88	-------						

[1] Expressed in percentage loss of the fresh weight per hour.

The rates of water loss during the drying period for the different size segments are given in table 6. These values were obtained directly from the curves in figure 5 by means of the Richards-Roope tangent meter (p. 6) and are expressed in percentage loss per hour, which is equivalent to stating them in grams lost per 100 g of fresh material per hour, or pounds lost per 100 pounds per hour. The values for the halves, eighths, and thirty-seconds have been plotted and are shown in figure 6. The curves for the eighths and thirty-seconds slope sharply downward at first, then gradually become more nearly horizontal; the curves for the halves slope downward much less sharply at first, but they also gradually become horizontal. Each curve intersects all of the others, and there is a tendency for them to intersect in the neighborhood of the same point. This suggests that if the fruit had been perfectly subdivided and the other conditions

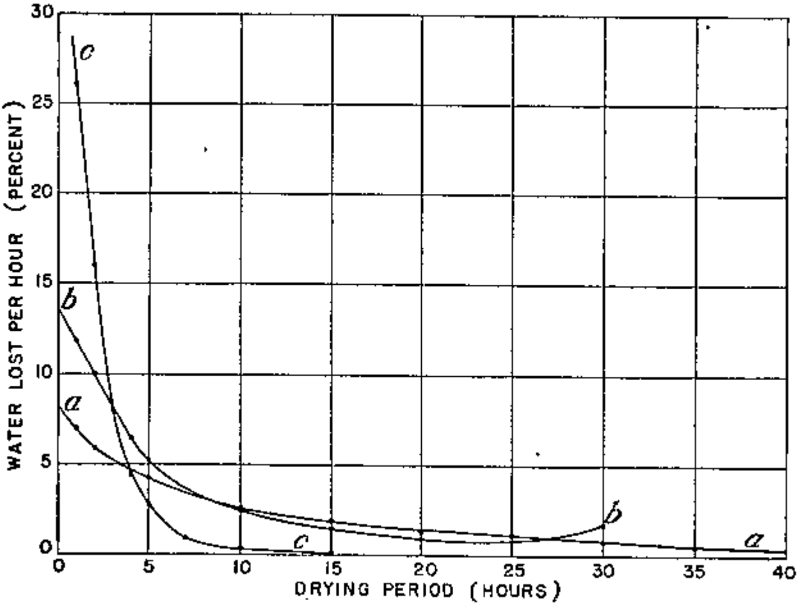


FIGURE 6.—Rate of change in water loss from Kieffer pears sliced into different size segments during the drying process expressed in percentage of loss of fresh weight per hour: *a*, Halves; *b*, eighths; and *c*, thirty-seconds.

had been exactly the same, the curves for the various sizes of segments would have crossed at exactly the same point. In any case there should be some uniformity in this respect, and this method of plotting the values should be useful in studying the drying processes.

The differences in the moisture content, the loss of water, and the rates of change in both cases have been noted, but the relationship between the different size segments and the drying time is not readily seen. To make this relationship clearer the size of the segment has been plotted against the time necessary to dry the material to different percentages of moisture, and the values have been arranged so as to be readily compared (table 7). In figure 7 the points along the abscissa represent fractional parts of the whole fruit; those along the ordinate represent the time in hours required to dry the material to a definite moisture percentage. Curve *A* represents the time required to dry segments of different sizes to a moisture content of 15 percent; *B*, 25 percent; and so on to *G*, which shows the number of hours required to dry the segments to only 75 percent moisture. It is noted that the points do not fall exactly on smooth curves; this is the result of errors probably due to irregularities in slicing, or to variations from the theoretical in size or weight. However, the values lie close enough to the curves to leave little doubt as to their general form.

It may be noted that the difference in the rate of drying of the halves and quarters is not so marked as their variation in weight would indicate, especially in the early part of the drying. The difference in the quarters and eighths is more marked as is also that in the other smaller segments. The rate of drying appears to be more nearly

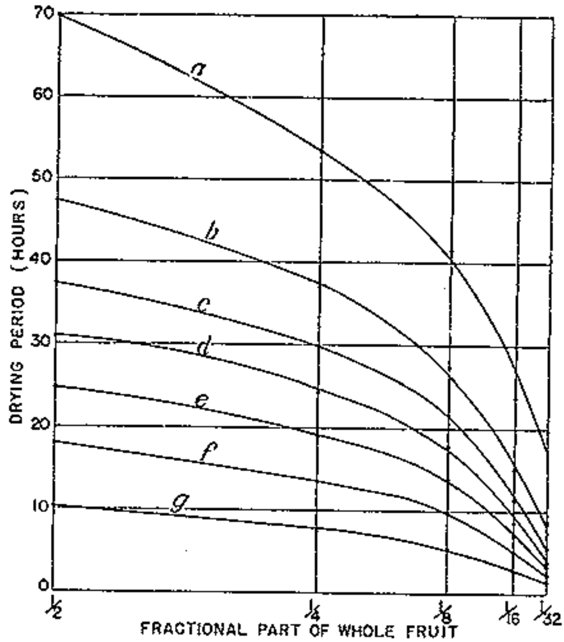


FIGURE 7.—Number of hours required to dry Kieffer pears sliced into different size segments to different moisture percentages: *a*, 15 percent; *b*, 25 percent; *c*, 35 percent; *d*, 45 percent; *e*, 55 percent; *f*, 65 percent; and *g*, 75 percent.

proportional to the ratio of the surface to the volume of the piece than to the weight. The thickness of the segment, therefore, is of great importance, for the water at the center of it must diffuse to the surface before it is carried away.

The water may be removed from the surface of the fruit and the surrounding atmosphere much more readily than it can diffuse from its center to the surface. This slowness of diffusion results in limiting the speed of drying, and under practical conditions is often the chief factor in artificial drying. As soon as a dry layer is produced at the surface, water from the inner, more completely saturated, material is drawn to the surface by hygroscopic forces. If the drying process is stopped, the surface will increase in moisture content until equilibrium is established. If the water is evaporated immediately after it reaches the surface, the moisture will continue to move from the center to the surface until the center, as well as the surface, approaches complete dryness. With these considerations in mind, the behavior of the large and small segments is not surprising.

TABLE 7.—*Time required to dry Kieffer pears, sliced into segments of different sizes, to various moisture percentages*

Moisture content percent	Drying time					Moisture content percent	Drying time				
	Halves	Quarters	Eighths	Sixteenths	Thirty-seconds		Halves	Quarters	Eighths	Sixteenths	Thirty-seconds
	Hours	*Hours*	*Hours*	*Hours*	*Hours*		*Hours*	*Hours*	*Hours*	*Hours*	*Hours*
15	70.00	53.50	41.50	23.75	19.75	55	24.75	19.00	13.75	7.00	3.25
25	47.25	37.00	27.25	15.00	8.50	65	18.00	13.50	9.75	5.00	2.25
35	37.50	29.75	21.50	11.25	5.50	75	10.25	7.50	5.25	2.75	1.25
45	31.00	24.25	17.75	8.50	3.75						

RIPENED COMPARED WITH UNRIPENED FRUIT

The unripened fruit used was quite green and hard, testing 13.9 pounds with the Magness and Taylor (*9*) pressure tester with 5/16-inch point; the ripened fruit tested 3.9 pounds. The tissues of the unripened fruit appeared coarse in texture but very crisp, whereas those of the ripened fruit were finer, juicy, and almost melting in character. The variations in the physical characteristics were so pronounced that considerable difference in the rate of drying was anticipated. The pieces of fruit, halves in this case, were so placed that the conditions of drying were as nearly identical as could be provided. The fruits were matched in size as closely as could be done by visual inspection, but the segments still varied from 64 to 73 g in weight. In order that the errors due to slicing, size of fruit, and other factors should be as small as possible the tests were repeated 12 times. The average weight of the halves after peeling and coring was 67.64 g for the ripened fruit and 67.41 g for the unripened, thus averaging almost the same weight, although the unripened was a little smaller. The results, given in table 8, are the mean for the 12 separate tests. The temperature employed in these tests was 35° C., the air velocity 3.46 miles per hour, and the relative humidity 18.3 percent.

TABLE 8.—*Percentage of moisture content of ripened and unripened Kieffer pears after drying for different lengths of time*

[Average of 12 tests]

Drying time (hours)	Moisture content		Drying time (hours)	Moisture content		Drying time (hours)	Moisture content	
	Ripened	Unripened		Ripened	Unripened		Ripened	Unripened
	Percent	*Percent*		*Percent*	*Percent*		*Percent*	*Percent*
2	84.3	84.2	22	62.5	58.9	42	34.3	31.2
4	82.4	81.8	24	59.8	56.0	44	32.1	29.3
6	80.3	79.5	26	57.2	53.1	46	30.1	27.6
8	78.2	77.1	28	54.2	50.0	50	26.7	24.7
10	76.2	74.7	30	51.2	46.9	54	23.0	22.2
12	74.2	72.2	32	48.0	43.8	60	20.7	19.4
14	71.9	69.7	34	45.0	40.9	70	17.0	16.3
16	69.7	67.1	36	42.0	38.1	80	14.2	14.1
18	67.5	64.4	38	39.2	35.5			
20	65.1	61.7	40	36.7	33.2			

It is noted that the moisture content of the unripened fruit was lowered a little faster than that of the ripened material. The difference in the rate of drying is not very great, and from a practical standpoint doubtless is of little importance. There was some variation in the individual tests, but, although small, it appears to be significant. There are several things that may account for the difference, but it is not very clear which of these is the chief factor.

Lutz, Culpepper, and Moon (*7*) have shown that the soluble pectin content of ripened fruit is higher than in the unripened. The difference in the rate of drying was due perhaps, for the most part, to the pectin that tends to obstruct the diffusion of water from the center to the surface of the segment in the ripened fruit. It may also form at the surface a layer slightly impervious to the passage of the water outward. The surface of the unripened fruit appeared slightly more roughened than the ripened, perhaps because the knife did not cut the hard, tough fruit as smoothly as it did the soft, ripened fruit. This may have resulted in some difference in the rate of drying.

PEELED COMPARED WITH UNPEELED FRUIT

Bartlett pears are sometimes dried without peeling, the cores only being removed. In considering this possibility for Kieffer pears the question immediately arises as to what effect peeling will have on the rate of drying. Nichols and Christie (*11*) have shown that the drying rate of unpeeled halves is very much slower than for similar fruit peeled; the fruit having been sulphured and steamed in both instances. In the present tests the fruit was untreated and was sliced into sixteenths and halves. The results are given in table 9.

The tests on the peeled fruit were repeated eight times, and those on the unpeeled fruit six times. Half the tests in each case were made with ripened fruit and the other half with unripened fruit. The difference between the ripened and the unripened fruit was not very great and by averaging all the tests, somewhat smoother curves were obtained. The peeled halves weighed 76.3 g and the unpeeled 74.8 g, whereas the peeled sixteenths weighed 10.18 g and the unpeeled 10.82 g.

TABLE 9.—*Difference in the moisture content of peeled and unpeeled Kieffer pears cored and sliced into halves and sixteenths after drying for different lengths of time*

[Average of eight tests for peeled fruit and six for unpeeled]

Time (hours)	Moisture content of—				Time (hours)	Moisture content of—			
	Halves		Sixteenths			Halves		Sixteenths	
	Peeled	Unpeeled	Peeled	Unpeeled		Peeled	Unpeeled	Peeled	Unpeeled
	Percent	*Percent*	*Percent*	*Percent*		*Percent*	*Percent*	*Percent*	*Percent*
2	84.4	85.8	78.3	80.1	80	12.9	55.1	10.7	
4	82.3	85.2	70.3	73.6	100		42.1		
8	77.0	83.0	50.2	59.5	120		31.0		
14	70.2	82.2	27.1	30.1	140		24.2		
24	56.2	79.1	14.8	20.9	160		19.2		
40	42.2	74.3	12.0	13.7					

It is noted that there is a decided difference in the rate of drying of the peeled and the unpeeled halves. At the end of 80 hours the moisture content of the peeled halves was 12.9 percent and that of the unpeeled fruit 55.1 percent. To reach a moisture content of approximately 42 percent required 40 hours for the peeled and 100 hours for the unpeeled; however, as the fruit is further subdivided the effect of peeling becomes less and less. In the case of the fruit sliced into six-

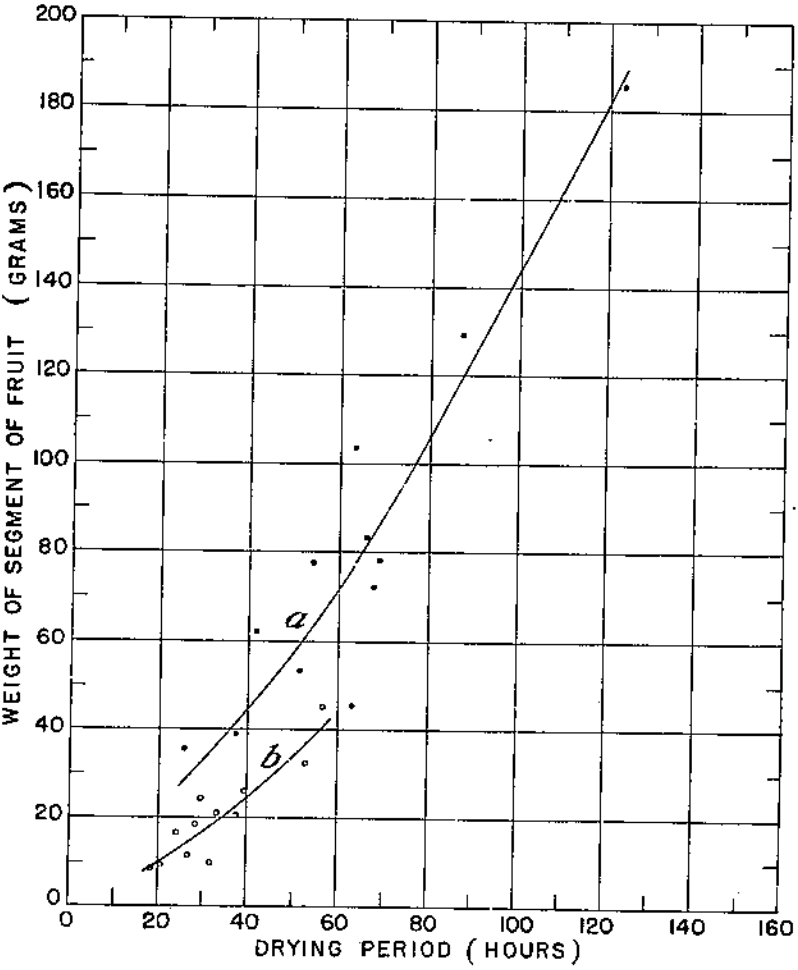


FIGURE 8.—Relationship between the size of the fruit of Kieffer pears and the time required to dry to a moisture content of 20 percent when sliced into halves and one-eighth segments. The temperature was 35° C. and the air velocity 5.72 miles per hour: *a*, Halves; *b*, eighths.

teenths the moisture content at the end of 14 hours was 27.1 percent for the peeled fruit and 39.1 percent for the unpeeled; at the end of 40 hours it was 12.0 percent for the peeled and 13.7 percent for the unpeeled. From these and other tests made in this connection it may be concluded that peeling is advantageous or justified, especially with fruit sliced into halves, because of the increased rate of drying and the improvement in the quality of the finished product.

EFFECT OF SIZE OF FRUIT UPON RATE OF DRYING

The time required to dry any moist substance depends upon its size or diameter. In considering Kieffer pears, however, it was recognized that the size of the core to be removed might make the rate of drying in the large and the small fruits more or less marked than their differences in weight would indicate. It was decided, therefore, to see what differences might be expected in fruits of various sizes. Twelve unripened fruits of about normal shape, but varying widely in weight, were selected, peeled, cored, sliced into halves and eighths, and dried. The results are illustrated in figure 8. It is noted that when the number of hours required to dry the pieces of fruit to a moisture content of 20 percent is plotted against the size of the piece, the line representing the relationship does not pass through all the points. The influence of factors other than size is clearly evident; these factors may be errors in coring, variation in size of the core, differences in shape of the fruit, or in the hygroscopic nature of the substances of the fruit. The line representing the relationship that is most probable for the 12 fruits is nearly straight, indicating that the drying rate is very nearly directly proportional to the size of the fruit. It is seen that the largest half requires about five times as long to dry to a moisture content of 20 percent as the smallest, which is approximately the same ratio as the weights of the whole fruits. This ratio does not exactly hold for fruit sliced into eighths, as the difference in drying time between the large and small sections is not quite so great. It is evident that to be certain of the exact relationship, a much larger number of fruits should be tested.

EFFECT OF AIR VELOCITY UPON RATE OF DRYING

It is obvious that the drying process cannot continue for any great length of time unless there is some means by which the evaporated water can be removed from the neighborhood of the fruit; otherwise the air would quickly become so completely saturated that no more water could escape from the fruit. This removal of evaporated water is accomplished by providing for an air current in which the pieces of material are kept during the drying process. Because a rapidly moving current of air dries faster than a slow current, the question immediately arises as to what air velocity is most desirable or most effective. A few tests were made with Kieffer pears to determine their drying behavior with different air velocities. The first test was conducted in almost still air, and was repeated four times; a second test, with air velocity of 0.458 mile per hour, was repeated six times; a third, with an air velocity of 5.72 miles per hour, was repeated eight times; and a fourth, with an air velocity of 12.55 miles per hour, was repeated eight times. The fruit was sliced into eighths and averaged 18.46 g, 19.92 g, 19.65 g, and 19.42 g for the four tests, respectively.

For the still-air series, the drying was done in a large constant-temperature room with no fans or ventilation. The volume of air in the room was so large that the evaporation for the small amount of fruit did not change the relative humidity materially. The air was not disturbed except by entering and leaving the room when the fruit was weighed, but even this somewhat influenced the rate of drying. The fruit had its entire surface exposed to the air, and diffusion of the moisture through the air away from the fruit proceeded under nearly uniform conditions.

Any pieces of fruit that showed evidence of spoilage were excluded from the results.

The moisture content of the fruit in the various air currents, after drying for different lengths of time, is given in table 10 and is illustrated in figure 9. A decided difference is noted in the moisture content of the fruit during the drying process when kept in still air and when kept in air moving at the rate of 0.458 mile per hour. At the end of 30 hours the former had a moisture content of 51 percent; the latter, 24.7 percent. It required 80 hours to dry the material to 14.8 percent moisture in still air and approximately 43 hours in an air current of 0.458 mile per hour. It is evident that the rate of drying is greatly increased even by a very gentle air current. The moisture content of the material in a current of 0.458 mile per hour was 42.9

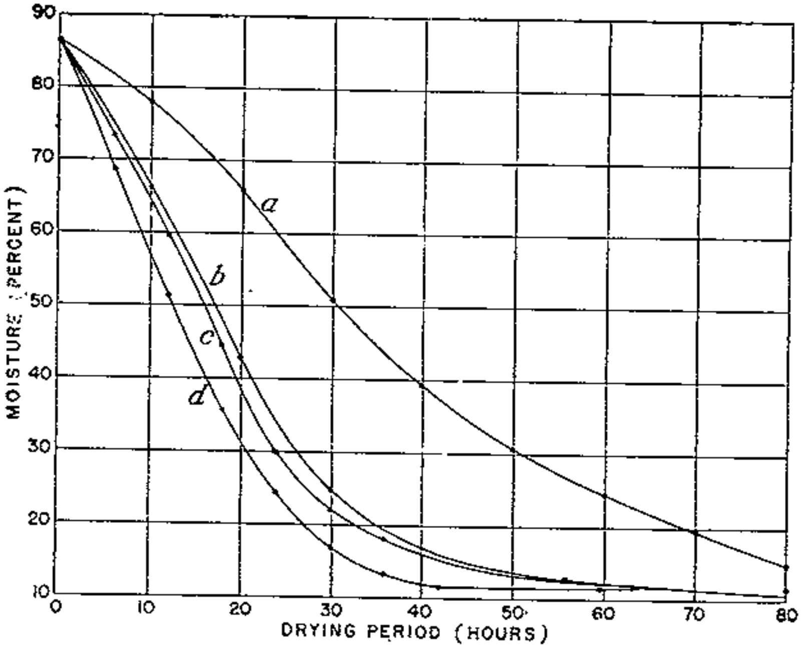


FIGURE 9.—Moisture content of Kieffer pears (one-eighth segments) during the drying process when different air velocities were employed. The relative humidity of the air was 16.2 percent and the temperature was 35° C.: *a*, Still air; *b*, 0.458 mile per hour; *c*, 5.72 miles per hour; and *d*, 12.55 miles per hour.

percent at the end of 20 hours; in a current of 12.55 miles per hour it was 31.2 percent. In the former it required 40 hours to reach a moisture content of 17 percent, and 30 hours to reach approximately the same moisture content in the latter. It is evident, therefore, that a gentle current is quite effective in removing the moisture-laden air surrounding the fruit, and that higher velocities can do comparatively little more.

It is evident also that other factors limit the effectiveness of the increased air velocity, chief of which appears to be the rate of diffusion of water from the moist inner tissues to the surface of the fruit where it can escape. The amount of water reaching the surface of the fruit is, to a considerable extent, independent of the air velocity at the surface. It is affected by the rate of diffusion which, in turn, is dependent upon the difference in the moisture content at the surface and at the center of the piece or the diffusion gradient. The air currents of higher speed can act only by making the surface very dry, thus increasing somewhat the diffusion gradient, or by conveying to the material a greater amount of heat which is necessary in evaporation.

TABLE 10.—*Moisture content of Kieffer pears sliced in one-eighth segments during drying process when different air velocities were employed*

Air velocity per hour (miles)	Moisture content after drying for—											
	0 hours	10 hours	12 hours	18 hours	20 hours	24 hours	30 hours	40 hours	50 hours	60 hours	70 hours	80 hours
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
Still air	------	77.9	------	------	66.0	------	51.0	39.3	30.7	24.5	19.5	14.8
0.458	74.6	60.3	------	------	42.9	------	24.7	17.0	13.0	12.2	------	------
5.72	73.5	64.4	59.7	44.1	38.7	30.0	22.1	16.0	13.2	12.0	11.3	10.7
12.55	68.6	57.0	51.3	35.5	31.2	24.4	16.8	11.9	11.5	11.5	11.5	------

One may conclude that it would be uneconomical to use air currents of velocities higher than 0.458 mile per hour, but, in actual practice where the fruit is piled on trays two or more layers deep, it may be necessary to make the air current of higher velocity in order to produce agitation sufficient to cause the air between the pieces of fruit to change even at the rate of 0.458 mile per hour.

EFFECT OF TEMPERATURE UPON RATE OF DRYING

In proposing to dry any fruit the question immediately arises as to the optimum temperature to be employed. The water-holding capacity of the air and the amount of heat that it carries, necessary for evaporation, are greatly increased by raising the temperature of the air; this is universally taken advantage of in practice to increase the rate of drying.

To find out how the Kieffer pear behaves when different temperatures are used in the drying process, tests were made, using ripened, peeled fruit, sliced into halves and dried in an air current of 4.15 miles per hour. All conditions in each of the tests could not be made exactly the same with only the temperature varying. Even in the tests at any particular temperature, the weight of the segments of fruit and the relative humidity varied somewhat; and to counteract this error to some extent the tests at each temperature employed were repeated several times. The average weight of the segments, the average humidity, and the number of times each test was repeated, as well as the different temperatures employed, are given in table 11.

TABLE 11.—*Effect of temperature upon rate of drying halves of Kieffer pears*

Temperature employed (°C.)	Replications	Relative humidity of drying air	Average weight of segments	Temperature employed (°C.)	Replications	Relative humidity of drying air	Average weight of segments
	Number	*Percent*	*Grams*		*Number*	*Percent*	*Grams*
23	8	24.1	68.4	41	8	12.1	69.4
30	8	21.7	72.8	50	10	7.2	71.3
35	15	16.2	70.2	60	10	4.1	73.2

The temperatures employed ranged from 23° to 60° C.; a few tests were made at temperatures higher than 60°, but they were not repeated sufficiently to be entirely reliable with respect to the rates of drying. However, enough was done to be fairly certain of the effect upon the quality of the product.

It is noted that the average weight of the fruit pieces differed somewhat in the tests at the various temperatures. The variations were not great and the weight is obviously close enough to the same value to be reasonably comparable. The method of peeling and coring was as uniform as possible, but it was subject to as great a variation as occurred in the size of the pieces. Also the shape of the pieces could not be made exactly the same in each test, but it is believed that the variations are not great enough to keep the tests from being reasonably comparable.

It may also be noted that the relative humidity was markedly lower in the tests at high temperatures than in those at low temperatures. However, the absolute humidity was very close to the same value for all temperatures, and the lower relative humidity was largely owing to the increased moisture-holding capacity of the air at the higher temperatures. The effect of the temperature is then about what would be expected in practice if air of a certain absolute humidity were heated to the higher temperatures. No attempt was made to carry out tests varying the temperature and maintaining the relative humidity constant.

Table 12 shows the number of hours required to dry the material to different percentages of moisture and to evaporate different percentages of water from the fresh fruit. The results are the averages of all tests made at the particular temperature. As stated above, the tests were not all repeated the same number of times and, therefore, all are not equally reliable. The values given for the 23° and the 30° C. tests are the least reliable; those at 35° the most reliable. However, all the tests were repeated a sufficient number of times to make the values at least reasonably comparable.

TABLE 12.—*Effect of various temperatures upon the percentage of moisture and the percentage of water lost during the drying process by Kieffer pears peeled, sliced into halves, and dried in an air current of 4.15 miles per hour*

Moisture (percent)	Time required to dry at—						Water lost
	23° C.	30° C.	35° C.	41° C.	50° C.	60° C.	
	Hours	*Hours*	*Hours*	*Hours*	*Hours*	*Hours*	*Percent*
80	13.25	8.25	6.00	4.75	3.75	2.75	32.50
75	22.00	14.25	10.75	8.25	6.00	4.75	47.00
70	29.25	19.75	15.00	11.50	8.50	6.25	55.00
60	41.50	29.75	23.00	17.75	12.50	8.75	66.25
50	52.50	37.75	30.25	23.75	17.00	11.00	73.00
40	63.00	47.25	37.50	29.75	20.75	13.00	77.50
30	78.50	57.50	46.00	36.50	25.75	17.50	80.70
20	95.00	73.00	60.00	48.50	34.25	22.50	83.12
10					54.50	36.00	85.00

CHANGES IN MOISTURE CONTENT

The changes in moisture content of the fruit while drying at different temperatures are given in table 12 and illustrated in figure 10. It is apparent that the moisture content changes much more rapidly at the higher temperatures than at the lower ones. It is well known that this is due to the increased water-holding capacity of the air at the higher temperatures and to the greater amount of heat necessary for evaporation. To dry the material to a moisture content of 20 percent at a temperature of 23° C. required 4.2 times as long as at 60°. To dry the fruit to a moisture content of 50 percent at 23° required 4.8 times as long as at 60°. A cubic meter of air at 23° holds 20.578 g of water and at 60° the same volume of air holds 130.5 g, or 6.3 times as much as at 23°. The change in the rate of drying, then, is not quite of the same order as the change in water-holding capacity of the air. The difference in the rate of drying would have been even less had the relative humidity of the air at the two temperatures been the same. Likewise, when the difference in the water-holding

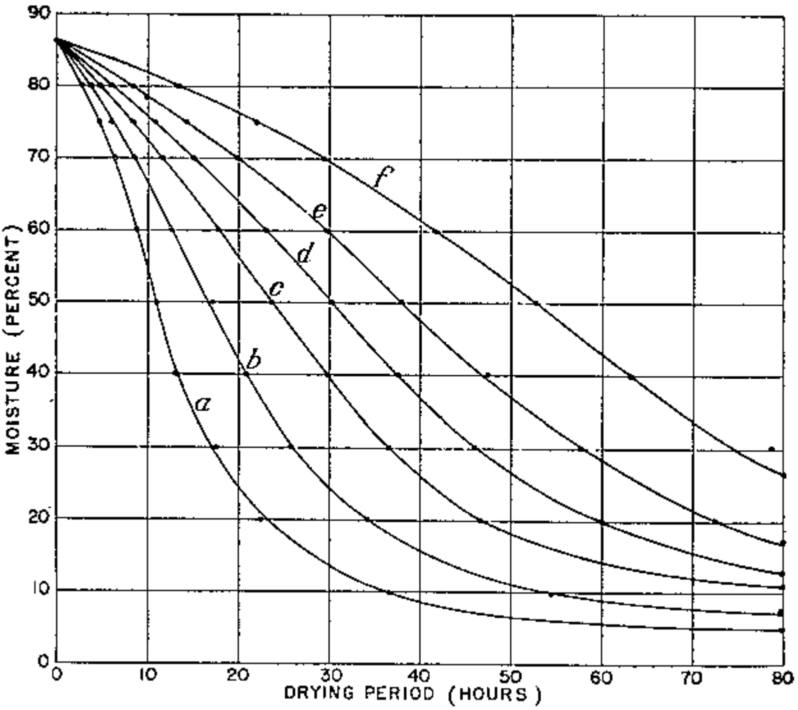


FIGURE 10.—Moisture content of Kieffer pears, ripened, peeled, and sliced into halves, during the drying process when different temperatures were employed: *a*, 60° C.; *b*, 50°; *c*, 41°; *d*, 35°; *e*, 30°; and *f*, 23°.

capacity at the other temperatures is compared with the difference in the rate of drying, the latter is proportionately less than is the difference in the moisture-holding capacity of the air. Undoubtedly this is due to the inability of the water to diffuse from the center of the pieces of fruit to the surface as fast as it may be evaporated from the surface. The rapidly dried material may form a more or less impervious layer at the surface of the fruit, further retarding the diffusion of the water. However, the solids of the pear are very hygroscopic and the dry layer at the surface would tend to draw water rapidly from the inner tissues to establish equilibrium. The so-called "case-hardening", when high temperatures are employed, appears to be of less importance in the pear than in other fruits, but it may be a factor even here.

It is evident that the moisture content near the end of the drying process is considerably higher when low temperatures are used. This is due to the difference in the relative humidities of the air at low and high temperatures, but it would not be the case if the relative humidity was the same at the various temperatures. However, in practical work, approximately these differences in humidity would prevail in raising the drying air from a lower to a higher temperature.

Perhaps the influence of the temperature is better shown in figure 11. The time required to dry the material to various moisture percentages is plotted against the temperature in degrees centigrade. The relation between the temperature and the time required to dry the material to a given moisture percentage is not linear, for it takes

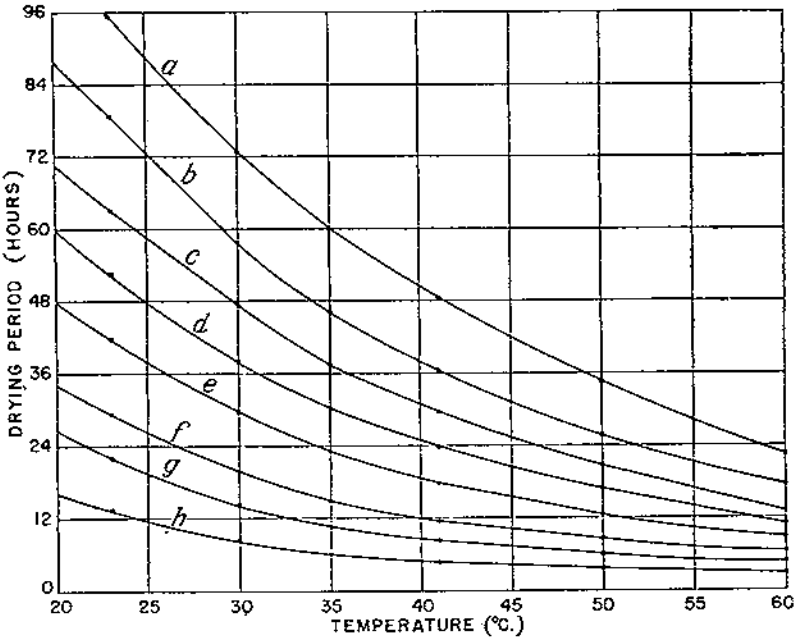


FIGURE 11.—Time required to dry Kieffer pears at various temperatures to different moisture percentages: *a*, 20 percent; *b*, 30 percent; *c*, 40 percent; *d*, 50 percent; *e*, 60 percent; *f*, 70 percent; *g*, 75 percent; and *h*, 80 percent.

an increasingly longer time to dry the material at the lower temperatures. The slope of the lines indicates that an increase in the temperature of the drying from 20° to 30° causes a greater change in the number of hours required to dry the material than does an increase of the temperature from 50° to 60°. The effectiveness of a temperature of 50° is immensely greater than a temperature of 20°, but an increase of 10° from 20° to 30° is more effective than a change of 10° from 50° to 60°. As already pointed out (p. 19), this is probably because of the slowness of the diffusion of moisture from the inner tissues to the surface and the formation of a layer at the surface of the fruit that retards, at least to some extent, the diffusion of the water to the surface.

LOSS OF WATER

The percentage of water lost during the drying process when different temperatures were employed is given in table 13 and shown in figure 12. It is noted that at all temperatures the greater part of the water is lost during the first part of the drying process. The curves showing the relationship between the loss of water and the temperature all have a similar form, sloping sharply upward at first and then flattening out toward the end of the process. The effect of different temperatures upon the rate of drying is perhaps more clearly shown when plotted in another way (fig. 13).

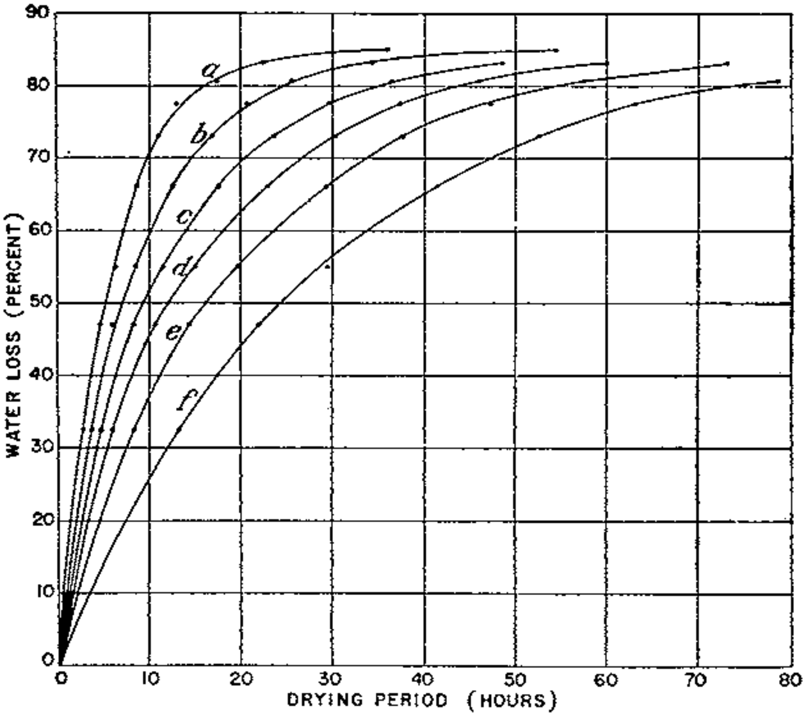


FIGURE 12.—Loss of water in percentage of fresh weight during the drying at different temperatures of Kieffer pears, ripened, peeled, and sliced into halves: *a*, 60° C.; *b*, 50°; *c*, 41°; *d*, 35°; *e*, 30°; and *f*, 23°.

The rates of water loss in percentage per hour are plotted against the drying time. The values of these rates are given in table 13 and were obtained directly from the curves in figure 15 by means of the Richards-Roope tangent meter. At the beginning of the drying the differences in rate are very great when different temperatures are employed. After between 10 and 15 hours, however, all the fruit is losing water at nearly the same rate. In the latter part of the drying process, the rates of loss for the different temperatures become reversed, the material held at the higher temperatures losing water more slowly. Thus it is noted that the curves all tend to cross each other in the neighborhood of the same point. If the tests could have been comparable in every way, it is probable they would cross at exactly the same point. However, whether this should be the case or not, this method of study would appear to be interesting and helpful if applied to different material.

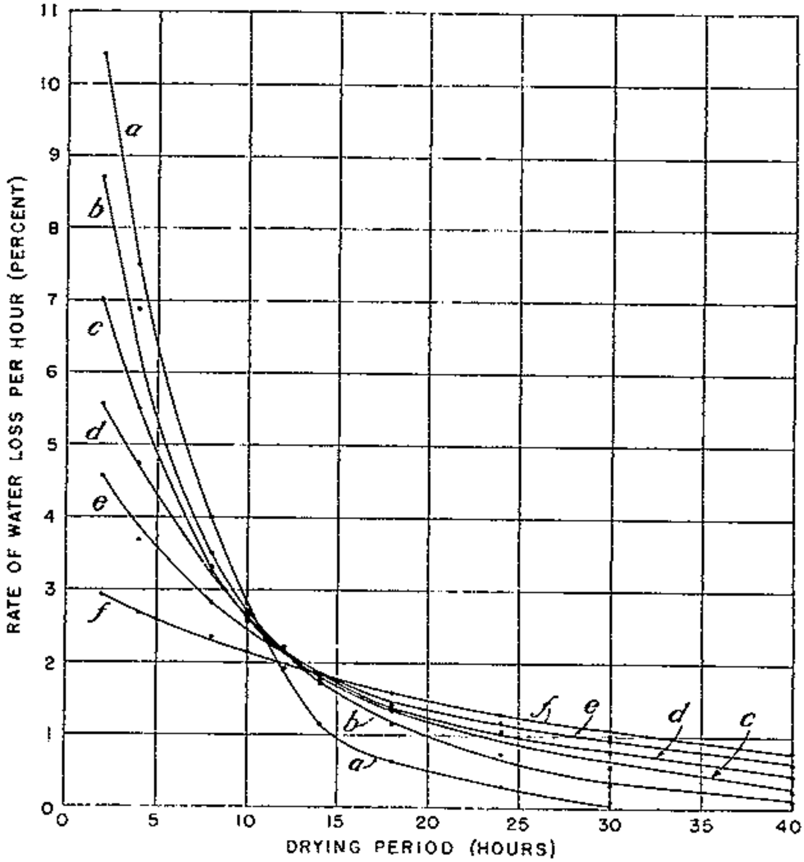


FIGURE 13.—Rate of water loss from Kieffer pears during the drying process when different temperatures are employed: *a*, 60° C.; *b*, 50°; *c*, 41°; *d*, 35°; *e*, 30°; and *f*, 23°.

TABLE 13.—*Rate of water loss of fruit sliced into halves during the drying process when different temperatures are used*

Drying temperature (° C.)	Loss in weight per hour per 100 g of fresh weight after—											
	2 hours	4 hours	8 hours	10 hours	12 hours	14 hours	18 hours	24 hours	30 hours	40 hours	50 hours	60 hours
	Grams	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
23	2.94	2.69	2.35	2.13	1.94	1.86	1.59	1.28	0.98	0.78	0.55	0.35
30	4.58	3.69	2.81	2.60	2.10	1.83	1.41	1.19	.95	.60	.32	.15
35	5.58	4.75	3.25	2.63	2.19	1.75	1.38	1.16	.78	.44	.21	------
41	7.00	5.60	3.31	2.50	2.19	1.74	1.35	1.04	.57	.23	------	------
50	8.70	6.88	3.50	2.58	2.18	1.73	1.13	.75	.32	.11	.02	------
60	10.40	7.50	4.00	2.80	1.94	1.14	.64	.28	.009	------	------	------

EFFECT OF HUMIDITY

No very thorough study of the rate of drying of the Kieffer pear in varying humidities could be attempted. A few tests were made, however, and the results are presented to show something of the behavior of the fruit with higher humidities than those used in the preceding tests. The humidity of the air at 35° C. was increased by arranging for the air to pass over a rather large surface of water before entering the air channel in which the fruit was placed. At 50° the humidity of the air was increased by introducing steam into the air intake. No automatic control was provided, but when the apparatus was properly adjusted, it provided a fairly constant humidity. Determinations of the humidity were made every few

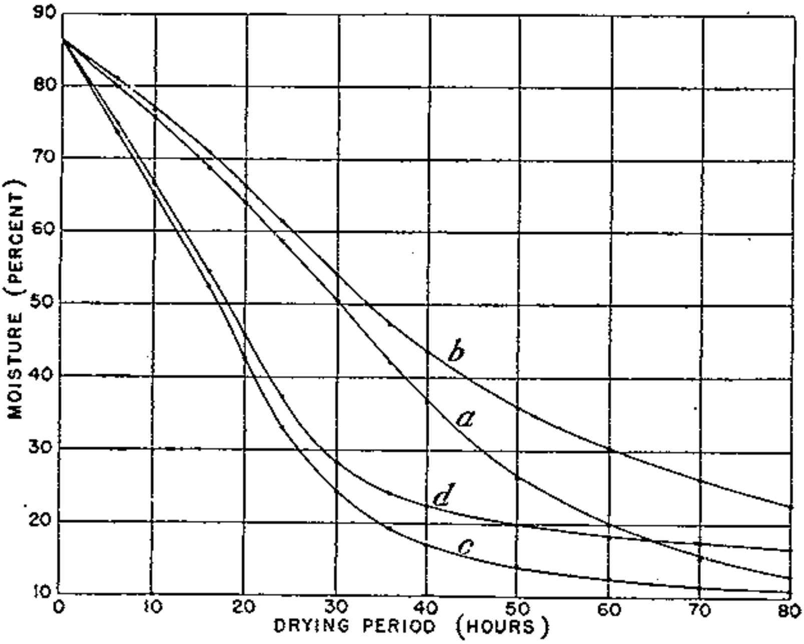


FIGURE 14.—Moisture content of Kieffer pears during the drying process when atmospheres of different relative humidities were employed: *a*, Halves at 16.2 percent; *b*, halves at 64.4 percent; *c*, eighths at 16.2 percent; and *d*, eighths at 64.4 percent. The temperature was 35° C. and the air velocity 4.15 miles per hour.

hours and adjustments were occasionally made to keep it as close to the desired point as possible. A variation of 4 or 5 percent relative humidity incidentally occurred.

At 35° C. two humidities were compared; 16.2 percent for the lower and 64.4 percent for the higher. The low-humidity test was repeated 15 times and the high-humidity test 10 times. The values given are the averages of all these separate tests. The halves of fruit at the start averaged 72.2 g in weight for the low humidity and 71.8 g for the high humidity. The eighths averaged 18.46 g for the low humidity and 17.86 g for the high humidity.

At 50° C. tests were made at 7.3, 24.6, and 45.8 percent relative humidity. The tests with the halves were repeated eight times in the atmospheres of 7.3 and 24.6 percent relative humidity, and six times for the tests in 45.8 percent relative humidity. The pieces of fruit averaged 71.3 g in weight for the tests at 7.3 percent humidity, 70.4 g at 24.6 percent humidity, and 72.0 g at 45.8 percent humidity.

The fruit sliced into eighths averaged 19.14 g for the tests dried in air of 7.3 percent humidity, 18.6 g in air of 24.6 percent humidity, and 19.0 g of 45.8 percent relative humidity. These tests were each repeated eight times and the values for the weights in all cases are averages of the results obtained.

The air velocity was 4.15 miles per hour for the tests at each of the humidities.

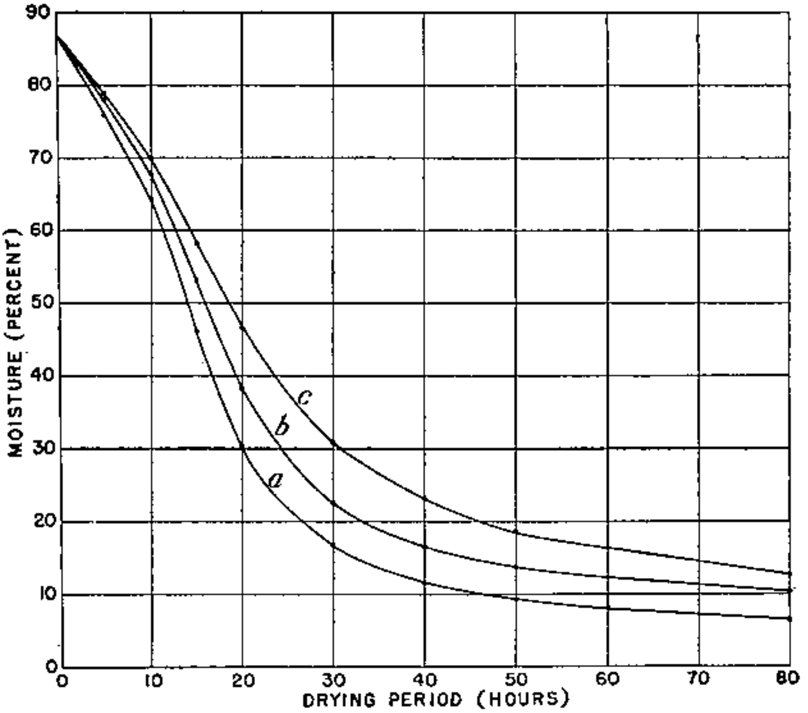


FIGURE 15.—Changes in the moisture content of Kieffer pears (sliced into halves) during the drying process when atmospheres of different relative humidities were employed: *a*, 7.3 percent; *b*, 24.6 percent; and *c*, 45.8 percent. The temperature was 50° C. and the air velocity was 4.15 miles per hour.

The results of these tests are recorded in tables 14 and 15 and illustrated in figures 14, 15, and 16. No tests were made with very high humidities. The changes in the moisture content are greater at the low humidity than at the higher ones, but the difference between the high and low humidities at the beginning of the process is generally less than might have been expected. However, toward the end of the process the difference becomes more pronounced. It is evident from the curves that in high humidity the material will always have a high moisture content at the end of the drying process, because the material retains large quantities of water in moist atmospheres.

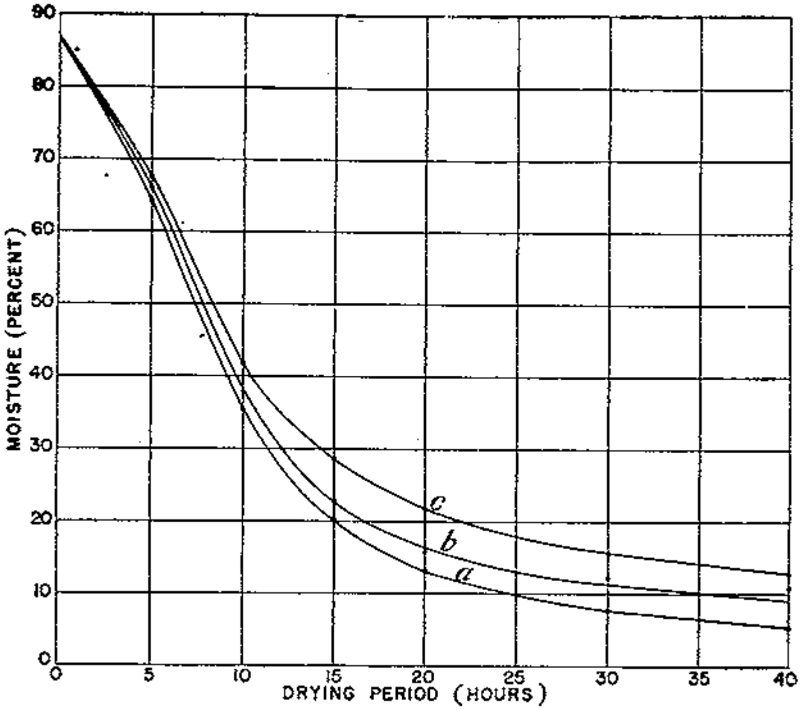


FIGURE 16.—Changes in the moisture content of Kieffer pears (sliced into eighths) during the drying process when atmospheres of different relative humidities were employed: *a*, 7.3 percent; *b*, 24.6 percent; and *c*, 45.8 percent. The temperature was 50° C., the air velocity being 4.15 miles per hour.

TABLE 14.—*Effect of relative humidity on rate of drying Kieffer pears at 35° C. and air velocity of 4.15 miles per hour*

Length of drying period (hours)	Halves				Eighths			
	Relative humidity 16.2 percent		Relative humidity 64.4 percent		Relative humidity 16.2 percent		Relative humidity 64.4 percent	
	Moisture	Water loss	Moisture	Water loss	Moisture	Water loss	Moisture	Water loss
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
6	80.0	32.5	81.0	28.9	73.7	48.0	74.9	46.2
10	75.7	44.4	77.0	41.3	65.0	61.4	66.7	59.4
16	68.8	56.7	70.9	53.6	52.3	71.7	54.5	70.3
20	64.0	62.5	66.3	59.9	42.7	76.4	45.8	75.1
24	58.8	67.2	61.4	65.0	33.2	79.8	37.2	78.5
30	50.6	72.6	54.0	70.6	24.3	82.1	28.3	81.1
36	42.0	76.7	47.4	74.3	19.1	83.3	24.1	82.2
40	36.7	78.0	43.6	76.0	17.0	83.7	22.4	82.6
50	26.5	81.6	35.9	78.9	14.0	84.3	19.8	83.1
60	20.0	83.1	30.5	80.5	12.4	84.5	18.3	83.4
70	15.7	83.9	26.1	81.7	11.5	84.7	17.5	83.6
80	13.0	84.4	22.7	82.5	11.0	85.0	16.8	83.7

At 50° C. the fruit sliced into halves lost 36 percent of water at 45.8 percent humidity and 44.2 percent water at 7.3 percent relative humidity in 5 hours. If the difference in the saturation deficits, or the inverse of the relative humidities, is compared with the difference in the amount of water lost, it will be found that there has been a decrease of 41.5 percent in the saturation deficit and an increase of only 22.7 percent in the amount of water lost. Again it is evident that the rate of drying is limited by some factor other than the moisture-absorbing capacity of the air.

TABLE 15.—*Effect of relative humidity on rate of drying Kieffer pears at 50° C. and air velocity of 4.15 miles per hour*

Length of drying period (hours)	Halves						Eighths					
	Relative humidity 7.3 percent		Relative humidity 24.6 percent		Relative humidity 45.8 percent		Relative humidity 7.3 percent		Relative humidity 24.6 percent		Relative humidity 45.8 percent	
	Moisture content	Water loss	Moisture content	Water loss	Moisture content	Water loss	Moisture content	Water loss	Moisture content	Water loss	Moisture content	Water loss
	Percent	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
5	75.8	44.2	78.1	38.3	78.9	36.0	63.9	62.6	66.0	60.3	67.5	58.4
10	64.2	62.2	67.7	58.2	69.9	55.1	35.2	79.1	37.8	78.3	41.8	76.8
15	46.0	75.0	53.0	71.2	58.3	67.6	20.1	83.1	22.5	82.5	28.0	81.1
20	30.1	80.7	38.1	78.2	46.5	74.7	13.1	84.4	15.7	83.9	21.8	82.7
30	16.8	83.7	22.5	82.5	30.9	80.4	7.0	85.3	------	------	15.7	83.5
40	11.6	84.7	16.6	83.8	23.1	82.4	5.5	85.7	10.9	84.8	12.8	83.9
50	9.2	85.1	13.8	84.3	18.9	83.3	------	------	------	------	------	84.6
60	8.0	85.3	12.3	84.6	16.4	83.8	------	------	------	------	------	------
80	6.5	85.5	10.4	84.9	12.5	84.5	------	------	------	------	------	------

Examination of the fruit at any time during the drying process reveals the fact that the surface is much drier than the inner tissues. It is evident, therefore, that the water diffuses outward rather slowly, and it is believed that this is the principal factor limiting the rate of water loss. Added to this is the retarding effect due to the tendency of the material to absorb and hold rather large quantities of water in moist atmospheres.

From a practical standpoint, all atmospheres having humidities up to 65 percent are quite effective in removing moisture from the fruit during the first part of the drying process. However, the unevaporated water in the material is always much greater at the end of the process with high humidities than with low ones. This suggests that if a very low moisture is desired at the completion of the drying process, relatively dry air must be provided at that time. If, at any time during the first part of the process, the apparatus discharges air not heavily laden with moisture, this air may, with advantage, be recirculated or passed over the fruit again. It would seem from these tests that in most cases it would be advantageous to introduce the fruit at the end of the drier where the air is discharged and to finish the process where the air is introduced. This, of course, will depend somewhat upon the moisture content desired in the product at the finish and the behavior of the fresh fruit at high initial temperatures.

DISCUSSION

EFFECT OF RATE OF DRYING UPON QUALITY OF PRODUCT

In the tests described in the foregoing pages, it has been noted that the rate of drying has more or less influence upon the flavor, color, and form of the finished product. Generally it is desirable for the product to retain as much of the natural flavor of the fresh fruit as is possible. During the drying process enzymes may be active and bring about changes that more or less completely alter the flavor of the product. This is avoided to a considerable extent by rapid drying. The present tests indicate that the Kieffer pear is altered somewhat less rapidly and not quite to the same extent as some other products. However, important changes occur that should be minimized as far as possible. If conditions are such that the drying is delayed, molds and fungi may start growth, in which case the material is completely lost. This frequently occurred in large pieces of fruit where the drying was being conducted in still air. In practice this might occur where trays were loaded with segments two or more layers deep with insufficient air circulation.

It is apparent that the more rapidly the material is dried the better the flavor of the product will be; also that the lower the temperature the better the flavor. However, in drying practice these two factors oppose each other. If, in order to get rapid drying, too high a temperature is used, the quality of the product is lowered. The optimum drying temperature to be used is therefore a compromise between the two opposing factors. It has been concluded that 50° to 55° C. is about the best temperature at which to finish the drying process, from the standpoint of quality. The fresh fruit just introduced into the dryer should not be subjected to this temperature unless the circulation of the air is adequate. In the ripened fruit there is a tendency for the juices to escape, giving rise to the so-called weeping when high temperatures are employed, but this may be prevented at nearly any temperature by using strong currents of dry air. Temperatures as high as 60° C. may be used, but the flavor is not quite so good and there is a slight tendency for the material to collapse or flatten out to an unnatural shape. This tendency rapidly increases above 60°, and at 70° it is so great that it appears inadvisable to use this temperature. Also, the alterations of the flavor increase rapidly above 60° so that at 70° or above the flavor is distinctly less pleasing.

These tests also indicate that as far as temperature and rate of drying are concerned the conditions that make for optimum flavor also make for optimum color. However, temperature is not the most important factor in color preservation. To secure the best color it is necessary to treat the fruit in some manner previous to drying, in order to inactivate the enzymes. This is usually accomplished by treatment with fumes of sulphur dioxide.

FINENESS OF SLICING

From these tests it is obvious that the most effective way of increasing the rate of drying is by subdividing the fruit. It is generally not desirable to divide the fruit into extremely fine segments because of the difficulty of handling during the drying process. Also the finely divided material is not so conveniently prepared, and it is not so attractive as the larger segments. If proper drying conditions are provided, the halves of the largest fruits may be satisfactorily dried, and this method appears to be most generally employed in drying other pear varieties. However, the present tests have led to the conclusion that, when all factors are considered, about the most satisfactory method is to divide the whole fruits into eight segments. The rate of drying is greatly increased over that of the halves and the difficulty of handling appears to be no greater, or even less, and generally this size piece is even more conveniently prepared for table use.

In actual practice, where artificial methods are employed, it is not convenient to maintain a constant temperature throughout the drier. Also, the absolute and the relative humidities must vary in order to make the drying process as economical of fuel as possible. The most economical procedure is to allow the dry, heated air to flow over a layer or layers of fruit for such a distance that the maximum amount of heat will be used in evaporating the water of the fruit. This distance will depend upon the velocity of the air, its temperature and humidity at the beginning, and the manner in which the fruit is exposed. Under practical conditions the temperature of the air decreases continuously along this distance as it becomes more heavily laden with moisture. Although constant conditions were employed in the tests in this study, the results are as applicable to practical problems as to theoretical considerations. If the distance the air must travel to pick up its load of moisture is the problem, it is evident that the size of the fruit, the degree of subdivision, and the hygroscopic nature of the fruit, the changes in temperature and the relative humidity of the air along the distance, as well as many other factors, must be taken into consideration.

Although these tests were repeated a sufficient number of times to make the results fairly reliable, it should be recognized that climatic and soil conditions may vary in different localities; this may affect the moisture content, the sugars, and other hygroscopic materials, as well as the water-imbibing materials. Any change in the amount of these elements will alter the rate of drying to some extent. The shape of the fruit may also vary somewhat, depending upon the conditions of growth, and this will also affect the rate of drying. The results will vary considerably with the method of peeling and coring. Coring, in particular, will influence the time necessary to dry the fruit. While the peeling and coring corresponded to that generally practiced in the trade, it is recognized that different individuals may perform these operations somewhat differently. Therefore, the values in the above tests should be regarded as comparative rather than absolute.

SUMMARY

A study has been made of the rate of drying of Kieffer pears during the entire drying process in atmospheres of different temperatures and relative humidities, and moving at different velocities. The results have been tabulated and illustrated. The fruit dries rapidly at first but gradually slows down toward the end of the process, which apparently is due to the slowness of the diffusion of water from moist to dry tissues, modified by the water-imbibing forces of the solids of the fruit.

Increasing the temperature appears to be the most effective way of increasing the rate of drying. This acts by increasing the rate of

diffusion of the water from the center to the surface of the fruit and decreasing the relative humidity or increasing the moisture-holding capacity of the drying air, and by conveying to the material a greater amount of heat necessary for evaporation.

There is a very great difference in the rate of drying of fruit in still air and in air moving at a relatively slow rate. Increasing the air velocity above a fraction of a mile per hour over small quantities of material was not accompanied by a corresponding increase in the rate of drying. Again this appears to be due to the slowness of the diffusion of water from the center to the surface of the fruit.

The relative humidity appears to affect the rate of drying in somewhat the same way as the velocity of the air current, but the moisture-holding capacity of the solids is so great that the percentage of moisture in the material at the end of the process is very much higher in moist than in very dry air.

The solids in the pear fruits are highly hygroscopic or have a large capacity for absorbing water from moist air. This characteristic appears to minimize the effect of case hardening or the formation of an impervious layer at the surface.

Almost any degree of subdivision may be used provided that the proper drying conditions are employed. It takes a comparatively long time to dry fruit sliced into halves, and while fruit sliced into 32 segments dries immensely faster, it is not so convenient to handle or so attractive when prepared for the table. All things considered, it appears that fruit sliced into eight segments is the most desirable.

There is a very great difference in the rate of drying of peeled and unpeeled halves, but the difference becomes less as the fruit is further subdivided. It appears to be advantageous to peel the fruit because of the increased rate of drying and the improvement of the quality of the product.

There appears to be a small but significant difference in the rate of drying of the ripened and the unripened fruit. The decrease in the rate in the ripened fruit is probably due to the higher percentage of soluble pectin in the ripened fruit or to other physical characteristics.

The drying rates for small and large fruits have been determined on a small number of fruits and appear to be nearly proportional to the weight of the fruit.

LITERATURE CITED

(1) CALDWELL, J. S.
1919. FARM AND HOME DRYING OF FRUITS AND VEGETABLES. U. S. Dept. Agr. Farmers' Bull. 984, 61 pp., illus.

(2) CARRIER, W. H.
1921. THE THEORY OF ATMOSPHERIC EVAPORATION, WITH SPECIAL REFERENCE TO COMPARTMENT DRYERS. Jour. Indus. and Engin. Chem. 13: 432–438, illus.

(3) CRUESS, W. V.
1924. COMMERCIAL FRUIT AND VEGETABLE PRODUCTS. A TEXTBOOK FOR STUDENT, INVESTIGATOR AND MANUFACTURER. 530 pp., illus. New York.

(4) ——— and CHRISTIE, A. W.
1921. SOME FACTORS OF DEHYDRATER EFFICIENCY. Calif. Agr. Expt. Sta. Bull. 337, pp. 277–298, illus.

(5) HAUSBRAND, E.
1933. EVAPORATING, CONDENSING, AND COOLING APPARATUS; EXPLANATIONS, FORMULÆ AND TABLES FOR USE IN PRACTICE. Transl. from 2d rev. German ed. by A. C. Wright. 5th English ed. rev. and enl. by B. Heastie. 503 pp., illus. London.

(6) LEWIS, W. K.
1921. THE RATE OF DRYING OF SOLID MATERIALS. Jour. Indus. and Engin. Chem. 13: 427–432, illus.

(7) LUTZ, J. M., CULPEPPER, C. W., and MOON, H. H.
1934. THE RELATIONSHIP OF RIPENING TEMPERATURES TO THE RATE OF SOFTENING, TEXTURE, AND FLAVOR OF KIEFFER PEARS. Amer. Soc. Hort. Sci. Proc. (1933) 30: 229–232, illus.

(8) ——— CULPEPPER, C. W., MOON, H. H., and MEYERS, A. T.
1933. FACTORS INFLUENCING THE DESSERT AND CANNING QUALITY OF KIEFFER PEARS. The Canner 77 (18) 2: 11–14.

(9) MAGNESS, J. R., and TAYLOR, G. F.
1925. AN IMPROVED TYPE OF PRESSURE TESTER FOR THE DETERMINATION OF FRUIT MATURITY. U. S. Dept. Agr. Circ. 350, 8 pp., illus.

(10) MOON, H. H., and CULPEPPER, C. W.
1934. FACTORS AFFECTING THE QUALITY OF PRESERVES MADE FROM KIEFFER PEARS. Fruit Prod. Jour. 14: 12–16.

(11) NICHOLS, P. F., and CHRISTIE, A. W.
1930. DRYING CUT FRUITS. Calif. Agr. Expt. Sta. Bull. 485, 46 pp., illus.

(12) RICHARDS, C. W., and ROOPE, P. M.
1930. A TANGENT METER FOR GRAPHICAL DIFFERENTIATION. Science (n.s.) 71: 290–291, illus.

(13) SHERWOOD, T. K., and COMINGS, E. W.
1933. THE DRYING OF SOLIDS. MECHANISM OF DRYING CLAYS. Indus. and Engin. Chem. 25: 311–316, illus.

ORGANIZATION OF THE UNITED STATES DEPARTMENT OF AGRICULTURE WHEN THIS PUBLICATION WAS LAST PRINTED

Secretary of Agriculture	HENRY A. WALLACE.
Under Secretary	M. L. WILSON.
Assistant Secretary	HARRY L. BROWN.
Director of Extension Work	C. W. WARBURTON.
Director of Finance	W. A. JUMP.
Director of Information	M. S. EISENHOWER.
Director of Personnel	W. W. STOCKBERGER.
Director of Research	JAMES T. JARDINE.
Solicitor	MASTIN G. WHITE.
Agricultural Adjustment Administration	H. R. TOLLEY, *Administrator*.
Bureau of Agricultural Economics	A. G. BLACK, *Chief*.
Bureau of Agricultural Engineering	S. H. MCCRORY, *Chief*.
Bureau of Animal Industry	JOHN R. MOHLER, *Chief*.
Bureau of Biological Survey	IRA N. GABRIELSON, *Chief*.
Bureau of Chemistry and Soils	HENRY G. KNIGHT, *Chief*.
Commodity Exchange Administration	J. W. T. DUVEL, *Chief*.
Bureau of Dairy Industry	O. E. REED, *Chief*.
Bureau of Entomology and Plant Quarantine	LEE A. STRONG, *Chief*.
Office of Experiment Stations	JAMES T. JARDINE, *Chief*.
Farm Security Administration	W. W. ALEXANDER, *Administrator*.
Food and Drug Administration	WALTER G. CAMPBELL, *Chief*.
Forest Service	FERDINAND A. SILCOX, *Chief*.
Bureau of Home Economics	LOUISE STANLEY, *Chief*.
Library	CLARIBEL R. BARNETT, *Librarian*.
Bureau of Plant Industry	FREDERICK D. RICHEY, *Chief*.
Bureau of Public Roads	THOMAS H. MACDONALD, *Chief*.
Soil Conservation Service	H. H. BENNETT, *Chief*.
Weather Bureau	WILLIS R. GREGG, *Chief*.

This bulletin is a contribution from

Bureau of Plant Industry	FREDERICK D. RICHEY, *Chief*.
Division of Fruit and Vegetable Crops and Diseases.	E. C. AUCHTER, *Principal Horticulturist, in Charge*.

U. S. GOVERNMENT PRINTING OFFICE: 1937

For sale by the Superintendent of Documents, Washington, D. C. - - - - - Price 5 cents

END